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16. Abstract

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 stablization of highway pavements and railroad grade crossings.

Equations are developed for the resilient modulus and the residual strain for fine grained soils with clay contents within the range tested. The most important terms in the equations are the number of load cycles and the soil suction, although the other factors that enter into the equations are degree of saturation, volumetric moisture content, volumetric soil content, deviator stress, and mean principal stress. Changes in the dynamic properties due to temperature variations from 72°F (22°C) are determined by a temperature correction factor for which another equation has been developed for each of the two dynamic properties.

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The powers and the constants of the equation for the resilient modulus temperature correction factor are related to the clay content and the plastic limit of the soil. The powers and the constants of the equation for the residual strain temperature correction factor are related to the clay content and the percent passing the #200 sieve. All of the equations have coefficients of determination above 0.50, which is better than any other published results on these dynamic properties.

The equations developed are to help the design engineer to incorporate the resilient modulus, residual strain and climatic conditions into design procedures for highway pavements and railroads, and especially in areas where the dynamic loading is important as, for example, in the case of intersections, railroad grade crossings, and bridge approaches.

DYNAMIC PROPERTIES OF SUBGRADE SOILS,

INCLUDING ENVIRONMENTAL EFFECTS

by

Earl V. Edris, Jr.

and

Robert L. Lytton

Research Report Number 164-3

Structural and Geometric Design of
Highway-Railroad Grade Crossings

Research Study 2-18-74-164

Sponsored by the
State Department of Highways and Public Transportation
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Federal Highway Administration

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

May, 1976

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PREFACE

This report describes the repetitive load testing of three different subgrade soils. The resilient modulus and the residual strain are studied in terms of the soil suction, deviator stress, temperature, degree of saturation, number of load cycles, and volumetric soil and moisture content. The initial behavior of the soils is related to the Thornthwaite Moisture Index. This report is one of a series of reports from the study entitled "Structural and Geometric Design of Highway-Railroad Grade Crossings." The study, sponsored by the State Department of Highways and Public Transportation in cooperation with the Federal Highway Administration is a comprehensive program to study the problems encountered at highway-railroad grade crossings, and to recommend methods of improving the serviceability of the crossings.

DISCLAIMER

LIST OF REPORTS

Report No. 164-1, "Structural and Geometric Characteristics of Highway-Railroad Grade Crossings," by Thomas M. Newton, Robert L. Lytton, and Robert M. Olson, describes the crossing distribution and geometric characteristics, crossing appraisals, drainage, dynamic loading, stabilization fabrics, and structural details for improved life and rideability.

Report No. 164-2, "Users Manual With Complete Description of Revised Program DYMOL," by Aziz Ahmad and Robert L. Lytton describes the revisions to the computer program DYMOL, including input formats of the program.

Report No. 164-3, "Dynamic Properties of Subgrade Soils, Including Environmental Effects," by Earl V. Edris, Jr., and Robert L. Lytton describes the work done in the repetitive load testing of subgrade soils and how the resilient modulus and residual strain of these soils are related to the climatic conditions.

ABSTRACT

Dynamic Properties of Subgrade Soils, Including Environmental Effects

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 railroad grade crossings.

Equations are developed for the resilient modulus and the residual strain for fine grained soils with clay contents within the range tested. The most important terms in the equations are the number of load cycles and the soil suction, although the other factors that enter into the equations are degree of saturation, volumetric moisture content, volumetric soil content, deviator stress, and mean principal stress. Changes in the dynamic properties due to temperature variations from 72^{o}F (22^{o}C) are determined by a temperature correction factor for which another equation has been developed for each of the two dynamic properties. The powers and the constants of the equation for the resilient modulus temperature correction factor are related to the clay content and the plastic limit of the soil. The powers and the constants of the equation for the residual strain temperature correction factor are related to the clay content and the percent passing the #200 sieve. All

IMPLEMENTATION STATEMENT

In Texas there are many areas where dynamic loading is important for example: highway-railroad grade crossings, intersections, and bridge approaches. A major reason for poor performance of these areas is the lack of design procedures incorporating the environmental conditions with the dynamic properties of the soil.

The data presented in this report represent a significant step forward in the prediction of the resilient modulus and residual strain. The relationships use volumetric soil and moisture content, degree of saturation, soil suction, deviator stress, mean stress, number of load cycles, and temperature. All of these terms may be determined in the laboratory or in the field, and by analysis.

The test results show a distinct change in behavior when the soils change from "effectively saturated" to "effectively unsaturated," at a point two percent dry of the optimum moisture content. This point where the behavior changes is related to the clay content of the soil and to a climatic moisture index.

Different types of soils have different indexes where the behavior changes. For any soil that has a wetter environment than this critical index, soil stabilization is necessary to prevent deterioration of the pavement areas where dynamic loading is important. Generally speaking, these data show that all pavements east of a line from Childress, Texas to Corpus Christi, Texas will require more pavement structure (thicker and/or stiffer) above them, particularly when dynamic loads are expected.

of the equations have coefficients of determination above 0.50, which is better than any other published results on these dynamic properties.

The equations developed are to help the design engineer to incorporate the resilient modulus, residual strain and climatic conditions into design procedures for highway pavements and railroads, and especially in areas where the dynamic loading is important as, for example, in the case of intersections, railroad grade crossings, and bridge approaches.

CHAPTER I

INTRODUCTION

The performance of highway pavements is controlled by the traffic loading, the properties of the materials encompassed in the pavement system, and the climatic condition. The important factors in the climate 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 subgrade soils are usually unsaturated, and their properties change as the temperature and the amount of water available to the subgrade changes. These two climatic variables should be included in the design of a pavement system because they significantly affect the performance of the pavement.

For many years highway pavements were designed to withstand static loads, but recently the trend has been to design pavements to withstand dynamic loads, which are the actual conditions caused by highway traffic. To design for dynamic loads, the dynamic properties of the different materials within the highway system must be known. The dynamic properties used to describe the subgrade soils are the resilient modulus and the residual strain which are obtained through repetitive load tests. Previous research by Shackel (36)* has shown that it should be possible to predict the resilient modulus and residual strain by knowing the soil suction and the stress condition in the soil. In this report, 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 soils with Unified Soil Classifications of ML, CL, and CH. By knowing how these subgrade soils behave in different climates, better pavements can be designed including the special pavement areas where dynamic pavement loading is important as, for example, in the case

*Numbers in parentheses refer to the corresponding items in the List of References.

of intersections and railroad grade crossings.

The climatic moisture index used in this study is the Thornthwaite Moisture Index, with which the soil suction has been related. Thornthwaite (40) developed this index to measure the climatic moisture in terms of rainfall and evapo-transpiration. This moisture index is:

$$I = \frac{100S_o - 60d}{E_p}$$

where:

S_o = yearly surplus of water in inches

d = yearly deficit of water in inches

E_p = yearly potential evapo-transpiration in inches.

Figure 1 shows how the Thornthwaite Moisture Index is distributed throughout Texas. Russam (20) developed the relationship shown in Figure 2 between soil suction at depths below seasonal influences and the Thornthwaite Moisture Index. Using this relationship, Carpenter (4) predicted the equilibrium suction for a clay subgrade that would be developed in Texas as shown in Figure 3. By knowing the location, the Moisture Index, and the soil type, the equilibrium soil suction can be determined.

The temperature influences the behavior of base course and subgrade soils by affecting the amount and ease of movement of the available water. Carpenter (6) has shown how the base course of pavements in west Texas react to freeze-thaw action. Although the subgrade in this area seldom freezes, a large temperature range is experienced as shown in Figure 4 (5). Wilkinson (41) and Taylor (38) have shown that as the temperature increases the soil suction decreases. This means that as the temperature increases there is more free water available to the soil. For a silty soil, the change in soil suction between 44^oC (111.2^oF) and 4^oC (39.2^oF) was about 17% (41). The major effect of the temperature on soil properties is in the way it affects the availability of the soil water, which in turn greatly affects the thermal coefficient of expansion and contraction.

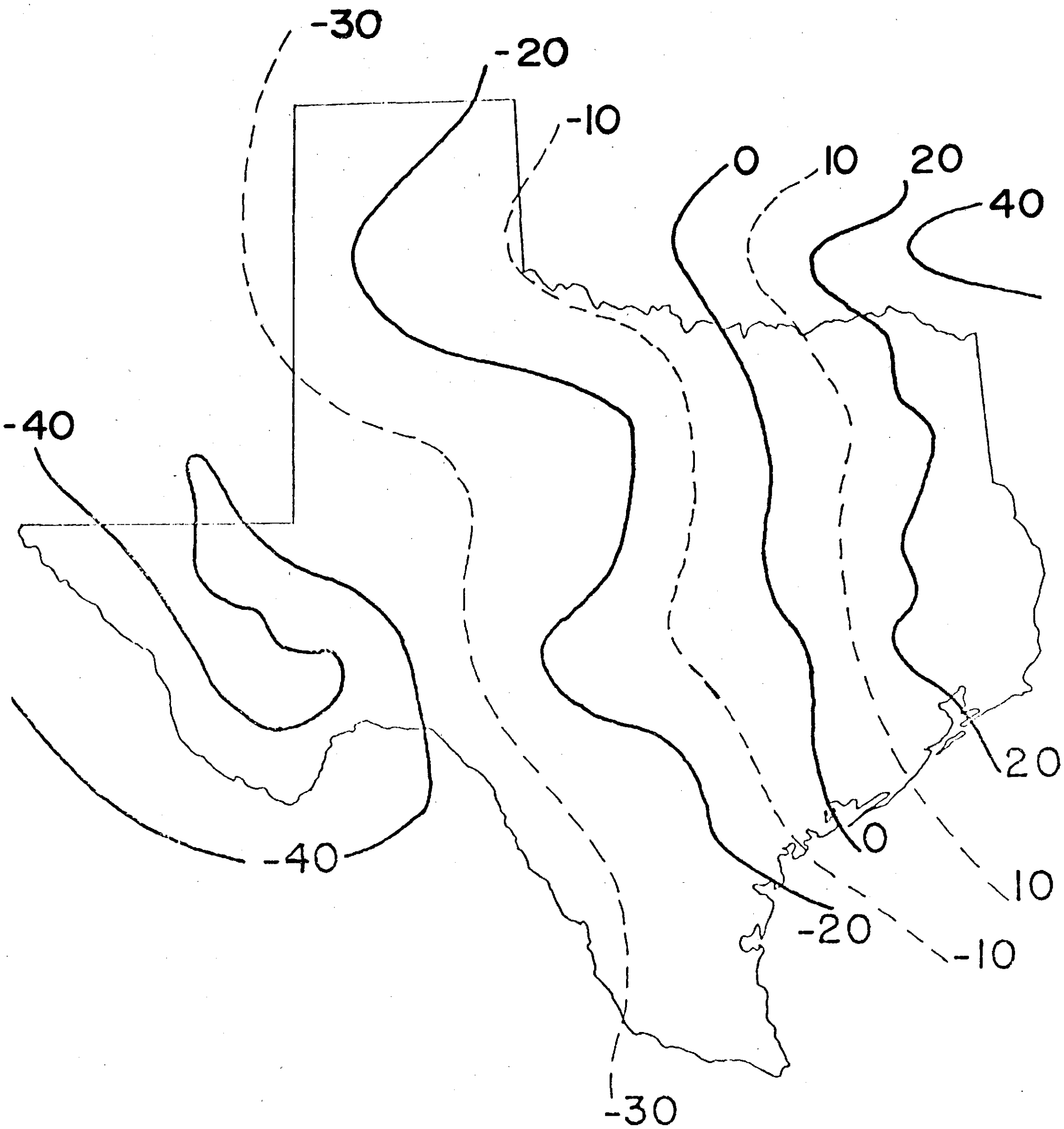


Figure 1. Thornthwaite Moisture Index Distribution in Texas (40)

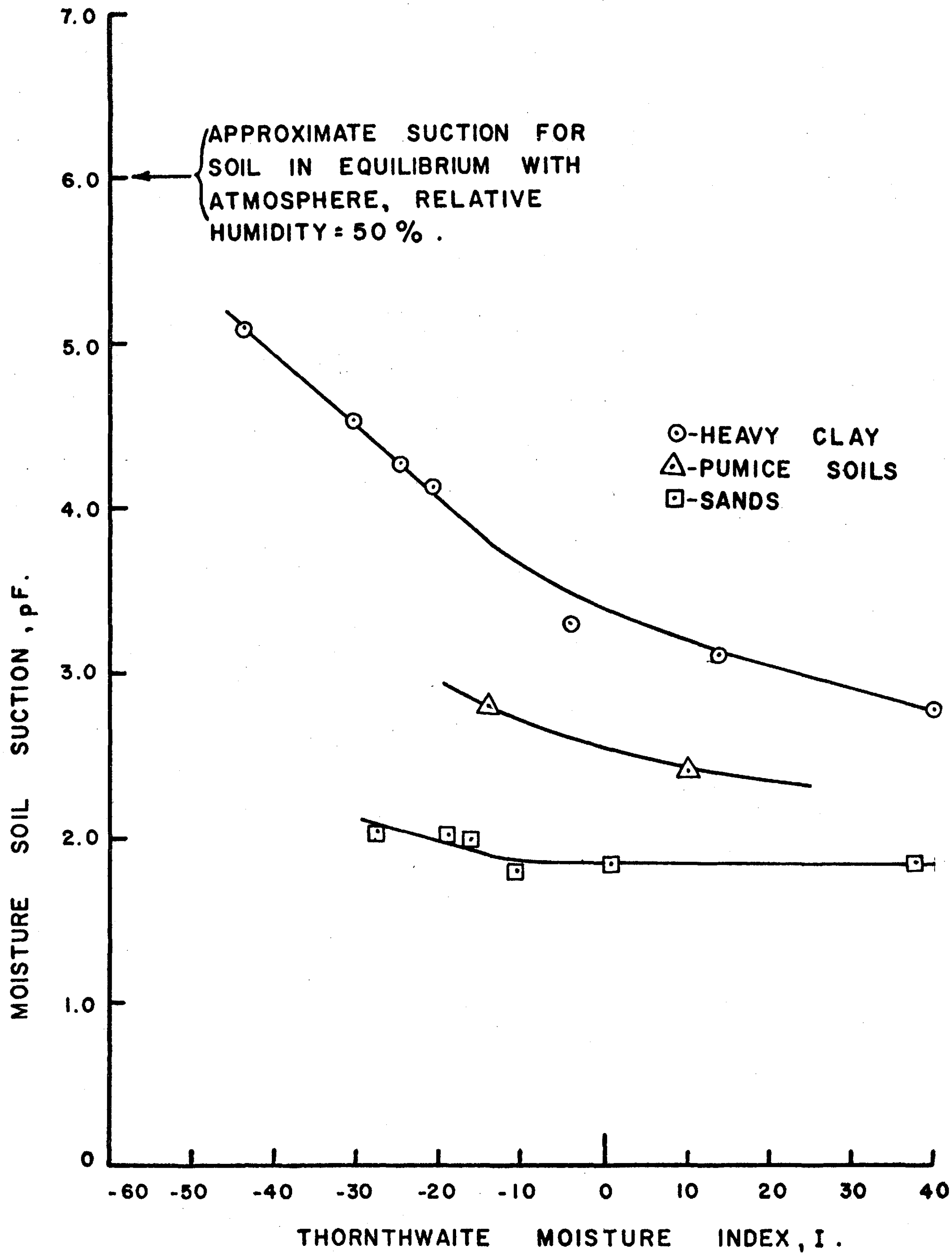


Figure 2. Subgrade Soil Suction as a Function of the Thornthwaite Moisture Index (20)

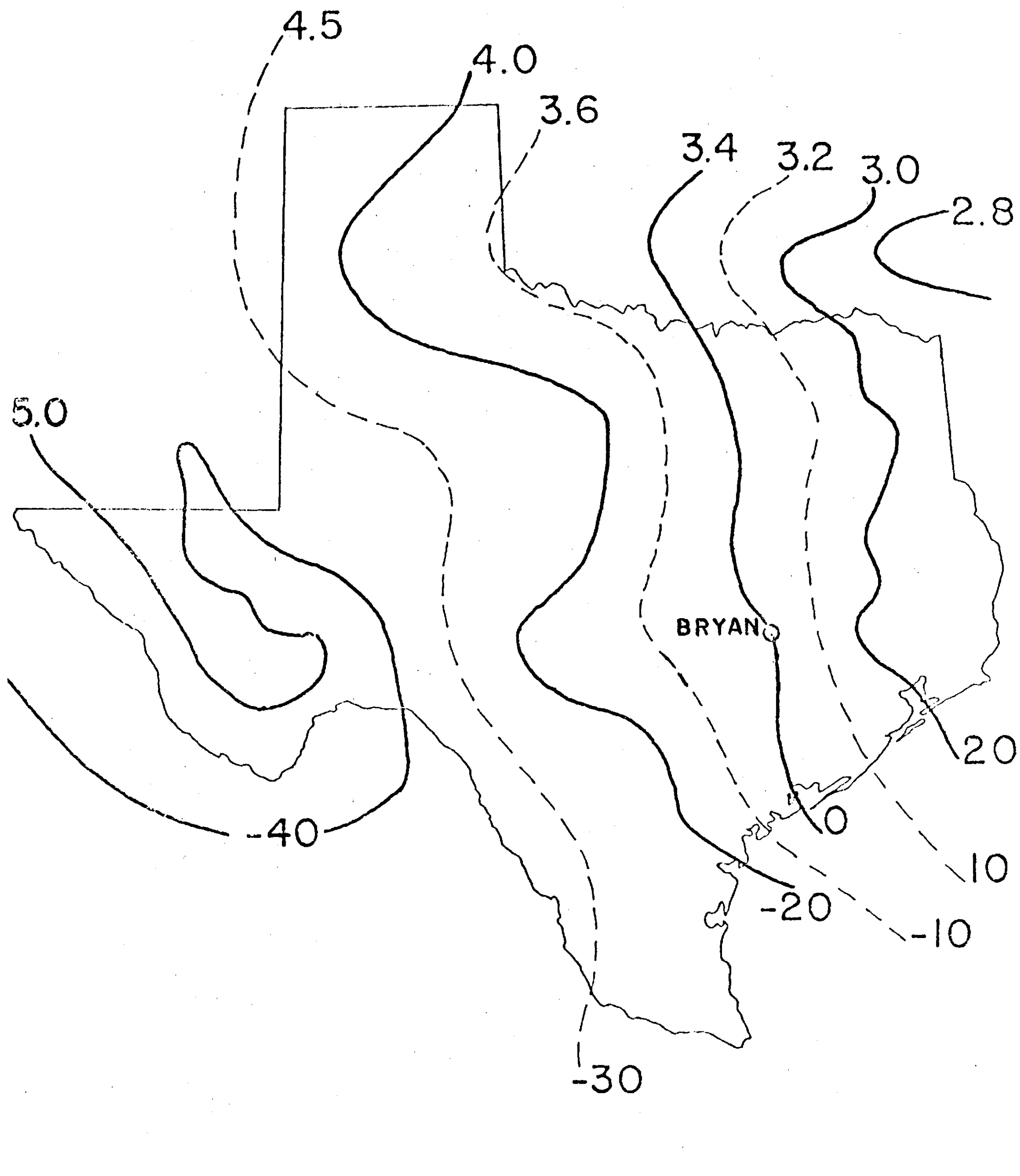


Figure 3. Predicted Soil Suction for a Clay Subgrade Below a Pavement (Upper Value, pF = log(cm of H_2O) Based on the Thornthwaite Moisture Index (4)

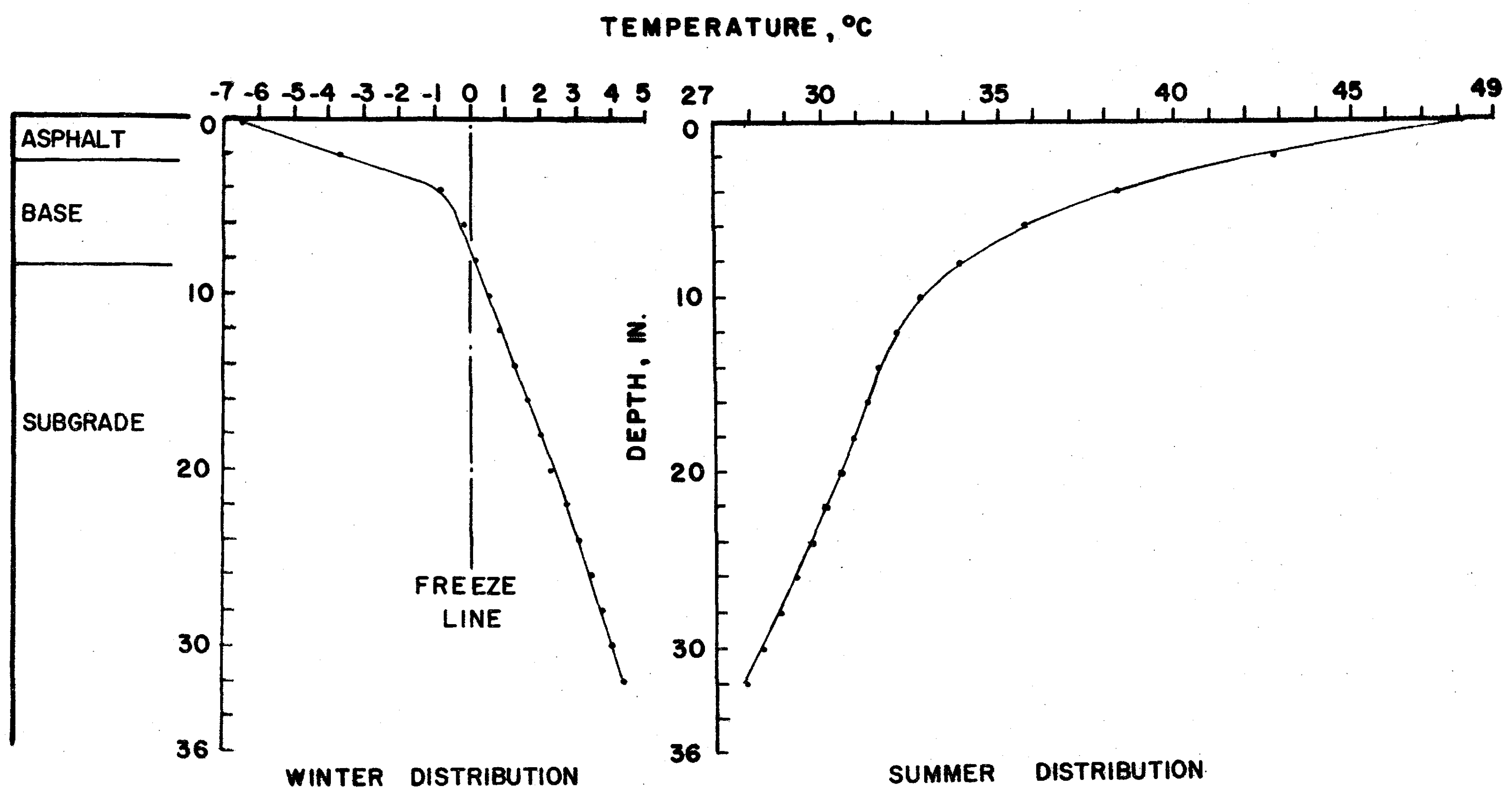


Figure 4. Temperature Distribution for Perryton, Texas (5)

Definitions

There are several terms which need to be defined:

Resilient deformation or recoverable deformation is that portion of the total deformation that is recovered after the load is removed, see Figure 5.

Residual deformation or plastic deformation is that portion of the total deformation that is not recovered before the next load application, see Figure 5.

Resilient strain or elastic strain is the ratio of the resilient deformation to the sample length.

Residual strain or plastic strain (ε_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.

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 soil suction or soil water potential consists of five major components:

a) osmotic or solute potential
b) matrix or capillary potential
c) gas pressure potential
d) gravitational potential
e) overburden pressure or structural potential.

The sum of these components comprises the total soil water potential. All of the above components of soil water potential, except (e), have been defined by the International Society of Soil Science (17). Overburden pressure is the influence of depth on the soil suction (14). This component of soil suction is only important at great depths in fine grained soils.

For the problem being dealt with, the gas pressure potential, gravitational potential, and the overburden pressure potential have such little effect on the total soil water potential that they need not be considered. Thus the total suction consists of the osmotic suction and the matrix suction. The osmotic suction is the suction

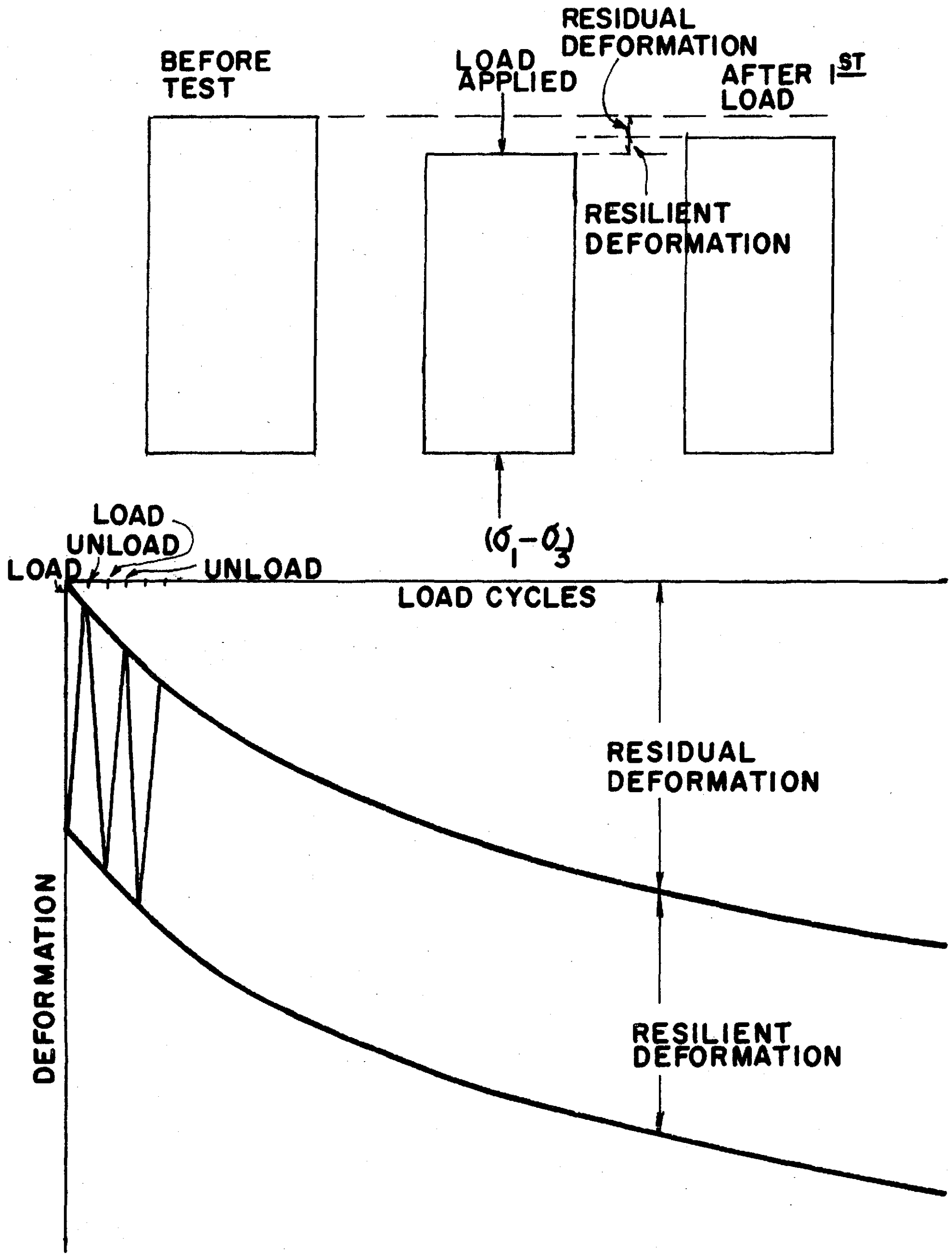


Figure 5. Residual and Resilient Deformations

due to the dissolved salts in the pore fluid, and the matrix suction is the suction due to the hydrostatic tension of the pore water (6).

The total soil suction can be measured as the negative gage pressure relative to the external gas pressure on the soil water, which in turn, can be determined by measuring the vapor pressure in equilibrium with the soil water. Thus 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):

$$h = \frac{RT}{gm} \log_e (P/P_o)$$

where:

R = gas constant, 8.314×10^7 ergs/^oC mol.

T = absolute temperature, ^oC

g = gravitational force, 981 cm/sec^2

m = molecular weight of water, 18.02

P = vapor pressure of soil water

P_o = vapor pressure of free water

P/P_o 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 used in this report for ease of discussion. Thus, a suction of -142 psi is referred to as a suction of 142 psi.

<u>Present Status</u>

Repetitive load testing has been used for the past 20 years in research to develop a better highway system. Most of the studies have been concerned with determining the dynamic properties of granular base course and subgrade materials. Nearly all the studies have tried to simulate the conditions that occur within the pavement system.

An early study of the factors affecting resilient properties was done by Seed, Chan, and Monismith (22) in 1955. This study showed that repeated loading of a sample produced more deformation than static loading. The concepts of resilient strain, residual strain and resilient modulus were established. This study of a silty clay showed the resilient modulus increased as the deviator stress increased.

Seed and McNeill (23, 24) reported the findings of two follow up studies. From these papers the results from the first study were reinforced. Also these studies showed a number of additional conclusions. Several of the most relevant conclusions are: (1) the higher the degree of compaction (range from 90-95 Modified AASHTO) the smaller the resilient deformation, (2) the characteristics of compacted clays change during the beginning of the test, and (3) slightly greater deformations occur when the confining pressure is pulsed in conjunction with the deviator stress. This increase caused by the pulsed confining pressure was not appreciably different from the results using a static confining pressure. In 1958, Seed and Chan (25) along with Seed, McNeill, and DeGuenin (26) reported that the frequency of stress applications affects the deformation of the sample. Also they reported that with a large number of stress applications the resilient strain of a clay soil decreased.

During the 1960's, there were several repetitive load test programs dealing with granular base course material. Dunlap and a number of graduate students at Texas A&M University had an extensive repeated loading program. Several graduate students (1, 10, 15) studied the effects of different confining pressures, the effects of different rate and frequency of loading, and the properties of different base course materials. Dunlap (9) developed a deformation law for base courses based on the confining stress. In 1967, Seed et al. (27) reported a unique relationship between the resilient modulus and the confining pressure of granular materials. In addition to base course material, Seed also tested some subgrade material that showed the resilient modulus varying with the applied stress. In addition it was reported that the degree of saturation affected the resilient deformation of the base course material. Larew and Leonards (13) developed the idea of a critical level of repeated deviator stress for fine-grained soils. They said that when the critical level is exceeded, shear failure occurs. This critical stress was related to the dry density and the moisture content. As the moisture content increased, saturation increased and the critical stress decreased. Thus, as the degree of saturation increased, the resilient deformation increased.

In the past few years, two programs have tried to relate the resilient modulus and the residual strain to the moisture properties of the soils. In 1971, Culley (7) reported the effect of several moisture properties on the resilient and residual strains of a glacial till material subjected to repetitive loading. Figures 6 and 7 show the effect of moisture content, saturation, and dry density on resilient modulus and residual strain. These figures show that over a small range, dry density is not influential in determining the dynamic properties. In a program currently in progress, Thompson and Robnett (39) are relating the resilient modulus of different fine grain soils to saturation, volumetric moisture content, Atterberg limits and deviator stress. None of their tests had confining pressure, and the deviator stress was increased during the tests. Figure 8 shows a typical resilient modulus, deviator stress relationship. At one deviator stress, the relationship that shows the best promise is the saturation or volumetric moisture content versus resilient modulus. The above studies show that for a fine-grain soil the best relationship with the resilient modulus and residual strain contains the saturation or the moisture content.

None of the previous studies used soil suction in trying to explain the changes in resilient modulus or residual strain. Seed showed the importance of saturation in relation to the dynamic properties for base course material, while Culley and Thompson used fine-grained soil. Besides saturation, moisture content, both

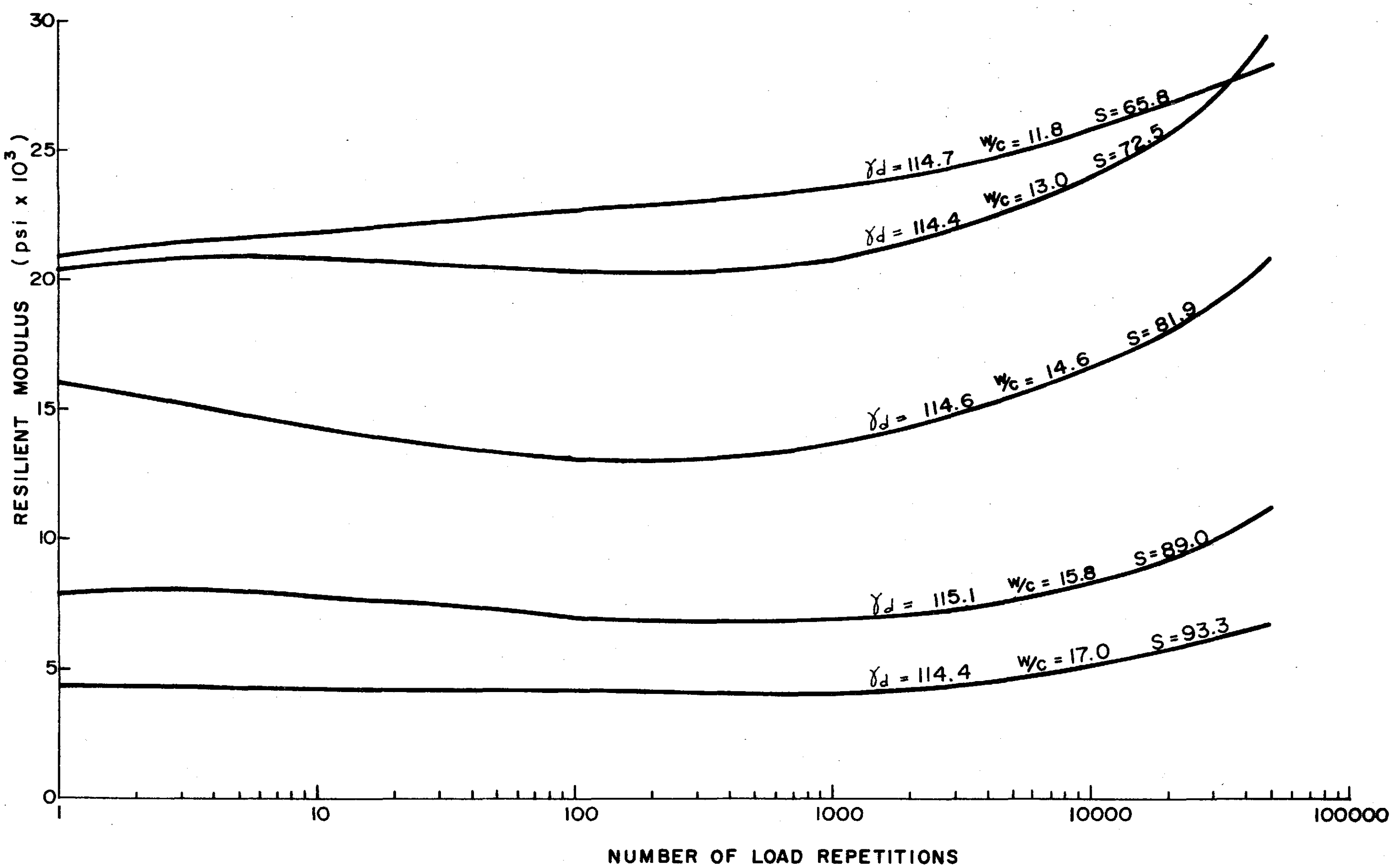


Figure 6. Resilient Modulus of Glacial Till Subgrade Soil as a Function of the Number of Load Cycles (7)

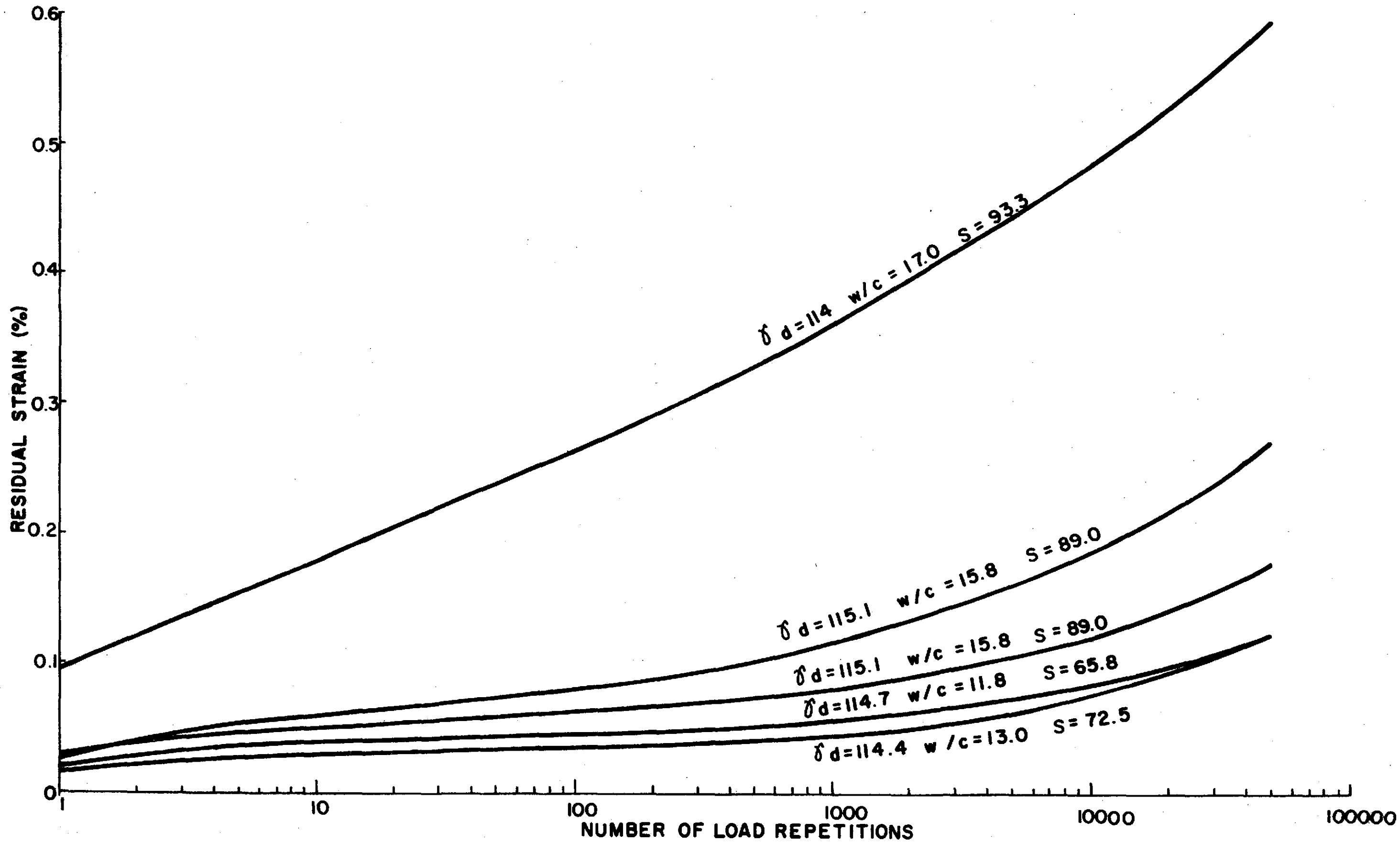


Figure 7. Residual Strain of Glacial Till Subgrade Soil as a Function of the Number of Load Cycles (7)

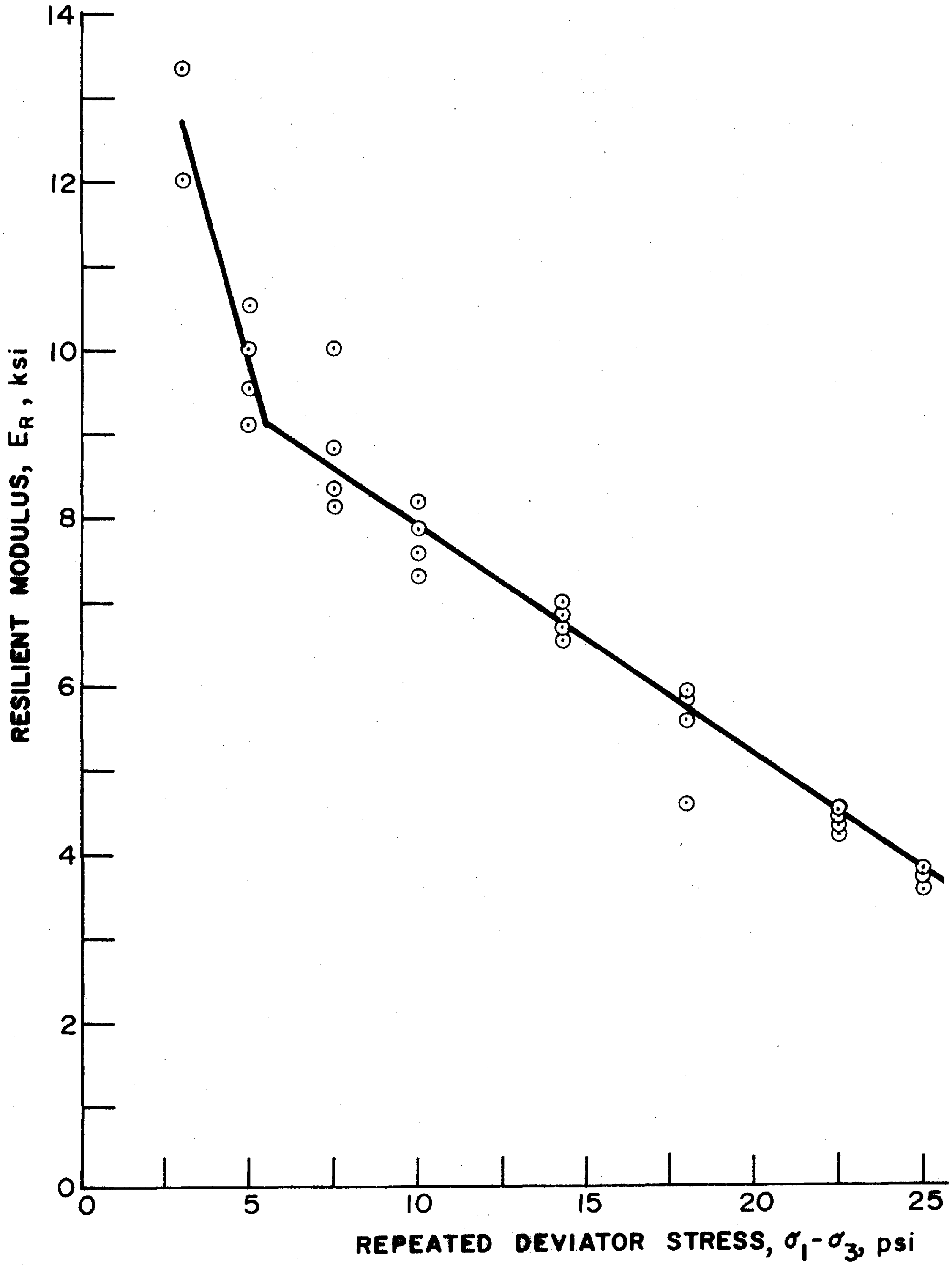


Figure 8. Resilient Modulus of Illinois Subgrade Soil as a Function of the Deviator Stress (39)

gravimetric and volumetric, has been related with the dynamic properties for fine grain soils by Culley and Thompson (7, 39). Soil suction is directly related to moisture content and saturation along with the internal stress state in the soil. Thus there should be a good relationship with the resilient modulus and the residual strain. Since the late 1960's, three studies have been reported in which the soil suction was measured and used in explaining the dynamic behavior of the soil.

Richards, et al. (18) reported the earliest study. This study was performed on an expansive clay in Australia. The soil suctions were measured by the psychrometric technique, after the sample was compacted and after the sample was brought to an equilibrium suction and tested. As seen in Figure 9, the resilient modulus versus suction graph varied with the compactive effort and the compactive moisture content.

Sauer and Monismith (21) performed field and laboratory tests on the same glacial till used by Culley. The authors measured the in-situ soil suction, using the gypsum block technique (see Table 2 in Chapter 2 for the different methods of measuring soil suction). Following this the authors compacted laboratory samples for repeated loading tests and soil suction tests. The soil suction, in the laboratory, was measured by use of the pressure plate technique (see Table 2), which is inferior to the psychrometric technique. Figures 10 and 11 show that the authors found that resilient strain and residual strain were dependent upon the moisture content. By using the relationship shown in Figure 12, they developed Figures 13 and 14. These figures show that for a soil suction variation from 0 to 110 psi (759 kN/m^2) the resilient modulus varied from 2,000 to 22,000 psi (13800 to 151800 kN/m^2) while the residual deformation varied from 0.60% to 0.015%. Sauer and Monismith concluded that to evaluate the engineering properties of soil, the soil moisture properties must be specified. The authors stated that the results are a first approximation of the range and magnitude of the values that could be expected with the glacial till tested. This report demonstrated the need of evaluating the soil properties in regard to the moisture environment during repeated load testing.

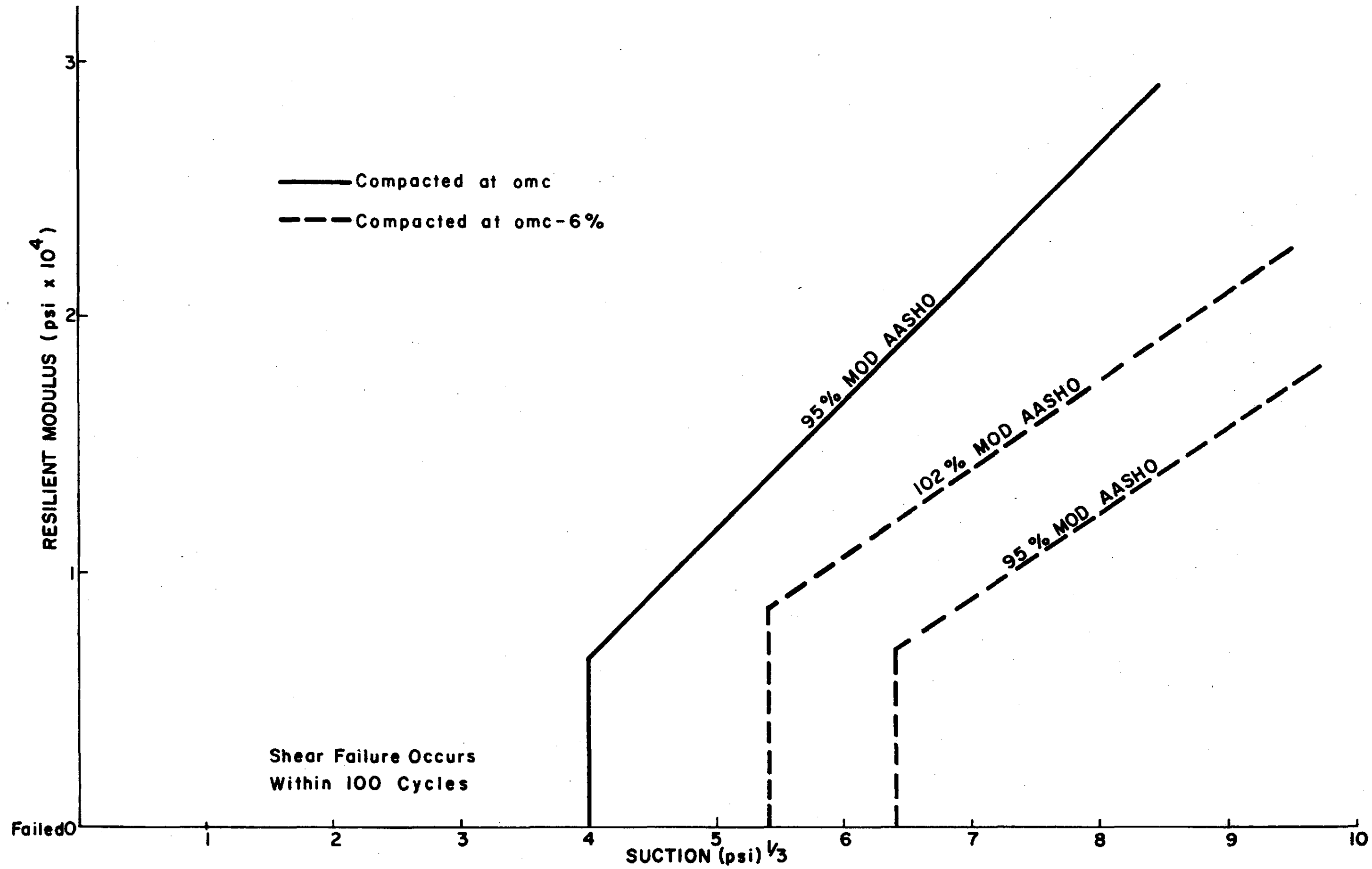


Figure 9. Resilient Modulus of Australian Clay as a Function of the Soil Suction (18)

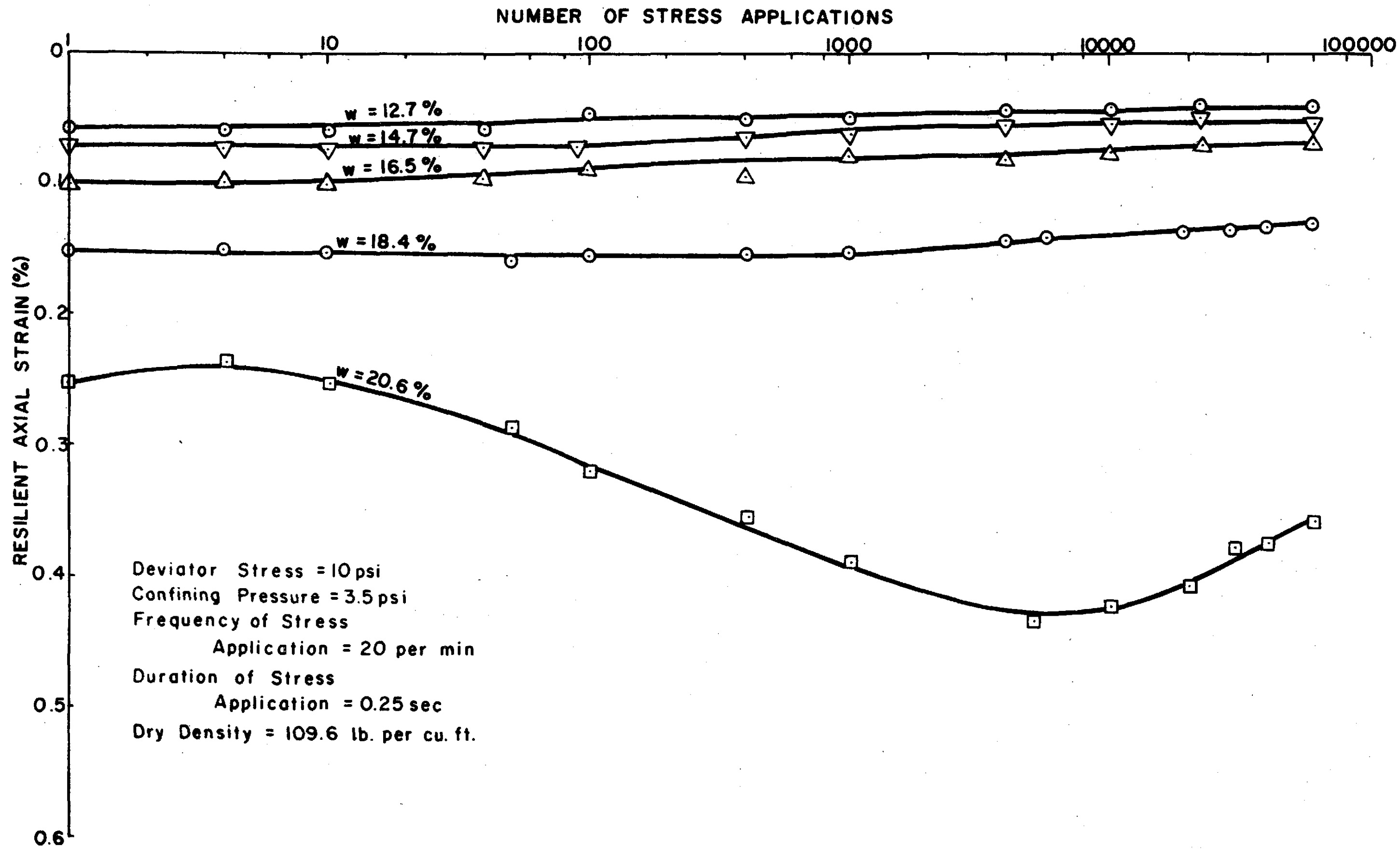


Figure 10. Relationship Between Resilient Strain, Molding Moisture Content, and Number of Stress Applications for Glacial Till Subgrade (21)

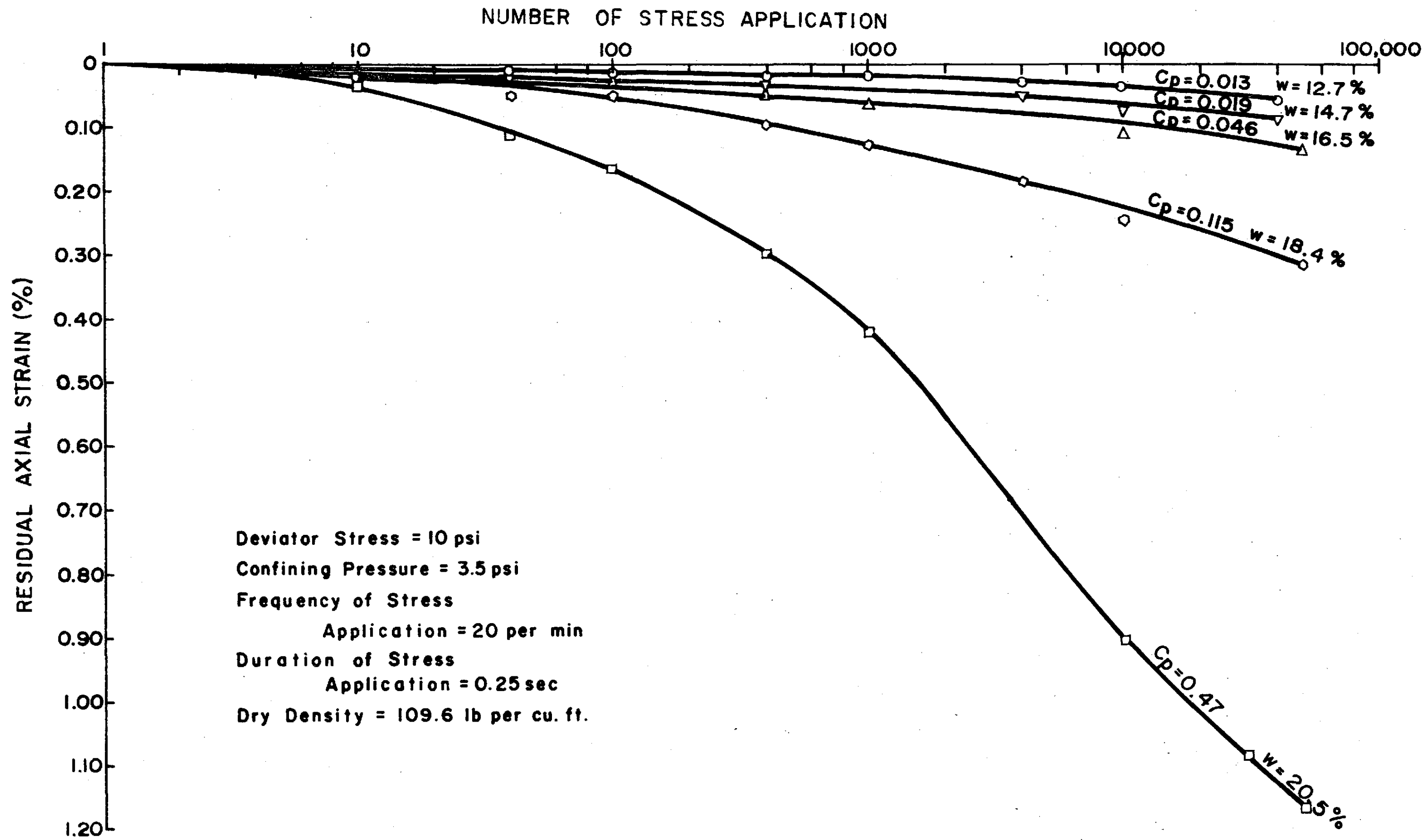


Figure 11. Relationship Between Residual Strain, Molding Moisture Content, and Number of Stress Applications for Glacial Till Subgrade (21)

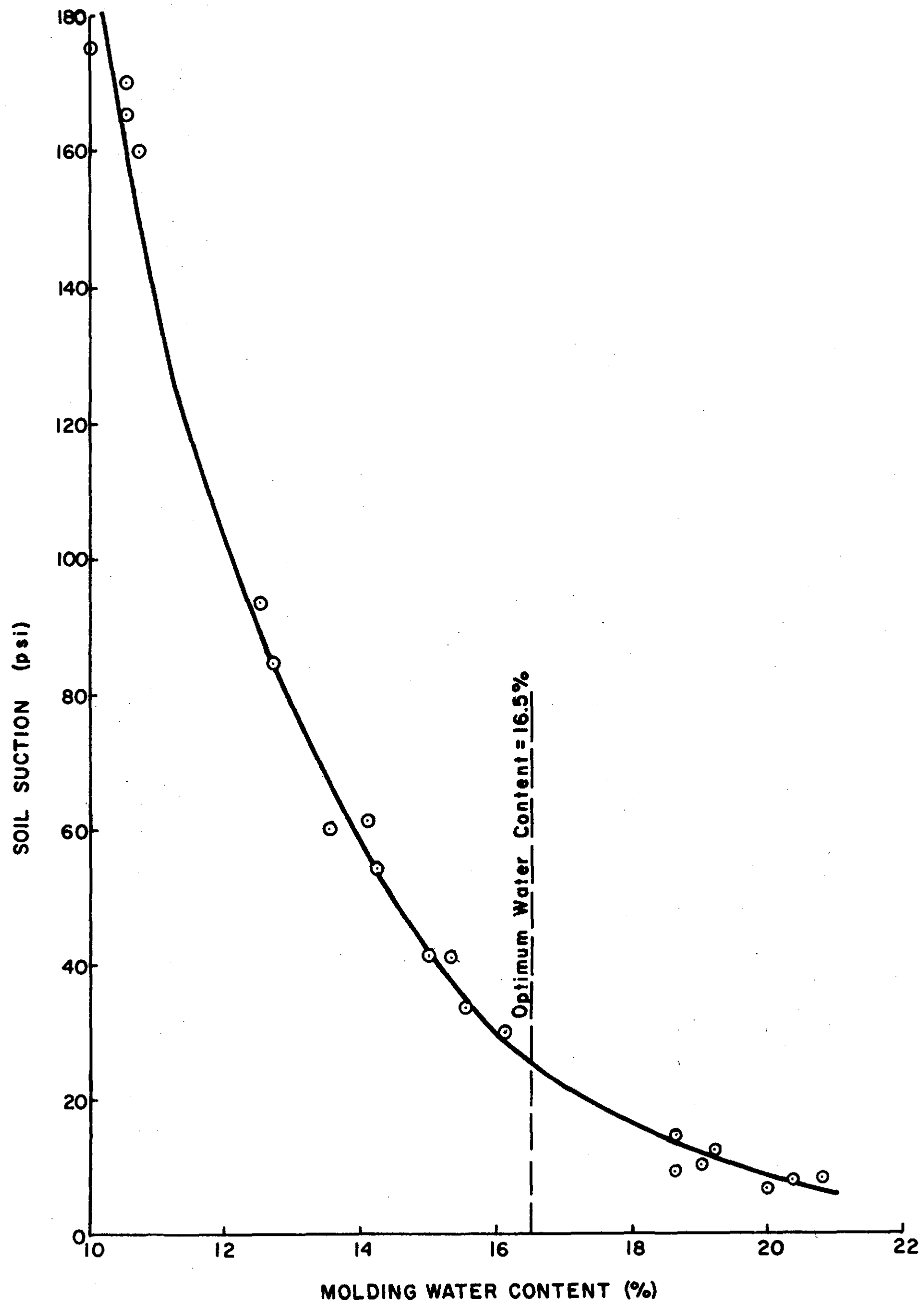


Figure 12. Soil Suction, Moisture Content Relationship for Laboratory Samples of Glacial Till (21)

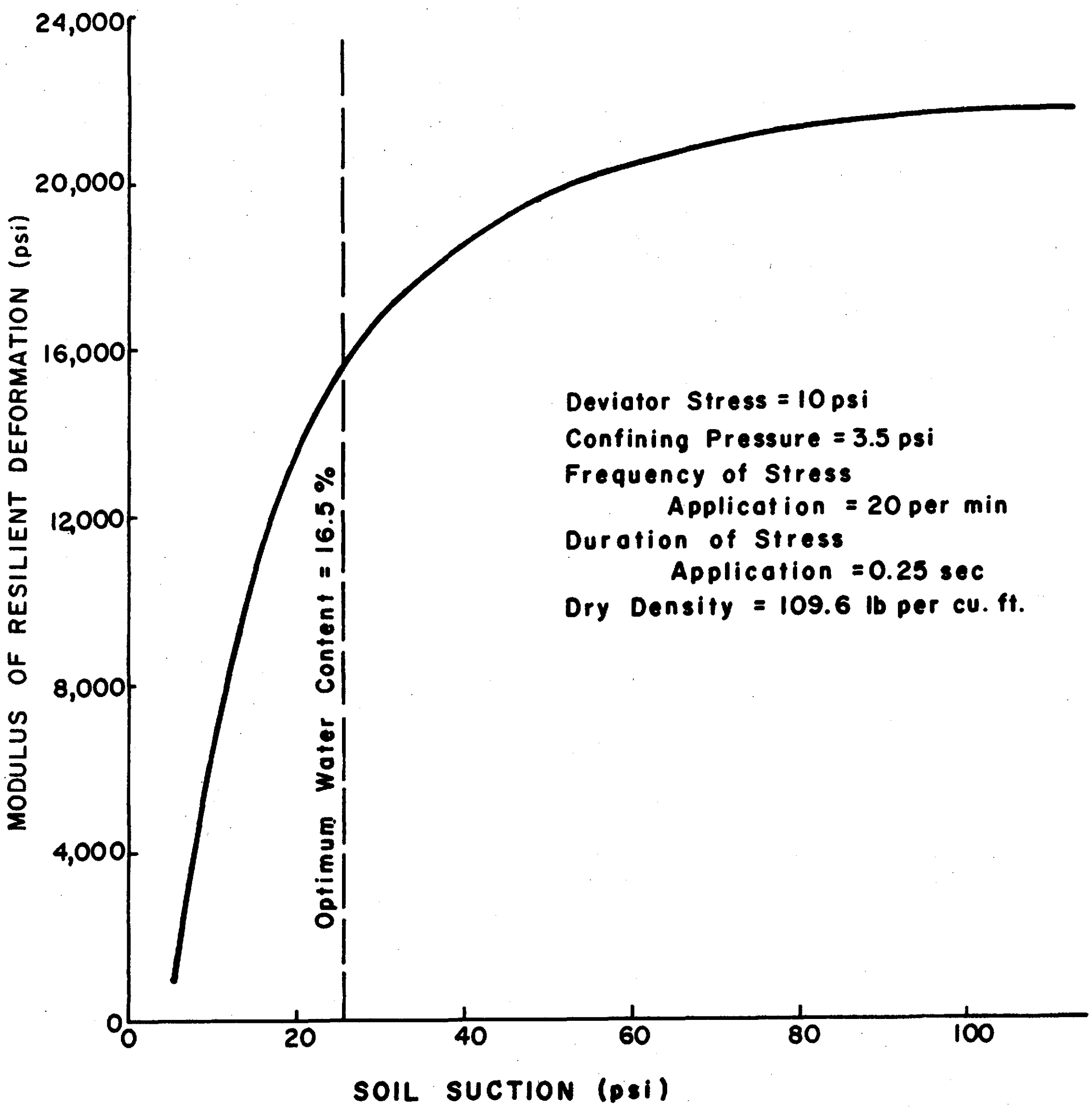


Figure 13. Resilient Modulus of Glacial Till as a Function of the Soil Suction (21)

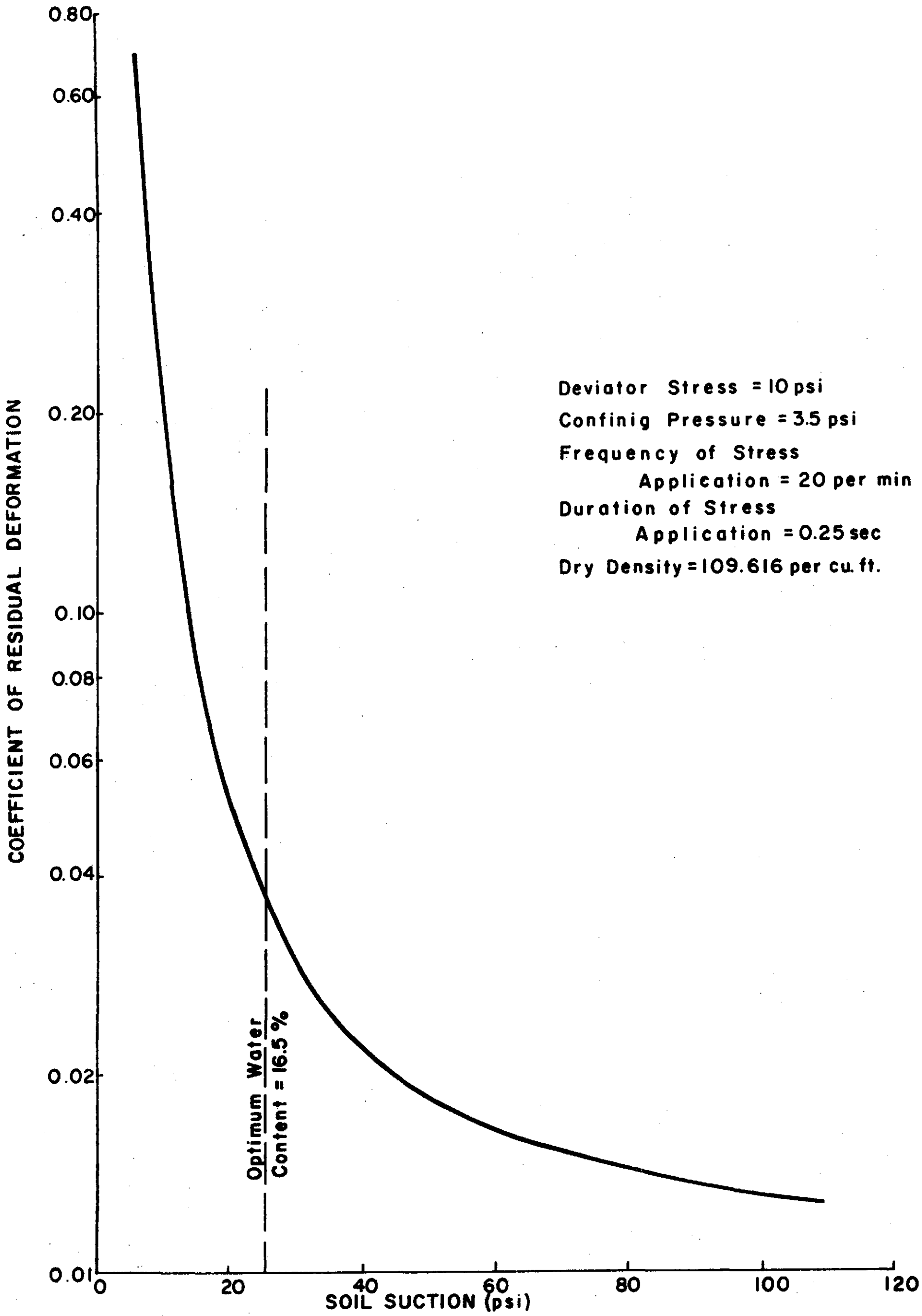


Figure 14. Coefficient of Residual Deformation of Glacial Till as a Function of Soil Suction (21)

Within the past few years Shackel (35, 36, 37) has published some reports dealing with the repeated load testing of a kaolinite-sand mixture. Shackel's objectives were to relate dry density, saturation, compressive and tensile strengths, and soil suction to the resilient and residual behavior of the soil. Shackel used a static compaction method to obtain uniform samples. Johnson and Sallberg (11) report that static compaction produces a different soil structure than the soil structure in the field. Based on the results of his tests, Shackel proposed the following deformation law for resilient modulus (M_R) and residual strain (ε_p):

$$M_R = k_m \frac{\sigma_{oct}^{x}}{\tau_{oct}^{y}}$$

and

$$\varepsilon_p = k_p \frac{\tau_{oct}^{a} N^{w}}{\sigma_{oct}^{b}}$$

where σ_{oct} = octahedral normal stress

τ_{oct} = octahedral shear stress

k_m, k_p, x, y, a, w, b = empirical constants.

Using a pressure membrane apparatus to measure the soil suction, Shackel showed that soil suction is related to dry density and saturation. He shows in Figures 15, 16, and 17 that: (1) soil suction decreases during repeated loading tests, (2) as the initial soil suction increases the residual strain decreases, and (3) the resilient strain decreases with increasing suction. Shackel made several conclusions: (1) repeated loading causes complex alterations of the soil structure, causing changes in the compressive and tensile strength of the soil, (2) there is a critical level of dry density, slightly on the dry side of the maximum dry density where the residual strain is a minimum and the resilient modulus is a maximum, (3) stress history affects the soil suction.

Design procedures presently in use in the United States do not

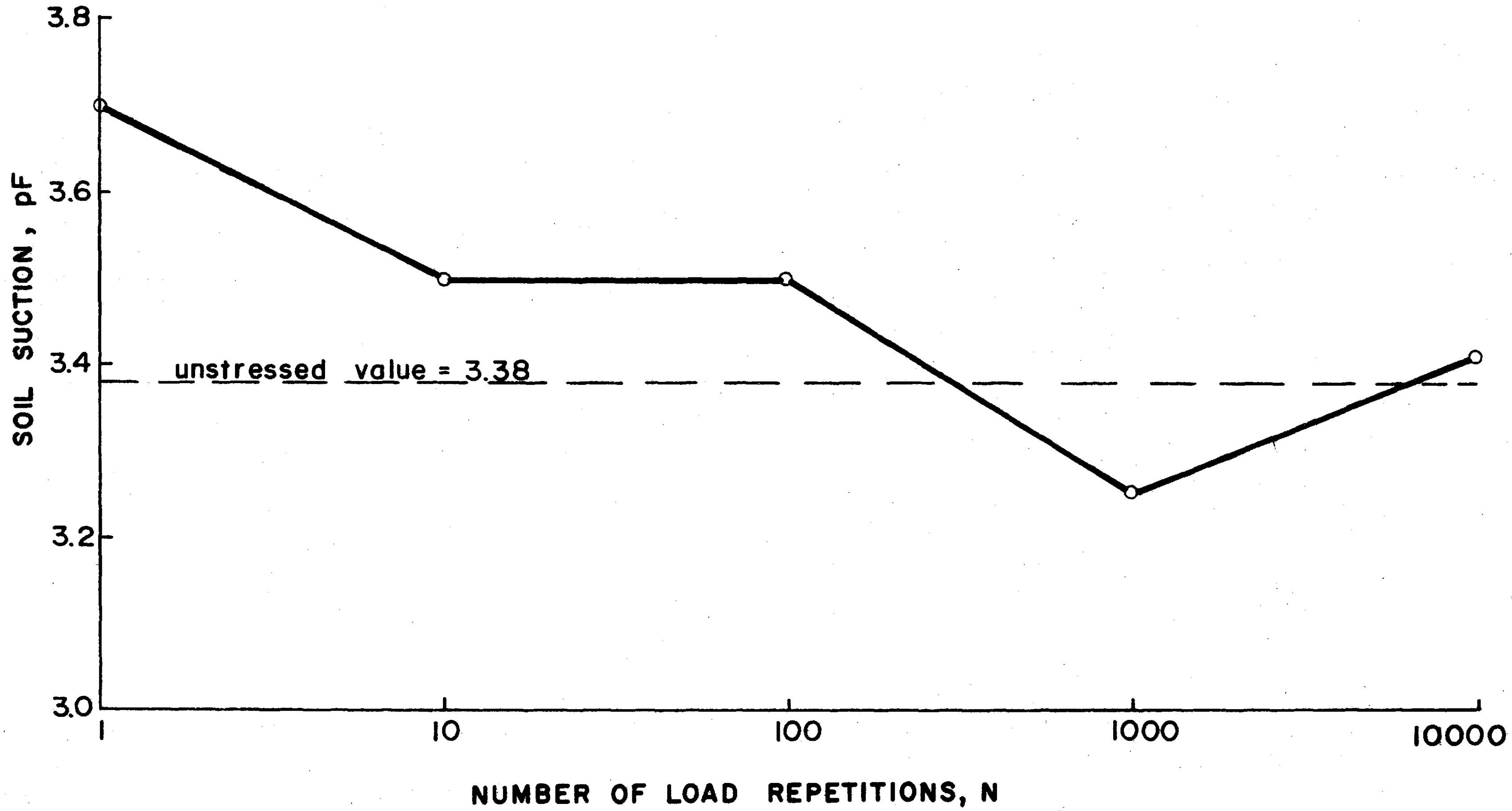


Figure 15. Soil Suction of Kaolinite-Sand Mixture as a Function of Number of Load Applications (36) (pF = log (cm of water))

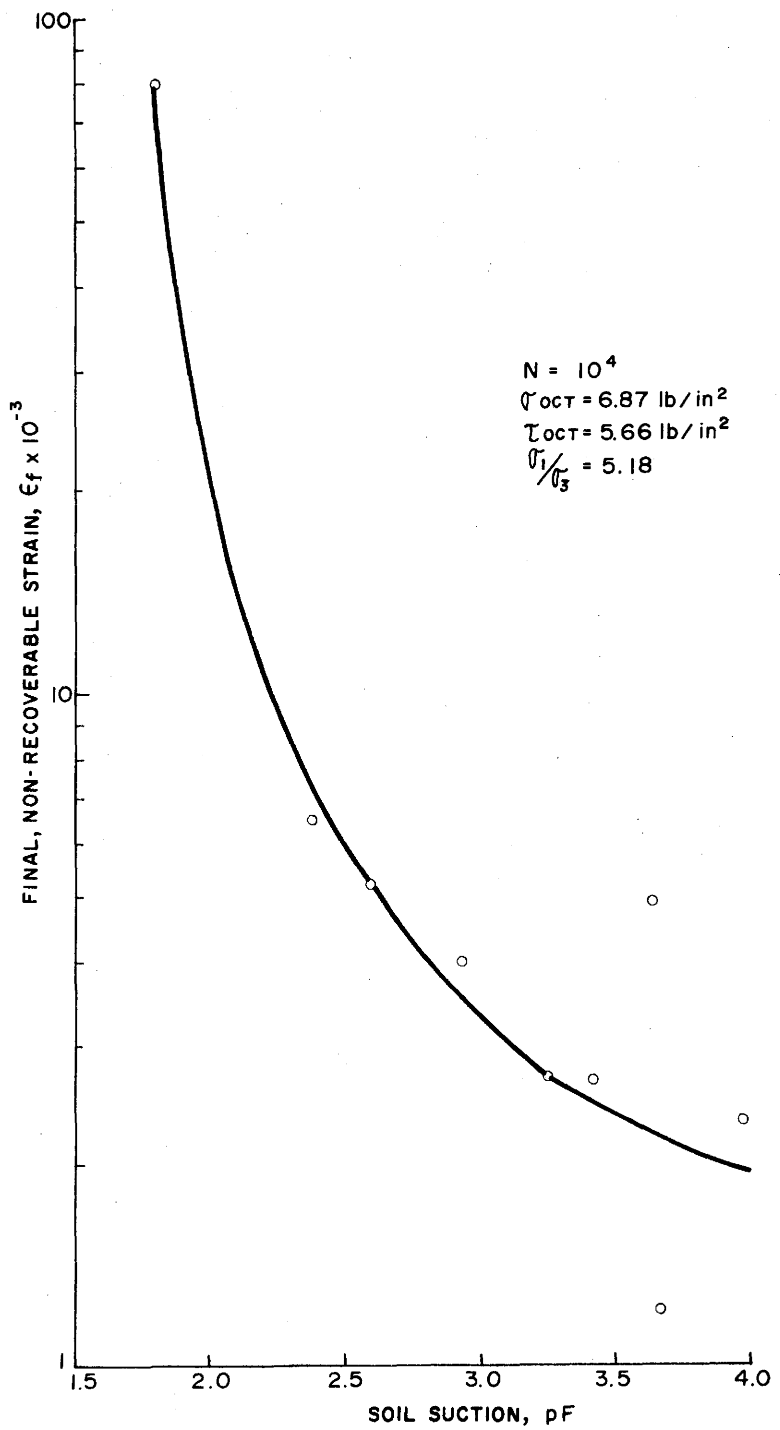


Figure 16. Residual Strain of Kaolinite-Sand Mixture as a Function of Soil Suction (36)

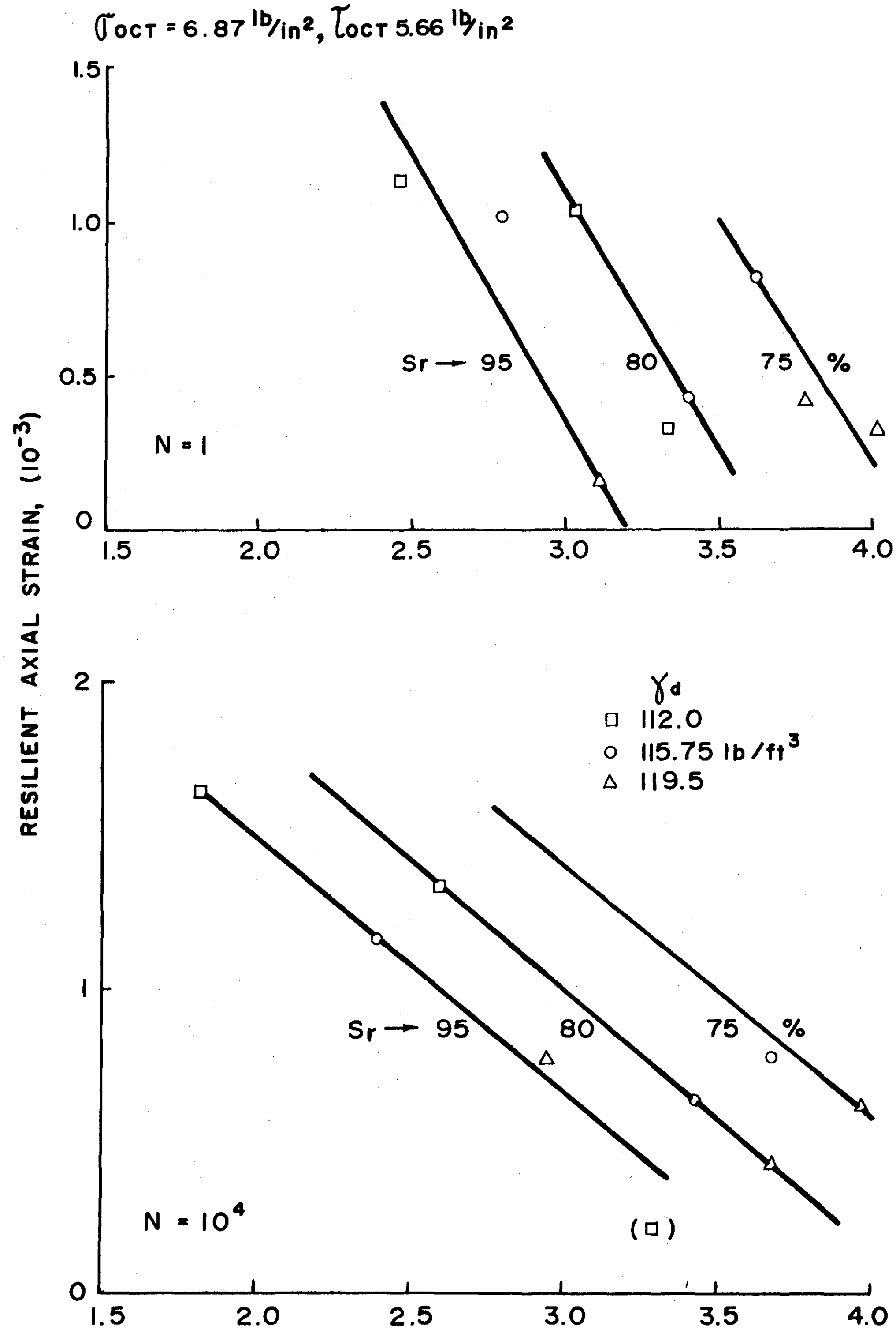


Figure 17. Relationship Between Resilient Strain, Soil Suction, and Number of Load Applications of Kaolinite-Sand Mixture (36)

take environmental effects into account. A number of authors previously described have shown that saturation of moisture content can be related to dynamic properties, but these relations are dependent upon each other. Soil suction is related to both saturation and moisture content; therefore soil suction can be related to the resilient modulus and residual strain as shown by Richards, Sauer and Monismith, and Shackel. Sauer and Monismith (21) concluded that soil suction is related to the environmental effects, and these effects can be used in the design of highways by relating them to the soil suction. This is especially important at critical areas like intersections and railroad grade crossings.

Objective

The objective of this report is to represent the residual strain and the resilient modulus of three typical fine-grained subgrade soils as a function of several engineering and physical properties. Some of the more important properties are soil suction, stress intensity and temperature. By relating the residual strain and resilient modulus to soil properties which are determined through simpler tests than the repeated loading test, the residual strain and resilient modulus will be available for use in the design of highway pavements, railroad grade crossings, and bridge approaches.

CHAPTER II

MATERIALS, TEST EQUIPMENT AND PROCEDURE

Materials

Three soils were used in this test program to study the effect of different soil types. The soils, classified by the Unified Soil Classification are CH, CL, and ML. For ease in identifying the different soils, the soil will be named for the town near which the soil was obtained. Figure 18 shows the location of the three towns where each soil was obtained. From this figure, the Thornthwaite Index for Moscow, Floydada, Allenfarm are 21, -17, and 0 respectively.

The CH soil was obtained from Moscow, Texas. The soil consists mainly of soil from the Wilson series (28). The Wilson series 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 (32). Table 1 lists the physical properties of the Moscow soil.

The CL soil was obtained from Floydada, Texas. The Pullman series comprises 80% of this soil (29). 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 (31). Table 1 lists the physical properties of the Floydada soil.

The ML soil was obtained from Allenfarm,Texas. This soil is composed primarily of the Miller-Norwood association (30). This association 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 (30). Due to the silt and larger particles, the water retention capacity is low. The physical properties of the Allenfarm soil are listed in Table 1.

The properties listed in Table 1 are the Atterberg limits, the specific gravity, and the complete grain size distribution. From these tests the soils were classified according to the Unified Soil Classification system and the AASHTO soil classification system. The Atterberg limits and specific gravity tests were done in accordance with the procedure described by Lambe (12). From the Atterberg limits, it can be seen that the Moscow soil has high plasticity, while the

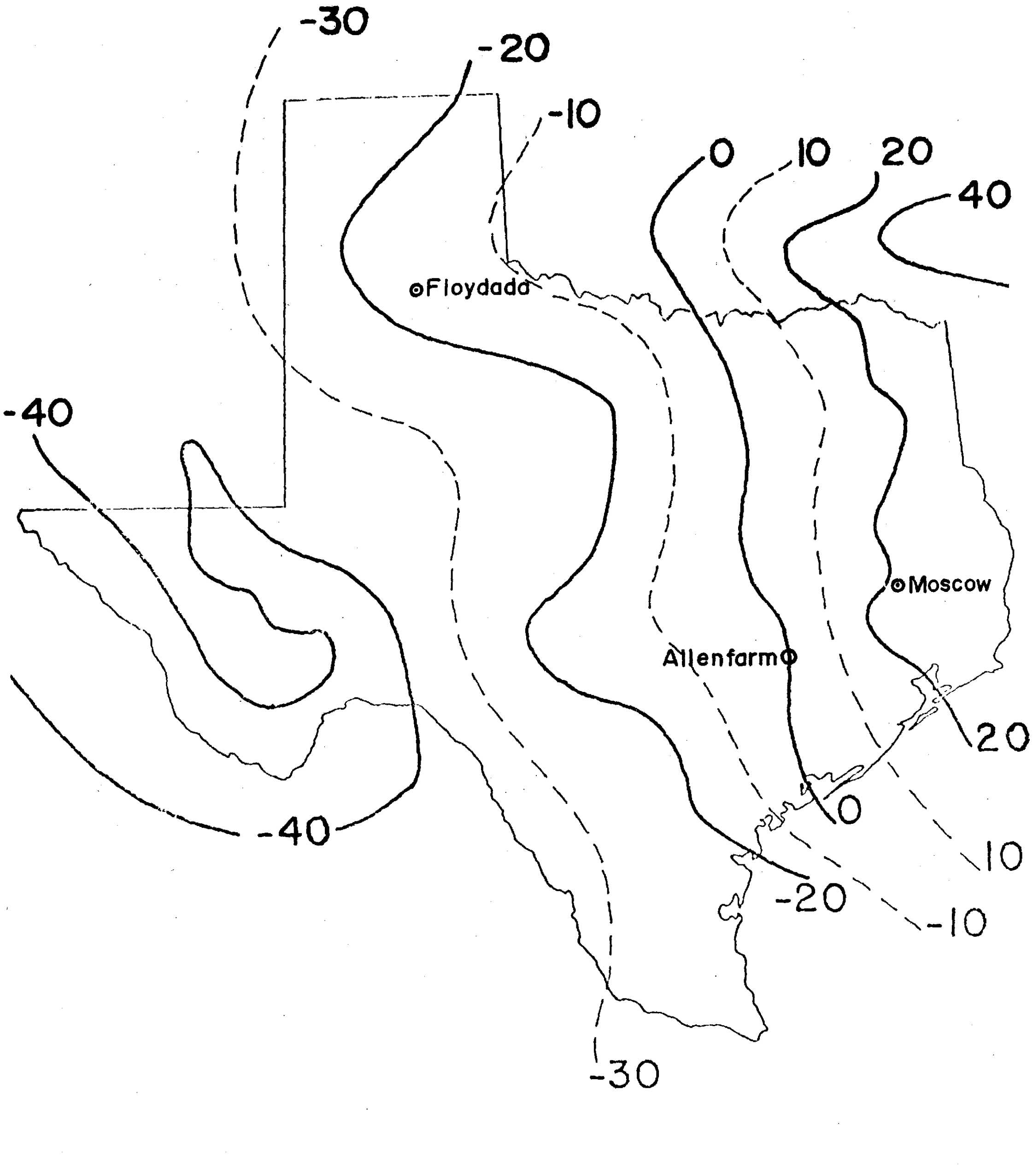


Figure 18. Location of the Three Towns Where Soil Was Collected, Shown With Reference to the Thornthwaite Moisture Index

TABLE 1

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 (2m)	70%	39%	20%

Allenfarm soil has very little plasticity. By comparing the difference between the shrinkage limit and the optimum moisture content, it can be seen that the Moscow soil has the largest difference, thus it would shrink and swell more than the other soils. In the same light, the Allenfarm soil would shrink and swell less than the other soils. The specific gravities are about equal for all the soils. Figures 19, 20, and 21 show the grain size distribution for the soils. The grain size distribution greater than 2 millimeters was determined by using a wet sieve analysis, because the small grains were coating the larger particles. The distribution of grain sizes for soils less than 2 millimeters was determined by using a hydrometer analysis in accordance with ASTM test D422-61T (2). 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. From the above soil properties, it can be seen that the Moscow soil is an active clay, while the Floydada soil is an average clay, and the Allenfarm soil is an average silt.

Test Equipment

The repetitive loading apparatus is a pneumatic operated testing machine that applies an axial load to a standard triaxial cell. The schematic layout is shown in Figure 22. 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 axial 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. Shackel (33) shows in Figure 23 what the actual pressure pulse, along with the other pressure pulses used by different researchers, looks like. The pressure pulse shown in Figure 24 is an example of the pulse used in this program, which consists of 0.2 seconds with the load applied and 1.8 seconds with the load off.

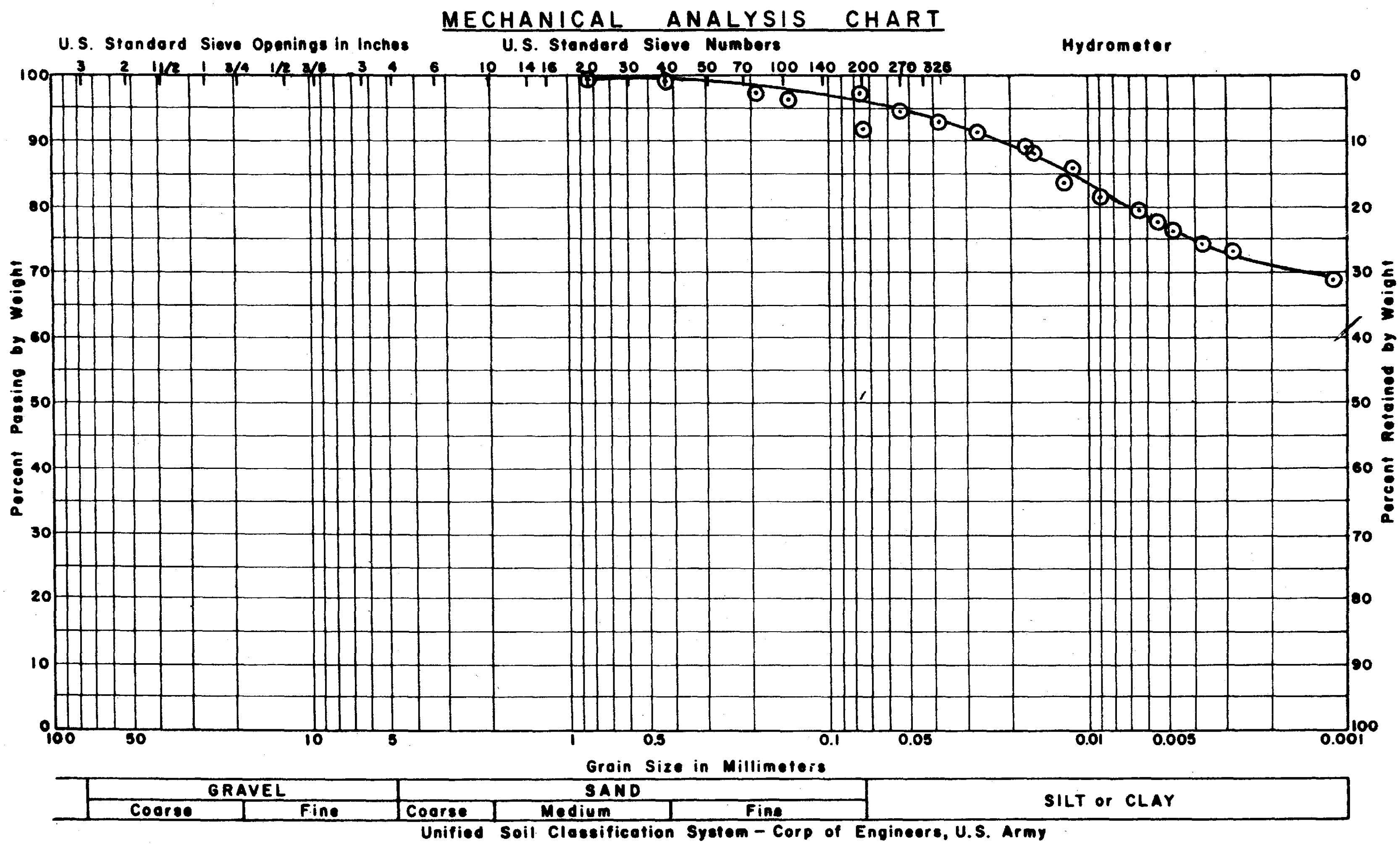


Figure 19. Grain Size Distribution of the Moscow Soil (CH)

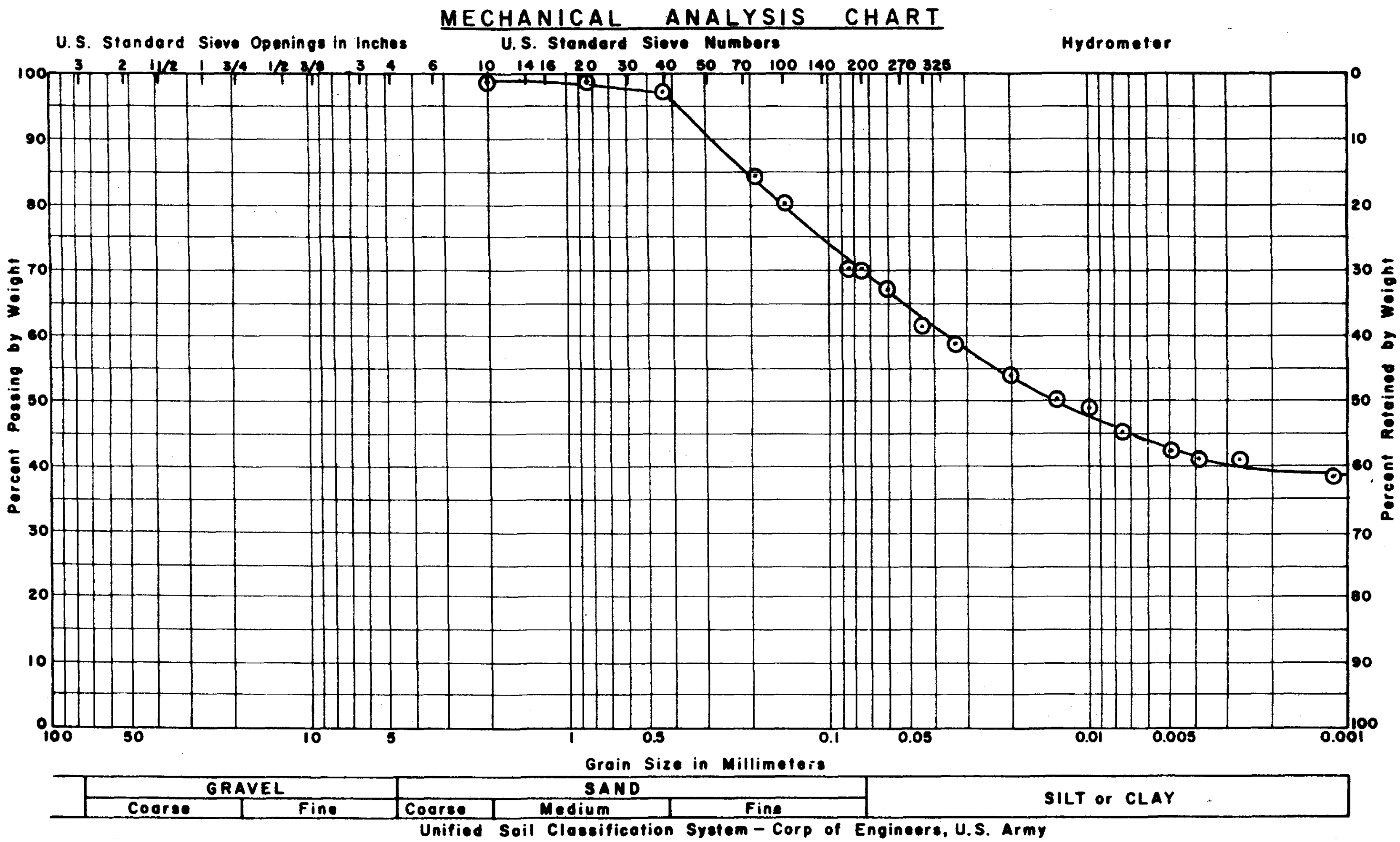


Figure 20. Grain Size Distribution of the Floydada Soil (CL)

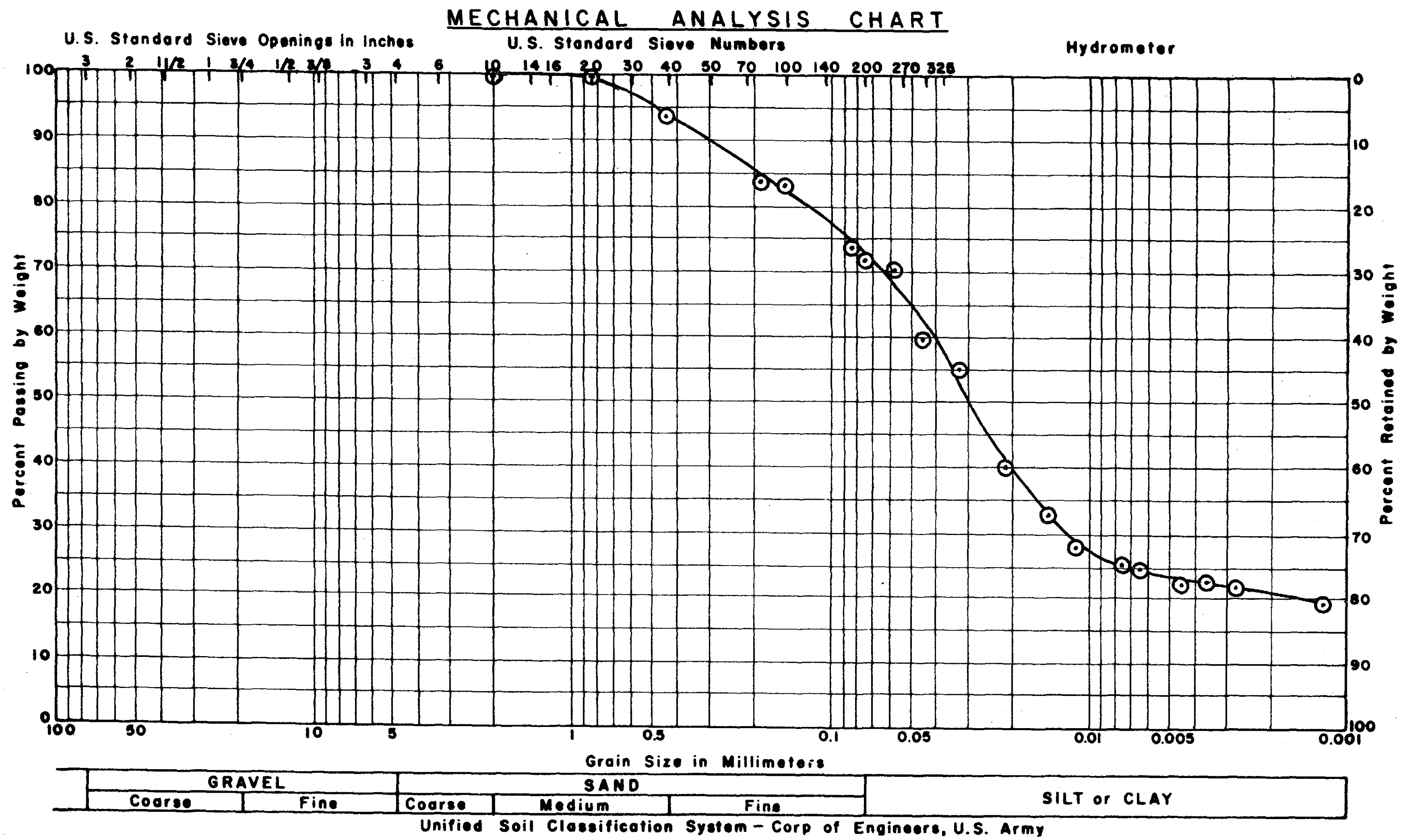


Figure 21. Grain Size Distribution of the Allenfarm Soil (ML)

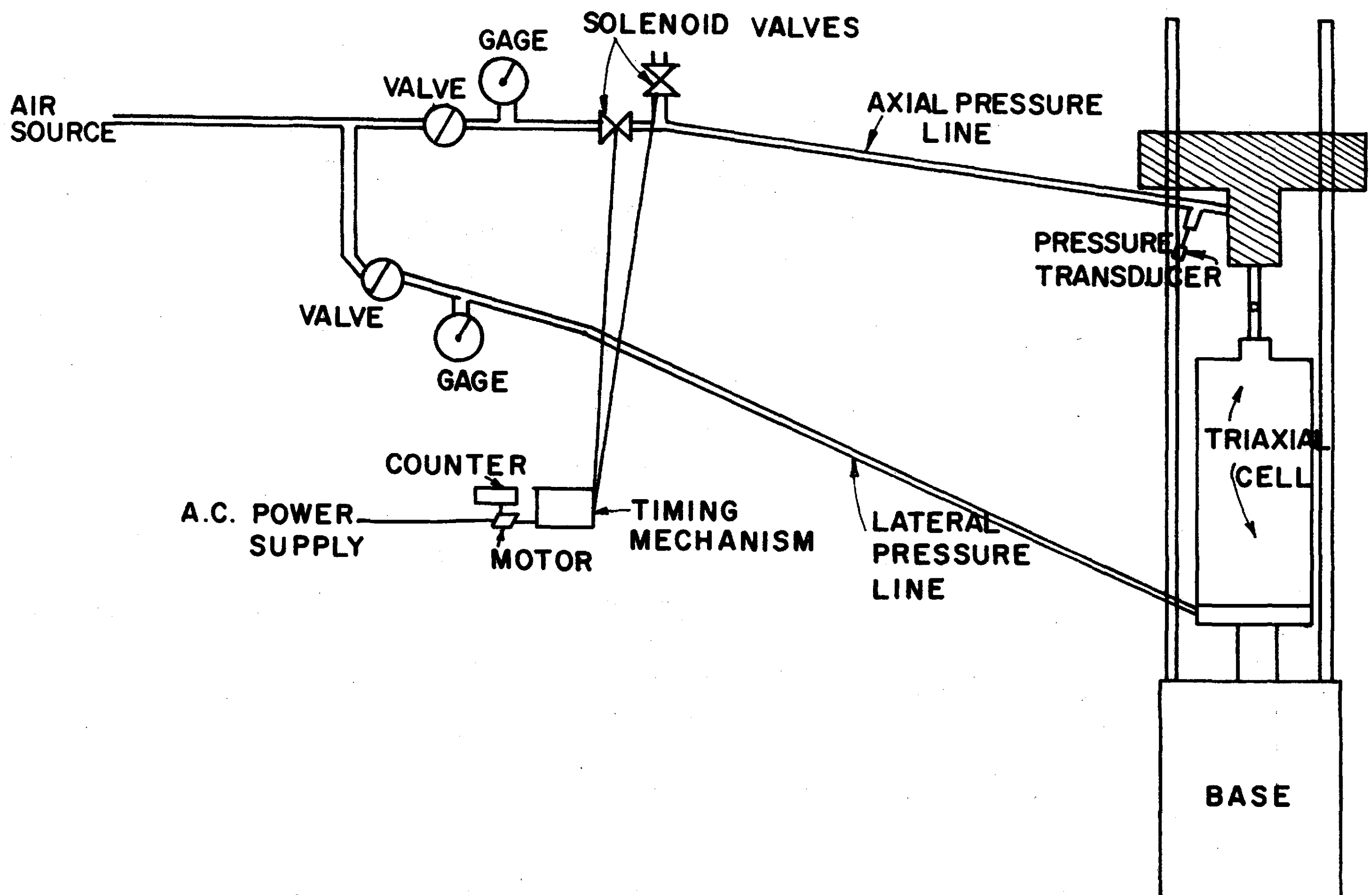


Figure 22. Schematic of Repetitive Loading Apparatus

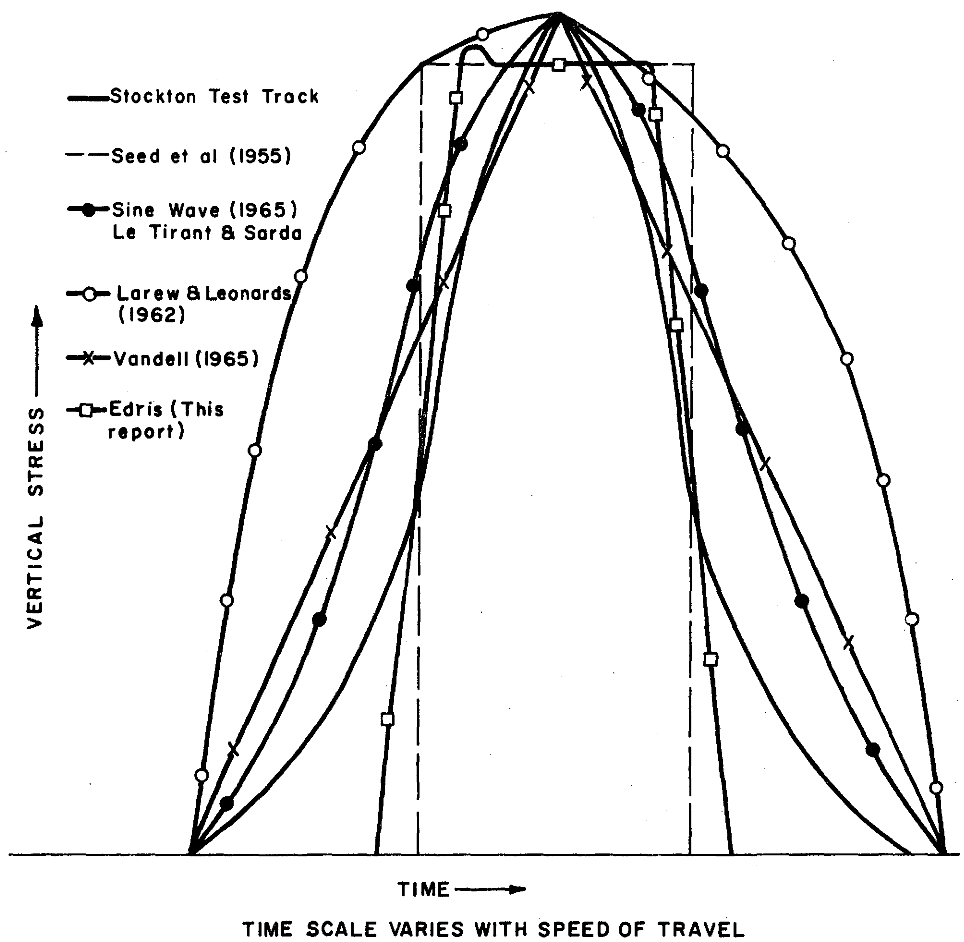


Figure 23. Pressure Pulses Used by Various Researchers as Compared to an Actual Pressure Distribution (33)

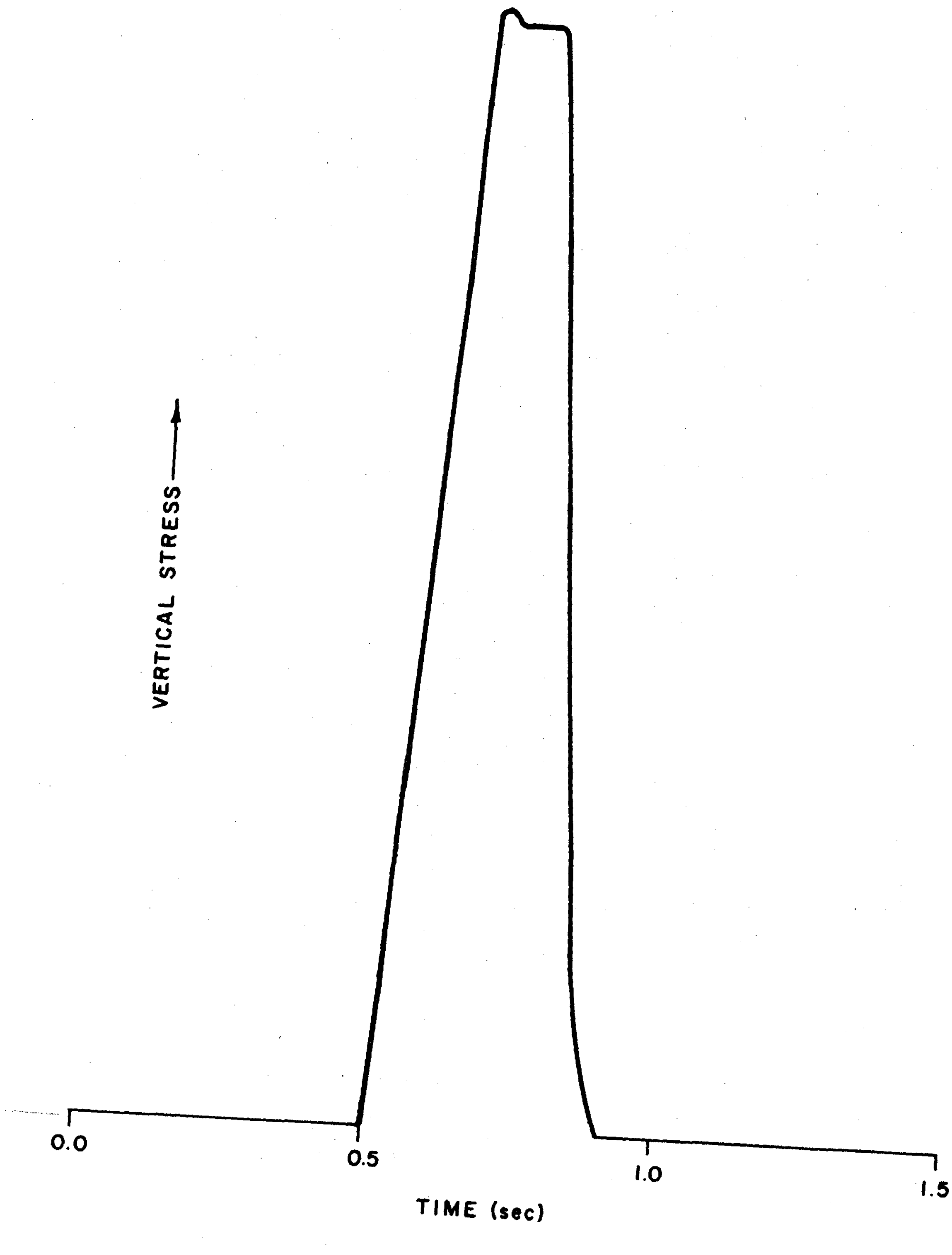


Figure 24. Pressure Pulse Used in Test Program

Armstrong (1) has shown that this stress frequency produced slightly more axial deformation than a frequency with a longer rest period. However, the difference is not enough to warrant a longer rest period. This frequency corresponds to a highway speed of 45 miles per hour (72.4 km/hr). This speed of travel is chosen to make possible comparison of these results with previous and future studies of the same sort. It should be noted that most intersections and railroad grade crossings are negotiated at speeds of less than 30 mph (48.2 km/hr) and thus the results are not strictly applicable to all grade crossings. However, because of the variable speeds of highway and train traffic crossing, it is unlikely that any selected speed would be generally applicable. It is certainly to be expected that the resilient modulus will be lower and residual strain will be higher at slower speeds. However, the viscoelastic nature of the subgrade soils, which cause the material property variations with traffic speed is necessarily the subject of another essential study which was not attempted in this testing program. For comparison the pressure pulse obtained in this program, using air to activate the loading piston, is shown in Figure 23.

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 soil suction of the fine-grained soil samples was measured with a psychrometer. There are a number of methods available to measure the soil suction, as the Review Panel of the Moisture Equilibra and Moisture Changes in Soils Beneath Covered Areas reported in the symposium as shown in Table 2 (17). The range of suctions expected to be encountered in the test program was 10 psi (69 kN/m^2) to 400 psi (2760 kN/m^2). Besides the range, a major requirement was that the suction could be measured during the test, without disassembling the test set-up. 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 ±5%. Appendix III describes the make-up of the

TABLE 2

METHODS OF MEASURING THE TOTAL SUCTION (17)

Measurement Technique	Suction Range (cm. water)	Suction Range (psi)	Sensitivity of Reading (%)
Freezing point depression	$1x10^3$ to $1x10^4$	14.2 to 142.	5
Sorption balance	$3x10^4$ to $1x10^7$	426. to 142000.	10
Nullpoint with vacuum desiccators	$3x10^4$ to $1x10^7$	426. to 142000.	10
Psychrometer	0 to $1x10^7$	0 to 142000.	5
Thermistor hygrometer	$1x10^2$ to $1x10^5$	1.42 to 1420.	25

psychrometer along with the dew point method of measuring soil suction. A psychrometer was installed in each end cap, as shown in Figure 25, 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 25. 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 ±0.0005 in. (0.0127 mm). Thus for an average sample length of 2.750 in. (6.985 cm), the error would be ±0.02%. Since the magnetic signal is not linear, a calibration curve was established for each test. The coils were calibrated with a screw micrometer, shown in Figure 26, which measured the distance between the coils within ±0.0005 in. (0.0127 mm).

The vertical load was measured with a pressure transducer located immediately before the load piston as seen in Figure 22. The transducer or pressure potentiometer has a range of 0 - 250 psi (0 - 1725 kN/m^2) which changes the resistance from 0 - 5000 ohms. There is a linear relationship between the change in pressure and the change in resistance. The transducer was used to make sure that the pressure at the regulator is the same pressure reaching the sample.

Experimental Design

The objectives of this program were to determine the effects of soil suction, stress intensity, and temperature on the resilient modulus and residual strain. To determine the effects of soil suction and stress intensity, a simple factorial test program was set up for each soil. The test program consisted of at least three suction levels tested at three stress intensity levels with each replicated twice. The effect of temperature was determined by testing a high and low suction at the three stress intensities at a temperature above and

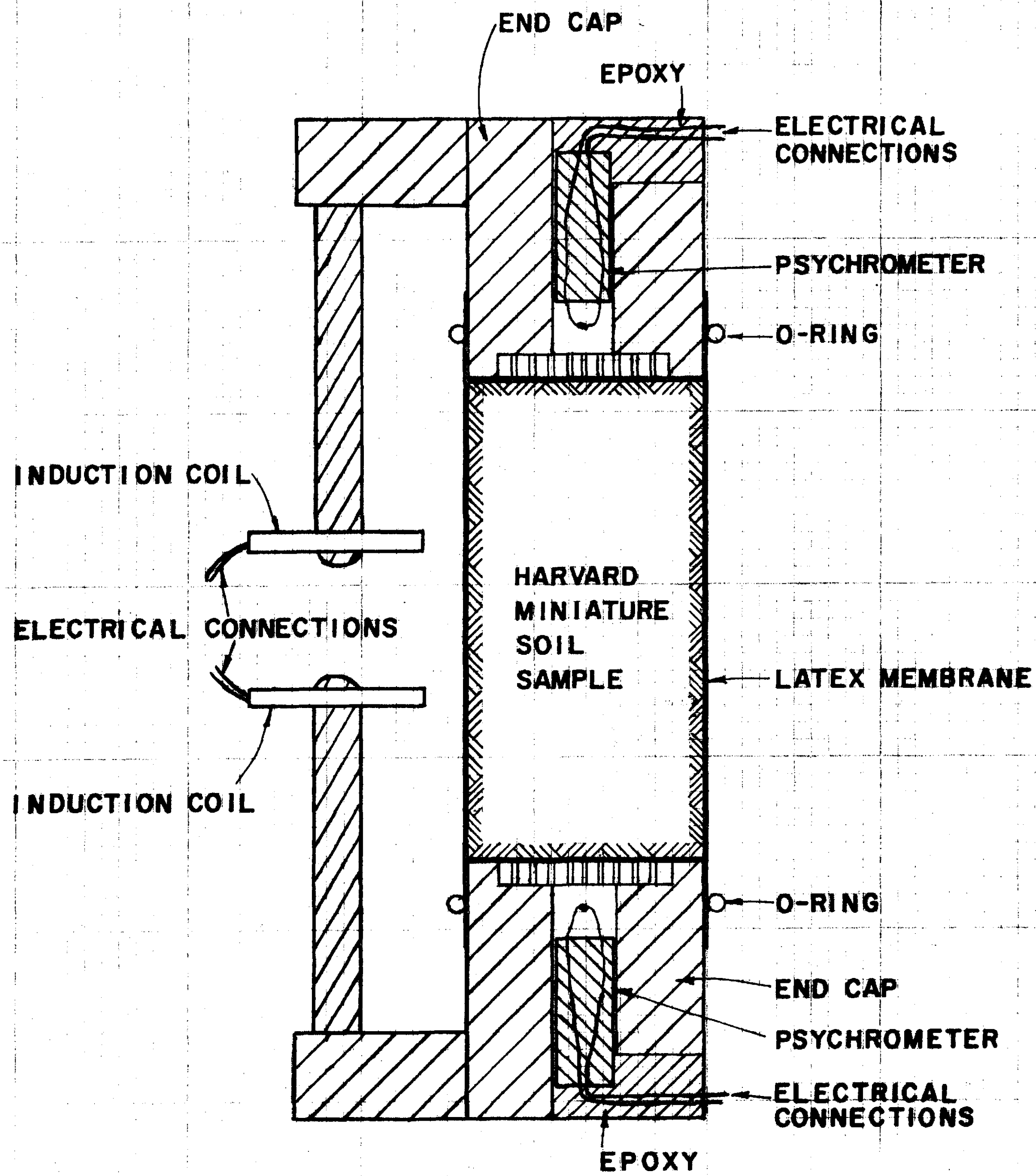


Figure 25. Cross Section of the Sample Set-up, Showing Endcaps With the Induction Coils and Psychrometers

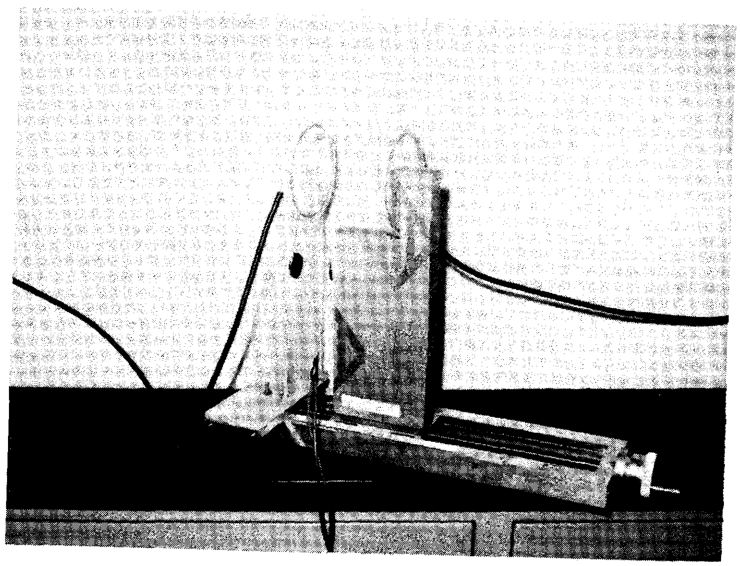


Figure 26. Photograph of Calibration Device

below a standard temperature.

Since the soil suction values change with the type of soil, the suction values were not the same for each soil. Table 3 shows the extreme soil suction values for each soil used in this program. From Table 1 and Table 3, one can see that as the percentage of clay increases, the soil suction increases as is shown in Figure 2. The approximate range of soil suction anticipated for any Thornthwaite Index range can be determined by knowing the amount of clay in the soil.

The temperatures used in this program were intended to represent actual field conditions. Figure 4 shows a temperature range of the top of the subgrade from 0.2^{o}C (32.4^{o}F) to 34^{o}C (93.2^{o}F). The majority of repetitive loading tests were done in the lab at room temperatures of 70^{o}F (21.1^{o}C) to 72^{o}F (22.2^{o}C). The temperature tests were performed in walk-in environmental rooms set at 33^{o}F (0.6^{o}C) and 100^{o}F (37.8^{o}C). The temperatures used represent an extreme temperature range that occurs in West Texas.

The stress intensities that were used are comparable to actual field conditions. The largest load a highway must withstand occurs at railroad grade crossings, where the stresses from trains are greater than the stresses from trucks. The BISTRO (16) program was used to determine the stresses that would occur at the top of the subgrade under the different loading conditions. Figure 27 shows the schematics of the pavement systems used in the computer program. The largest stress used was approximately equivalent to the stress produced from the heaviest train engine in use. The smallest stress used was approximately equivalent to the stress produced from an 18 kip axle load, with the middle stress approximately equal to the stress produced by an average weight train engine. The values of the stresses are shown in Table 4.

<u>Procedure</u>

After the soils were collected from the field, dried at 230^{o}F (110^{o}C), broken down to their original size and stored, Harvard miniature samples were made. The largest grain size encountered had a diameter of 0.0787 in. (2.0 mm) which is 16½ times smaller than the diameter of the Harvard sample (1.31 inch (3.33 cm) diameter). The

TABLE 3

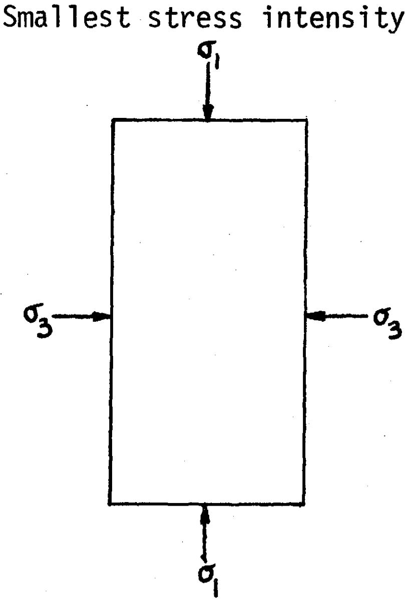
RANGE OF SOIL SUCTION AND MOISTURE CONTENT

	Range of Suction Values	Range of Moisture Contents
Moscow Soil (CH)	42 psi - 300 psi	35.4% - 24.2%
Floydada Soil (CL)	19 psi - 180 psi	19.5% - 12.4%
Allenfarm Soil (ML)	6 psi - 220 psi	17.6% - 6.6%

TABLE 4

STRESS VALUES USED IN TEST PROGRAM

	σ_1	σ_3	$(\sigma_1-\sigma_3)$	σ_m
Largest stress intensity	35 psi	20 psi	15 psi	25 psi
Middle stress intensity	25 psi	15 psi	10 psi	18.3 psi
Smallest stress intensity	17.2 psi	3.5 psi	13.7 psi	8.1 psi



σ_1 = largest principal stress, applied in axial direction

σ_3 = smallest principal stress, confining stress

$\sigma_1-\sigma_3$ = deviator stress

σ_m = mean stress = $\frac{\sigma_1+2\sigma_3}{3}$

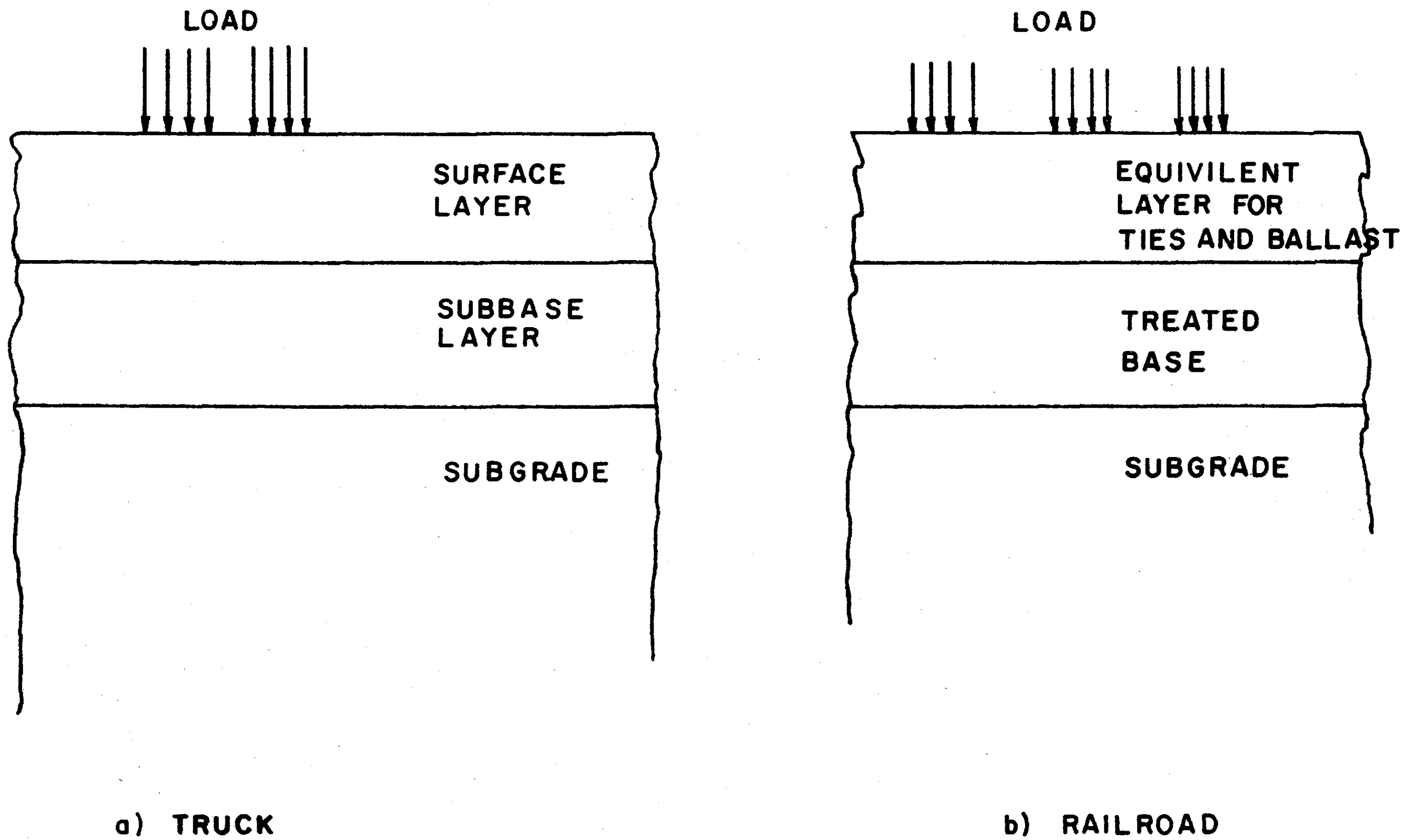


Figure 27. Schematic of Layered Systems Used to Determine Stresses

samples were compacted using the kneading compaction method, with a compressive force of 20 psi (138 kN/m^2) applied 25 times per layer. There were five layers per sample. Johnson and Sallberg (11) reported that the laboratory compaction that best represents the structure obtained in the field is the kneading compaction. Since soil suction is influenced by the soil structure, the sample soil structure should be as close as possible to the field soil structure. A problem in compaction is that the moisture is not distributed uniformly (34). To evenly distribute the moisture, the samples were sealed in foil and wax, and stored for at least two weeks at a constant temperature.

The compaction curve and soil suction contours were determined for each soil. The Floydada and Allenfarm soil samples were compacted at two different times by two people. Thus the compaction curves are different. After the samples had come to equilibrium, the soil suction was measured with psychrometers that were installed when the samples were sealed. By measuring the soil suction for a number of samples of a soil, a regression equation for the soil was developed:

$$\log_{10} h = a + b \log_{10} w$$

where: h = soil suction

w = moisture content

a, b = regression constants.

The correlation coefficient for the equations were generally in the range of 0.80 or higher. The equations used for each soil are shown in Table 5. The soil suction contours were entered on the compaction curves as shown in Figures 28, 29, and 30. By knowing the expected soil suction, the samples to be tested could be chosen.

After the samples were chosen, they were prepared for the repetitive loading test. The first step was to set-up the sample with the end caps and the latex membrane as shown in Figure 24. The sample was completely sealed. At the elevated temperature a layer of silicone grease was applied to the latex membrane to seal the sample. The sealed sample was centered on the pedestal of the triaxial cell which in turn was sealed. The triaxial cell was allowed to come to temperature equilibrium, while at the same time the soil suction was coming to equilibrium, which took overnight. At this point the sample

TABLE 5

EQUATIONS RELATING SOIL SUCTION WITH MOISTURE CONTENT

Soil		Equation	R^2
Moscow (CH)		log h = 9.939-5.414 log w	0.98
Floydada	curve #1	log h = 6.351-3.818 log w	0.69
(CL)	curve #2	log h = 6.819-4.265 log w	0.86
Allenfarm	curve #1	log h = 6.343-4.535 log w	0.82
(ML)	curve #2	log h = 5.536-3.724 log w	0.92

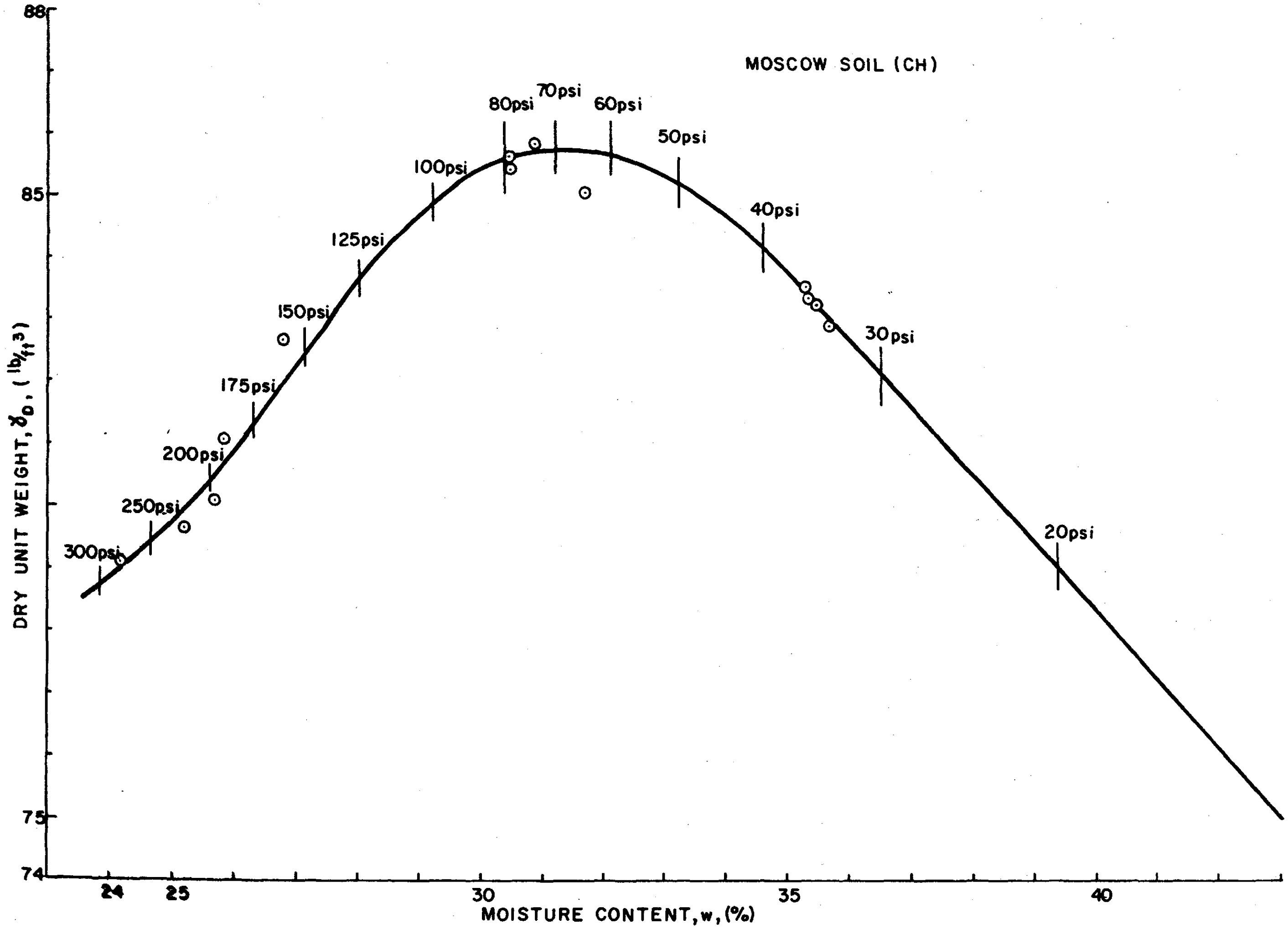


Figure 28. Compaction Curve for the Moscow Soil Showing the Soil Suction Contours (in psi, 1 psi = 6.9 kN/m^2)

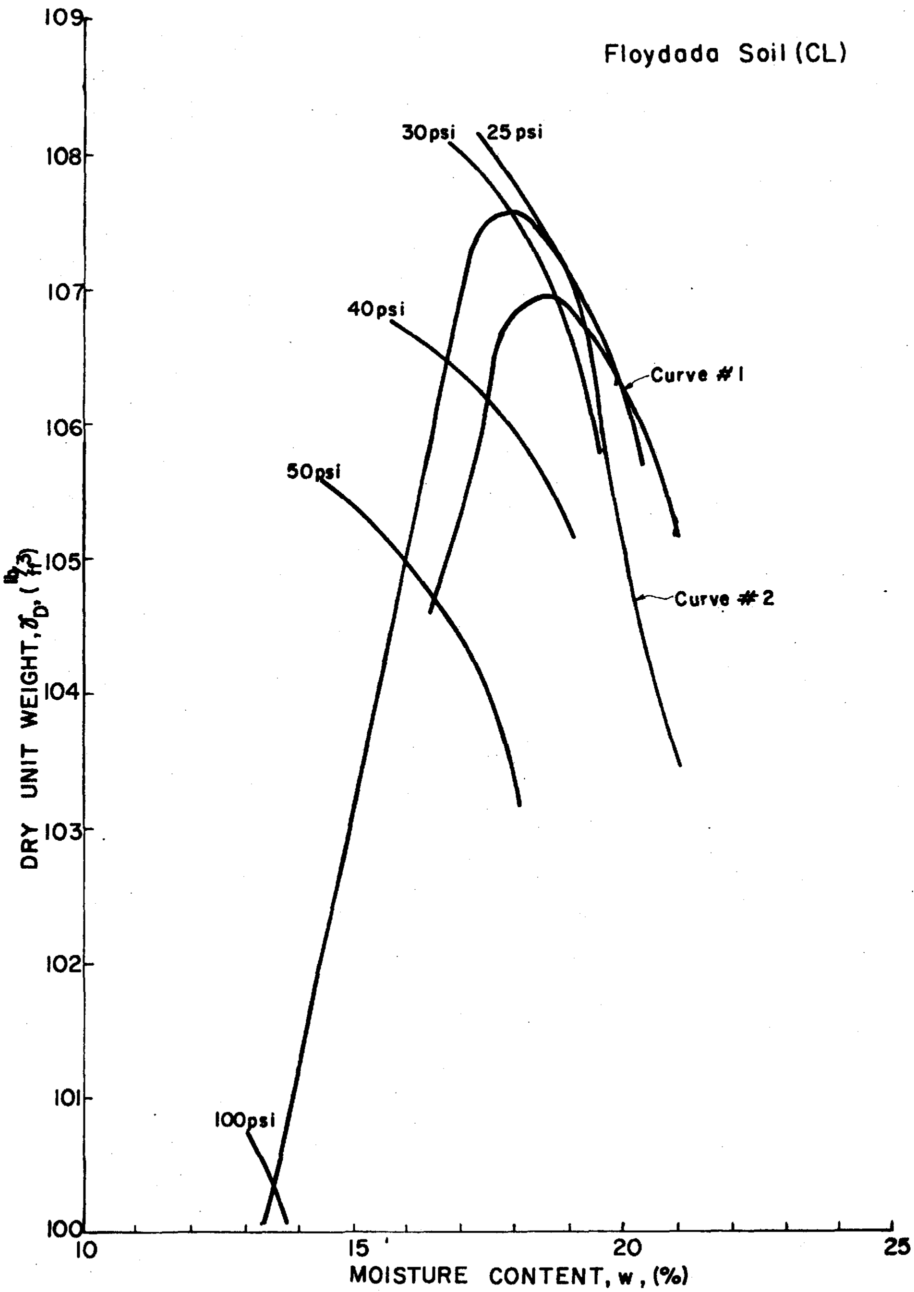


Figure 29. Compaction Curve for the Floydada Soil Showing the Soil Suction Contours (in psi, 1 psi = 6.9 kN/m^2)

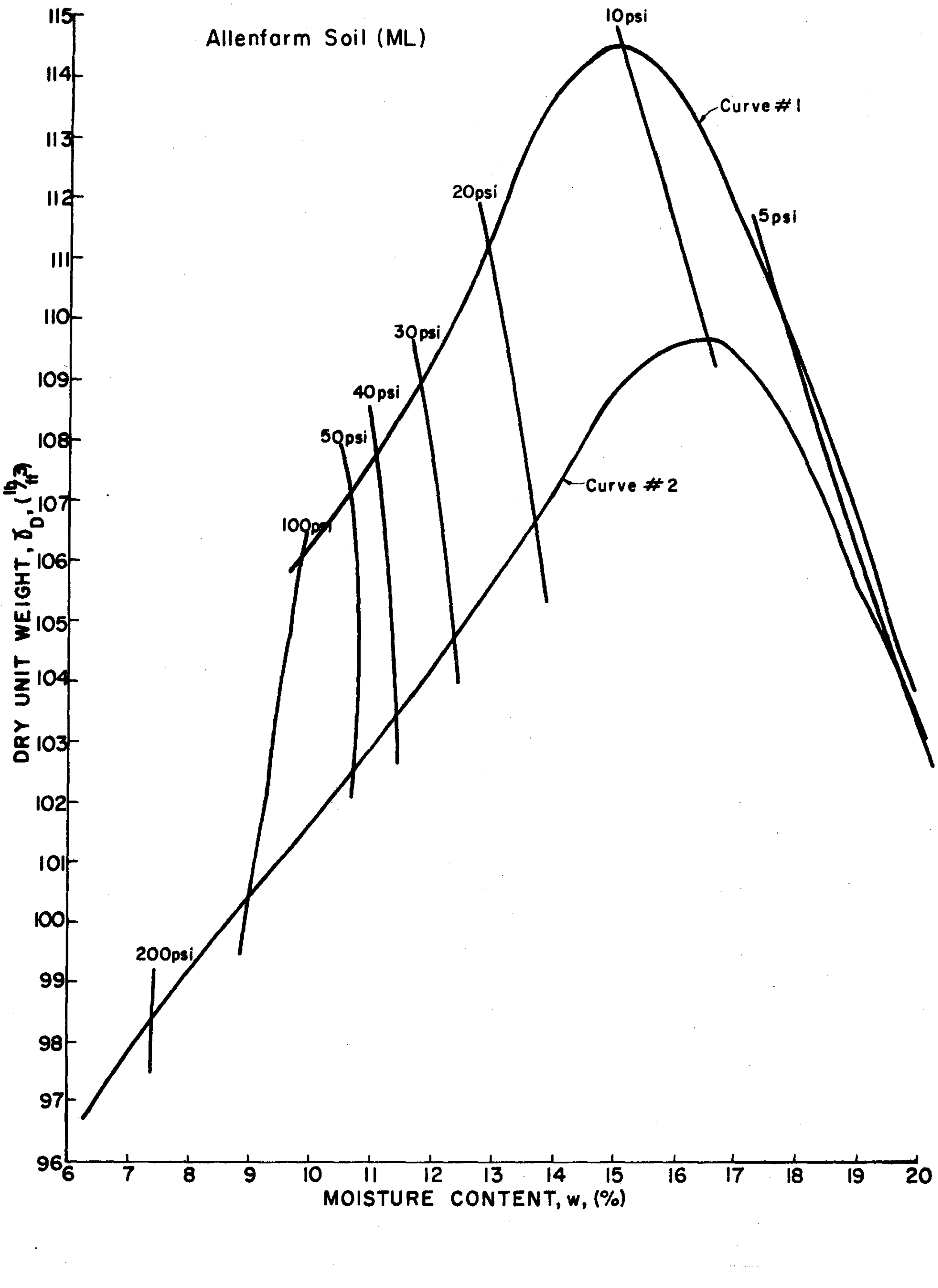


Figure 30. Compaction Curve for the Allenfarm Soil Showing the Soil Suction Contours (in psi, 1 psi = 6.9 kN/m^2)

was ready to be tested.

The repetitive load test took about a day and a half to run. The morning following the equilibrium period, soil suction readings were taken, after which the confining pressure was applied. Richards, Low, and Decker (19) reported that for a silty sand there was no measurable change in the total suction over the range of confining pressure used in this report. The soil suction was measured with the confining pressure applied. If the suction values changed more than expected then there was a leak in the membrane and the proper adjustment could be made. The repetitive loading part of the test was started. The resilient and residual deformations were recorded for the first one thousand cycles because typically if a sample lasted that long, it would not fail during the remainder of the test. After the one thousandth repetition readings were spaced throughout the test. The repetitive loading lasted at least 40,000 repetitions, at which time the sample set-up was taken down. A moisture content was taken while the majority of the sample was used to get a soil suction. With the final suction taken the test is completed for that sample.

The data acquired from this repetitive load test are in the form of soil suction readings and resilient and residual deflections from an X-Y-Y plotter. The soil suction readings in microvolts must be converted to pounds per square inch by use of a calibration curve as explained in Appendix III. The deflections must be converted to resilient and residual deformations in thousands of an inch. This conversion is accomplished by scaling the deflections and the calibration scale from the X-Y-Y plotter paper. Once the deformations are in thousands of an inch the resilient modulus and residual strains are calculated, which along with the soil suction readings was the objective of a single test.

CHAPTER III

DATA OBTAINED

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

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

The resilient modulus, residual strain, and temperature effects are discussed in detail in the following sections. The soil suction will be discussed in the individual sections on resilient modulus and residual strain and will not have a separate section.

Each sample has several basic properties that describe the amount of water and soil that are in that sample. Besides the moisture content and the dry density, the following properties are calculated:

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

The above properties will be used in the development of the predictive relationships presented in the next chapter.

Resilient Modulus

The resilient deformation has been defined in Chapter 1 on page 7. One complete loading cycle is shown in Figure 31. The points where the load is applied and removed can be seen in this figure. 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. A material that exhibits viscoelasticity has properties that are time and temperature dependent. The time dependence of the soils tested is brought out in Figure 31 while the temperature dependence is discussed later in this chapter.

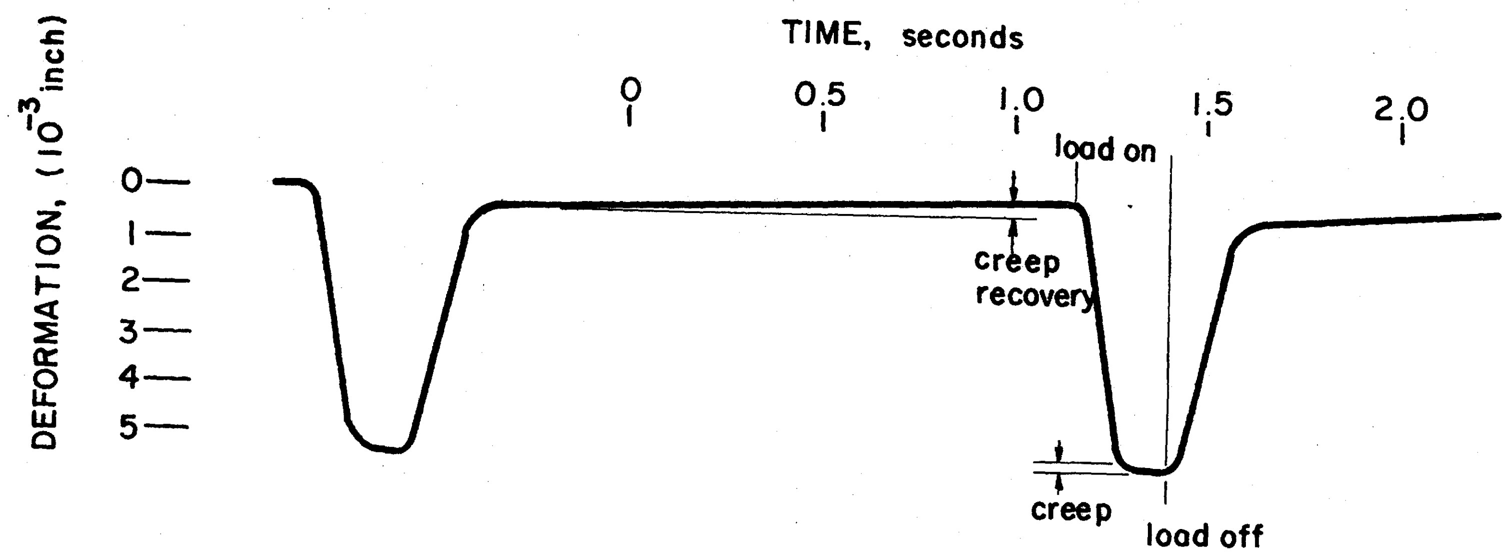


Figure 31. Typical Deformation Trace for One Load Cycle

The resilient deformation is used to determine the resilient modulus which is calculated from the following equation:

$$M_R = \frac{(\sigma_1 - \sigma_3)}{\varepsilon_R}$$

where: $(\sigma_1 - \sigma_3)$ = deviator stress
ε_R = resilient strain; resilient deformation/sample length.

From this equation it can be seen that as the resilient deformation increases the resilient modulus decreases. Thus the softer the sample, the lower the resilient modulus, and the stiffer the sample, the higher the resilient modulus.

As mentioned above, Figure 32 shows how the resilient modulus varies as the number of load cycles increases. This figure is an example of several typical tests and the curves for all the samples tested are shown in Appendix IV. From this figure it is seen that as the number of load repetitions increases, the resilient modulus increases, that is, the sample gets stiffer. The initial suction, saturation, moisture content and dry density are shown for each sample. It can be seen that the moisture content and the dry density do not have a significant effect on the resilient modulus of the sample. These same facts are brought out in Figure 6, where Culley showed the results of repetitive load testing on a glacial till material (7). This indicates that the relationship between the resilient modulus and the number of load repetitions from this test program compares well with the relationships developed in other programs. The resilient modulus of the samples tested at room temperature are compared with the following basic moisture properties to determine if a simple relationship can be developed: saturation, volumetric moisture content, volumetric soil content, and soil suction. In the figures that follow, Figures 33 through 59, the curves are sketched by hand to indicate the trend of the data and do not represent a curve fitted by regression analysis.

<u>Saturation</u> (S). Figures 33, 34, and 35 show the graph of these two terms for each soil. Each graph contains three curves which correspond to the three deviator stresses. Figures 34 (Floydada Soil) and 35 (Allenfarm Soil) show that as the saturation decreases,

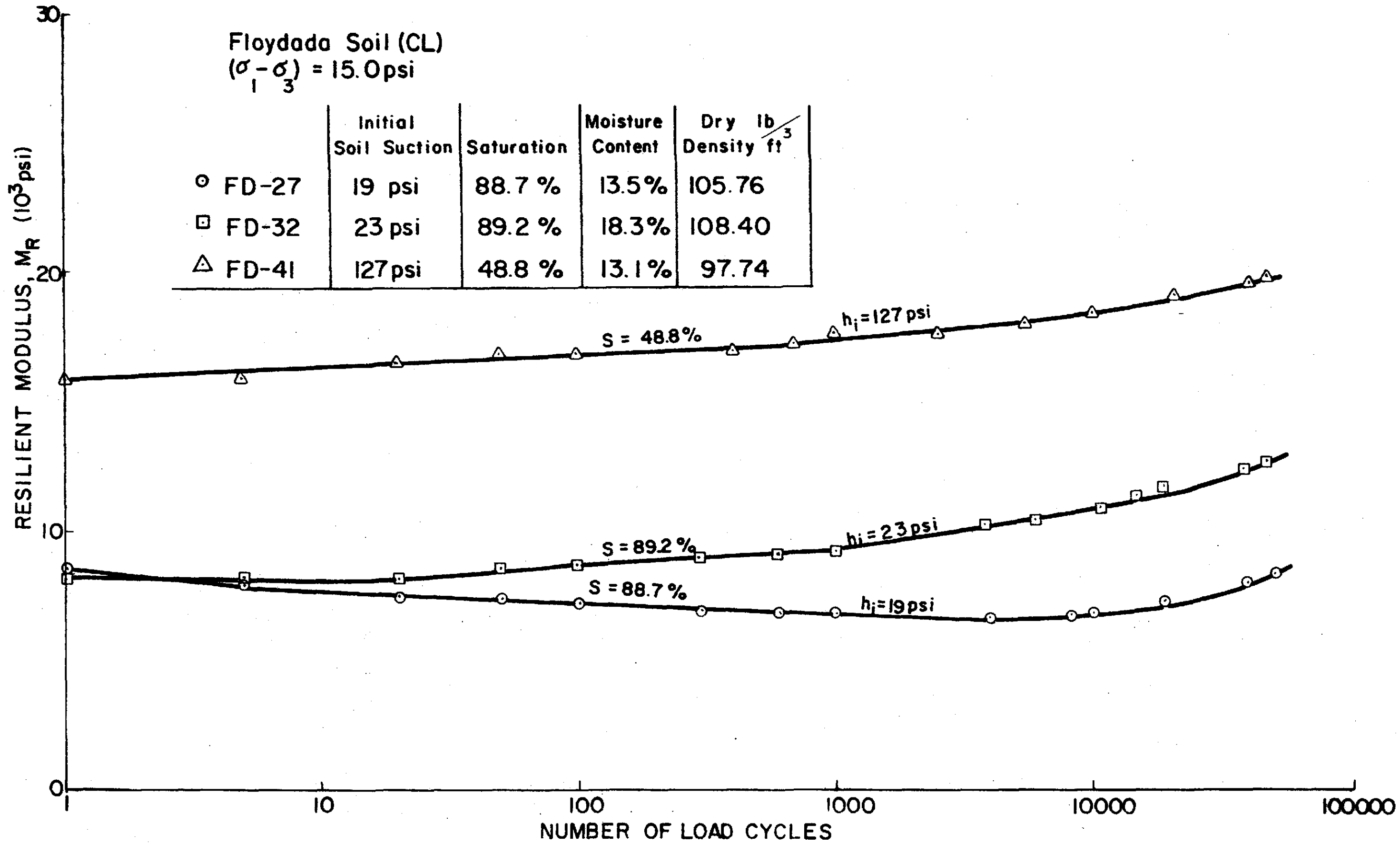


Figure 32. Variation of the Resilient Modulus With the Number of Load Cycles, Floydada Soil (CL) 15.0 psi Deviator Stress

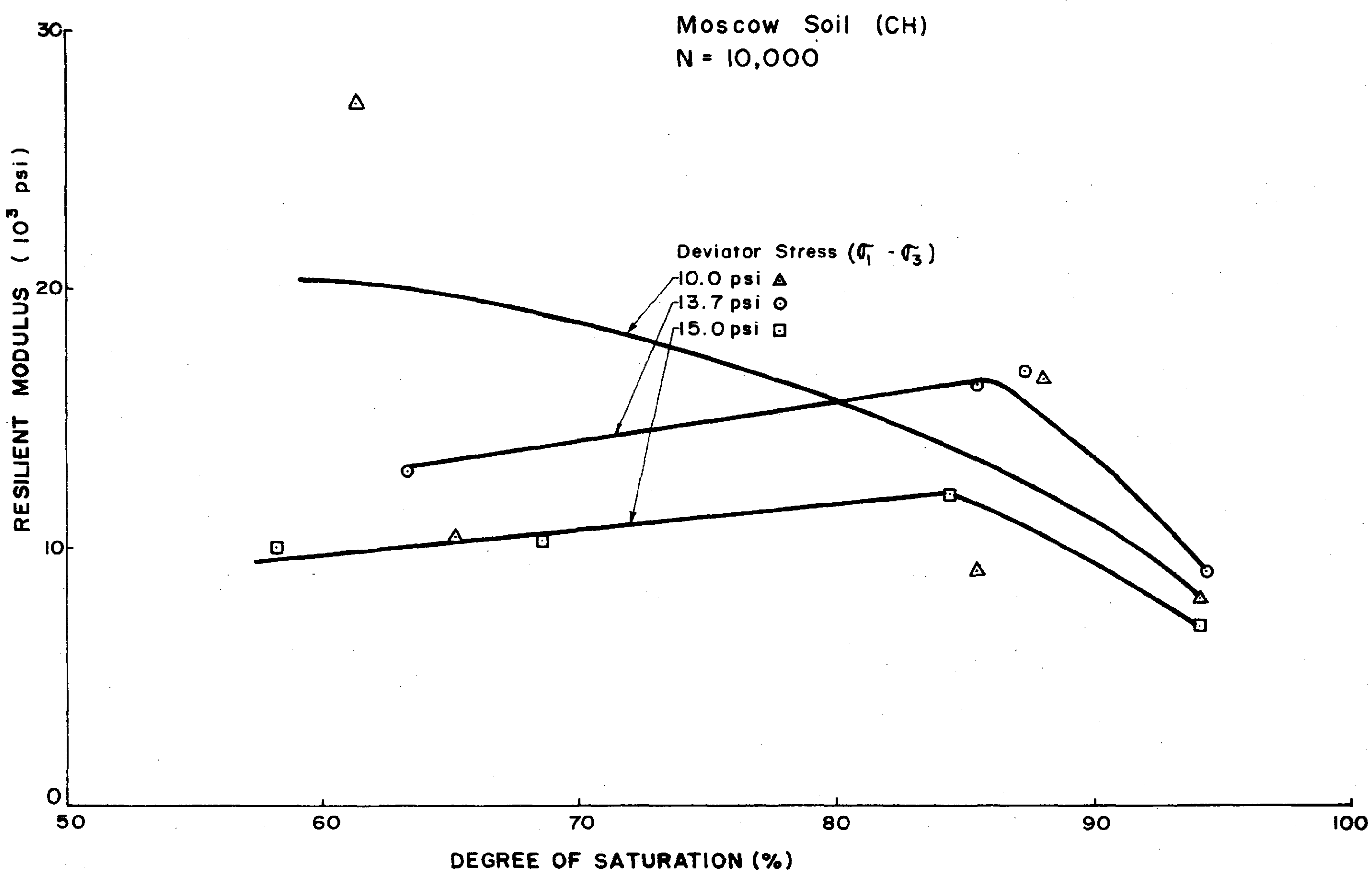


Figure 33. Resilient Modulus of the Moscow Soil (CH) as a Function of the Degree of Saturation at 10,000 Load Cycles

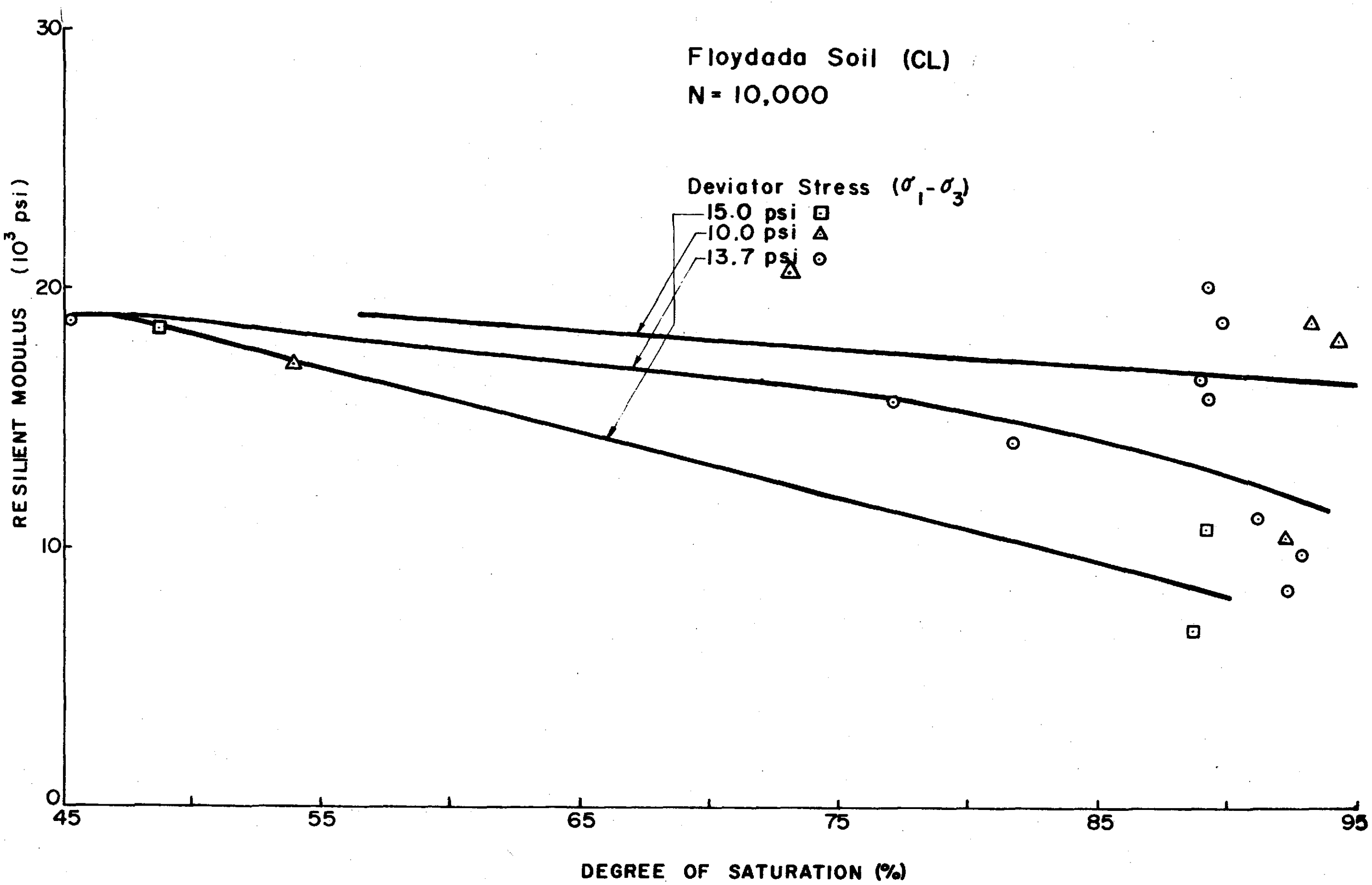


Figure 34. Resilient Modulus of the Floydada Soil (CL) as a Function of the Degree of Saturation at 10,000 Load Cycles

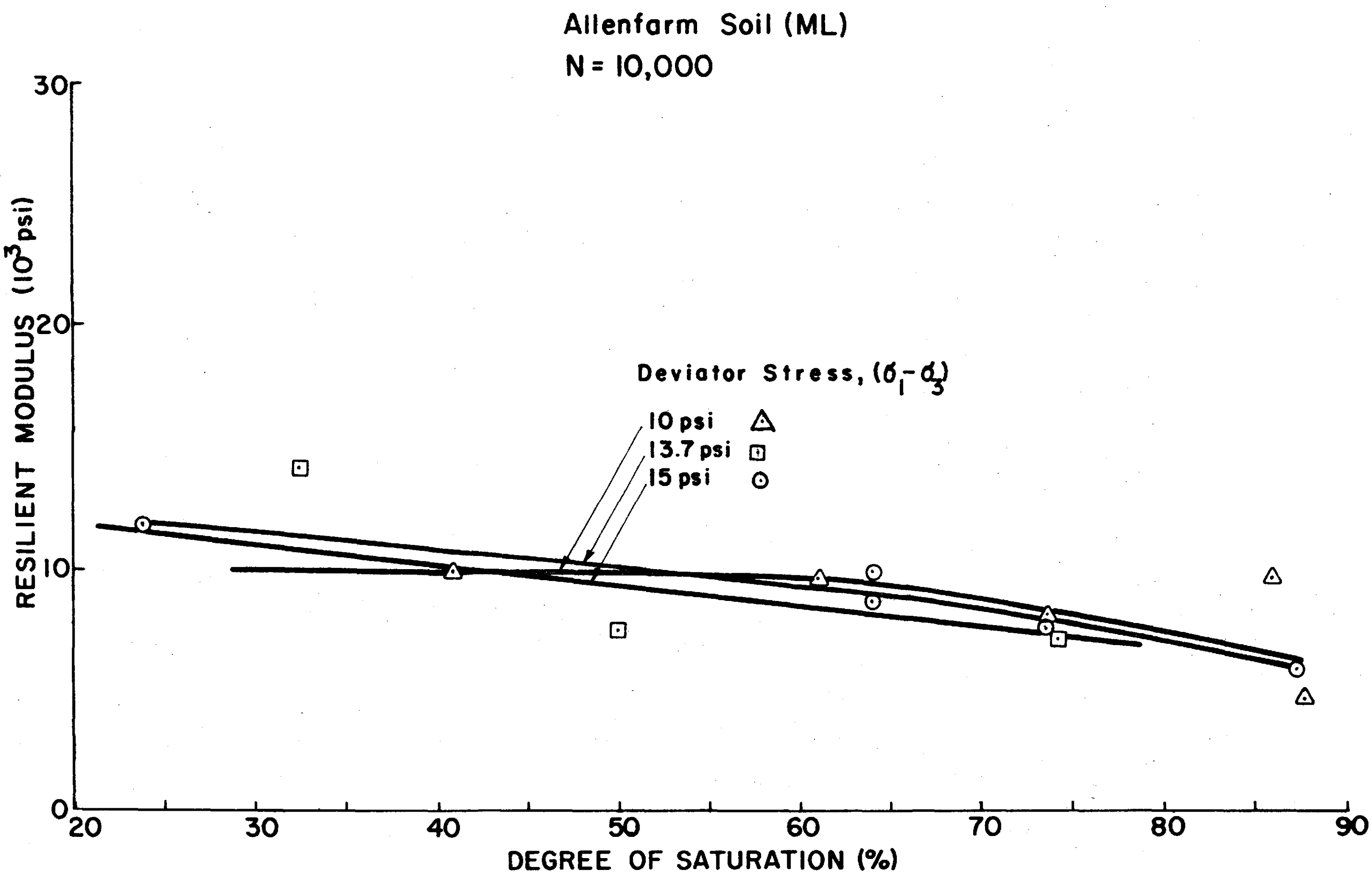


Figure 35. Resilient Modulus of the Allenfarm Soil (ML) as a Function of the Degree of Saturation at 10,000 Load Cycles

the resilient modulus increases. At the smallest deviator stress in Figure 33 (Moscow Soil), the curve increases but at the other two stress levels in that figure the curves reach a peak at a saturation of 85%, which is the saturation that occurs at the optimum moisture content. This peak is probably the result of a high clay content and a high deviator stress acting on a sample such that the structure breaks down and the sample gets softer. This is reinforced by the fact that the smallest deviator stress generally has a higher resilient modulus, and the highest deviator stress generally has the lower resilient modulus. The resilient modulus of the Moscow soil (CH) is generally lower than the resilient modulus of the Floydada soil (CL) which is generally higher than the resilient modulus of the Allenfarm soil (ML). Thus, as the clay content increases, the resilient modulus reaches a maximum and then decreases. The correlation between the resilient modulus and the saturation is a poor one, but there is a definite trend that could be used with other factors in developing a relationship.

Volumetric Moisture Content (nS). Figures 36, 37, and 38 show the graph of this variable versus the resilient modulus for each soil. All of the curves shown in these figures have the same general shape, except for the low deviator stress in Figure 38 (Allenfarm Soil). Each curve has a different maximum height or rotation dependent upon the deviator stress or the clay content. The peak of the curves occurs at the volumetric moisture content which corresponds to the optimum moisture content. The Allenfarm soil, Figure 38, has very little curvature to the curve. At the lowest deviator stress, the relationship of the Allenfarm soil is a straight line. As the clay content decreases, the curve becomes flatter. Thus the shape of the curve is dependent upon the clay content. As with the saturation curves, the resilient modulus increases from the Allenfarm soil to the Floydada soil, then decreases to the Moscow soil. There is a definite trend between the resilient modulus and the volumetric moisture content that could be used with other factors in developing a relationship.

Volumetric Soil Content (1-n). The volumetric soil content is defined as one minus the porosity, (1-n). Since the curves where

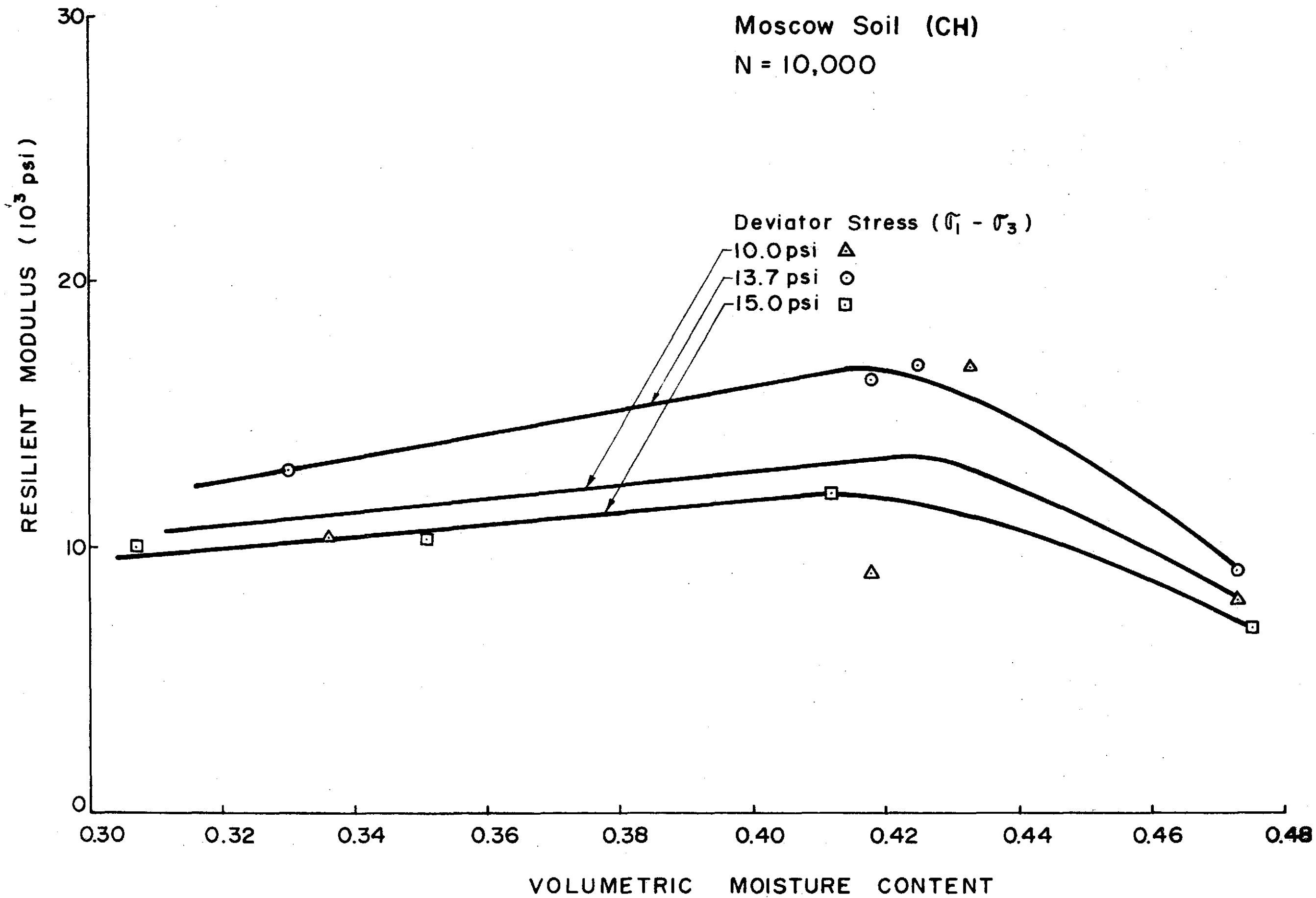


Figure 36. Resilient Modulus of the Moscow Soil (CH) as a Function of the Volumetric Moisture Content at 10,000 Load Cycles

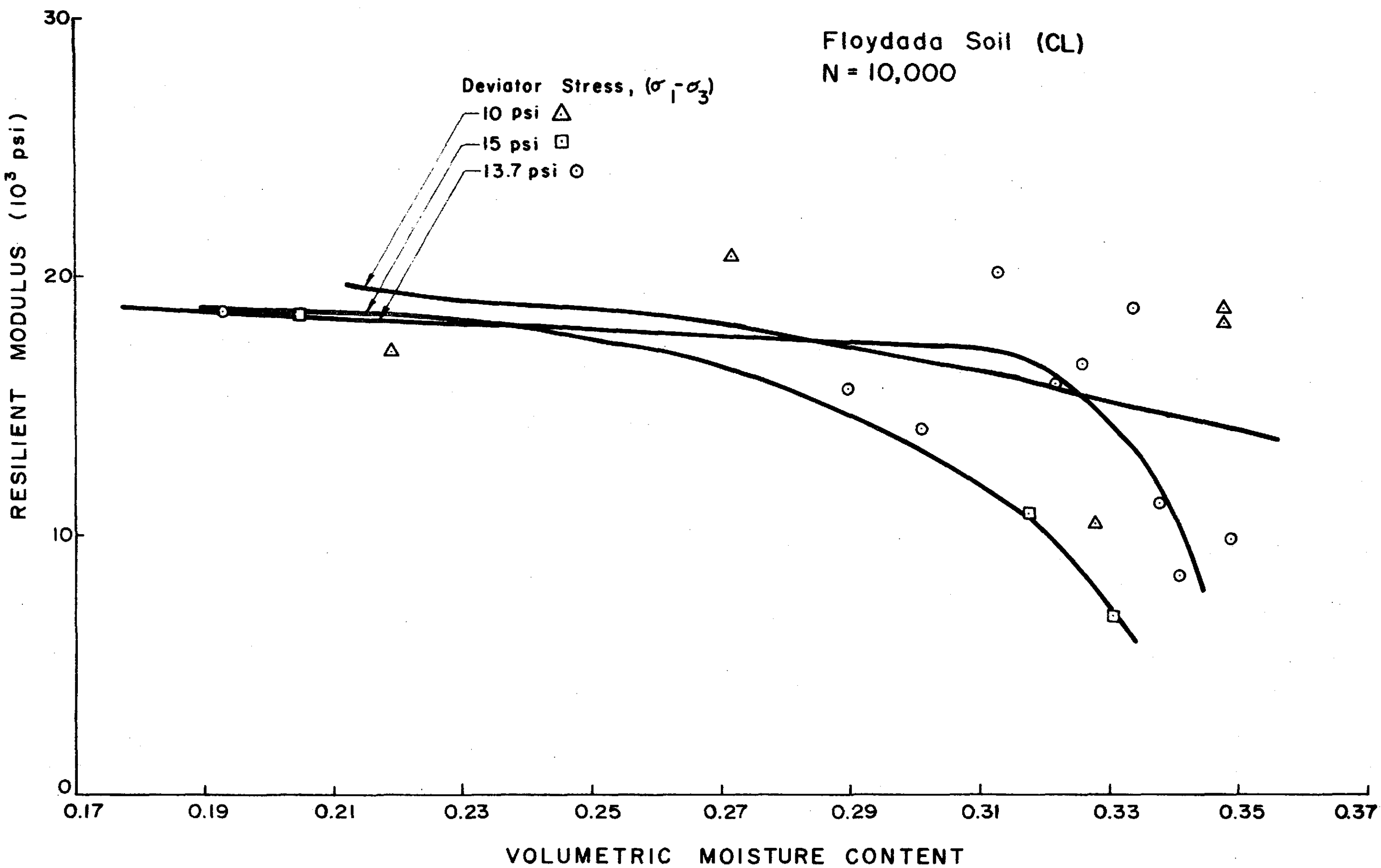


Figure 37. Resilient Modulus of the Floydada Soil (CL) as a Function of the Volumetric Moisture Content at 10,000 Load Cycles

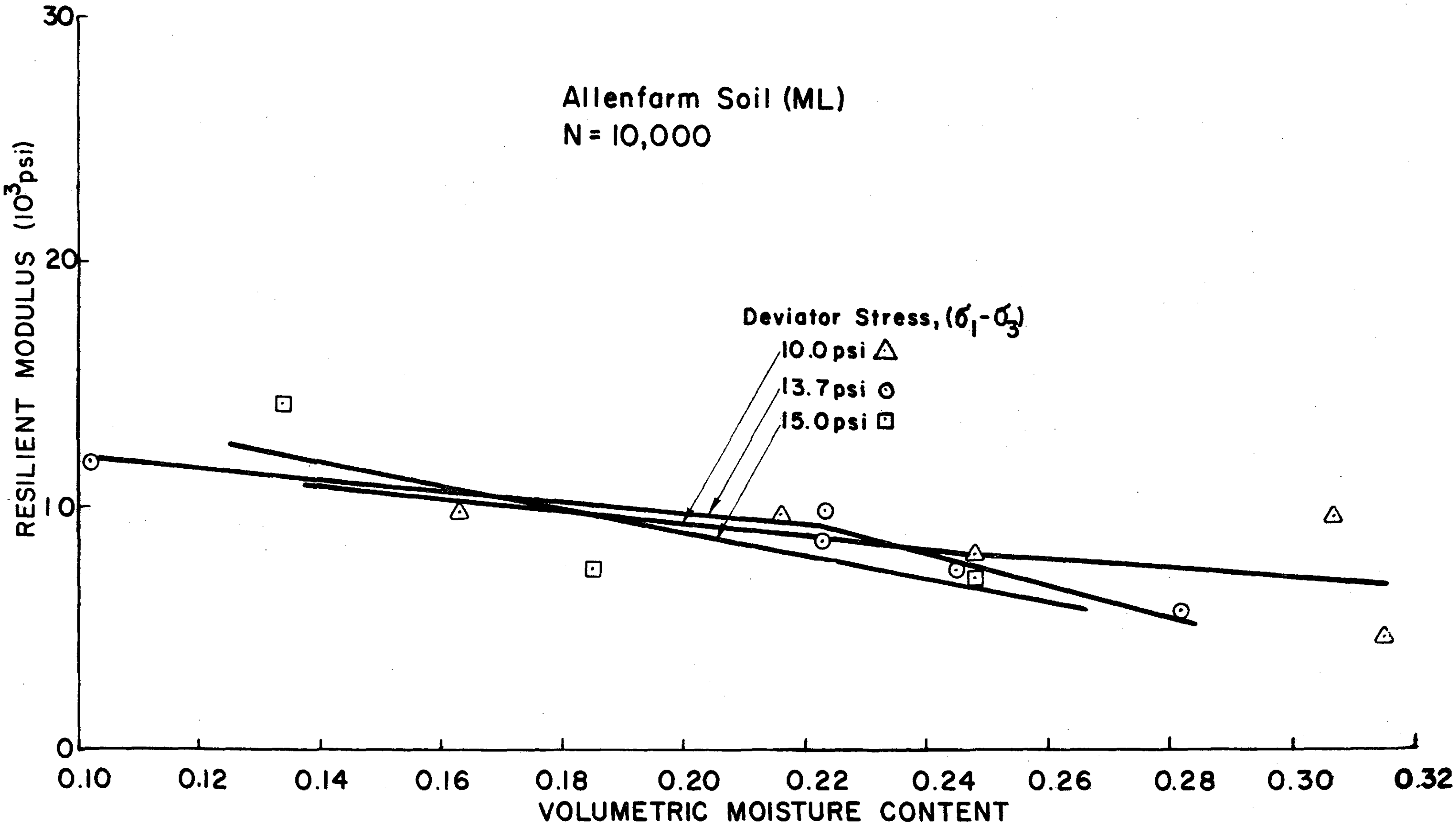


Figure 38. Resilient Modulus of the Allenfarm Soil (ML) as a Function of the Volumetric Moisture Content at 10,000 Load Cycles

the volumetric soil content is plotted against the resilient modulus are roughly the inverse of the volumetric moisture content (nS) curves shown in Figures 36, 37, and 38, the graphs are not reproduced here.

Soil Suction. Besides being related to the moisture content as described earlier, soil suction can be related to the saturation as Shackel has shown (36). Figures 39, 40, and 41 show the graphs of the resilient modulus and the initial soil suction, which is the suction measured at the beginning of the test. The test suction is measured during the test, with the minimum measurements taken at 1000, 10000 and 40000 load cycles. The final suction is the suction which is measured after the test has stopped. When the test suction and final suction are plotted against the resilient modulus, the curves have the same shape but are shifted slightly from the curves shown in Figures 39, 40, and 41.

Moscow Soil (CH). Figure 39 has a peak in the highest deviator stress curve. This peak corresponds to a moisture content about three percent dry of the optimum moisture content. The lowest deviator stress has some scatter in the data, but the best curve is a straight line. This scatter could be the result of the deviator stress being just large enough to cause some soil structure breakdown, but not large enough to do this in all the samples. The middle deviator stress level curve increases sharply until a soil suction corresponding to a moisture content of about two percent dry of optimum moisture is reached. From there the curve increases gradually. 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. In this suction range, the deviator stress of 13.7 psi (94.5 kN/m^2) produces a larger resilient modulus than the other stress levels.

Floydada Soil (CL). Figure 40 shows that the curves are flatter than the curves of the Moscow soil. The highest deviator stress curve is nearly the same as the middle deviator stress curve in the Moscow soil graph. The curve flattens out at a suction corresponding to a moisture content that is two percent dry of the optimum moisture

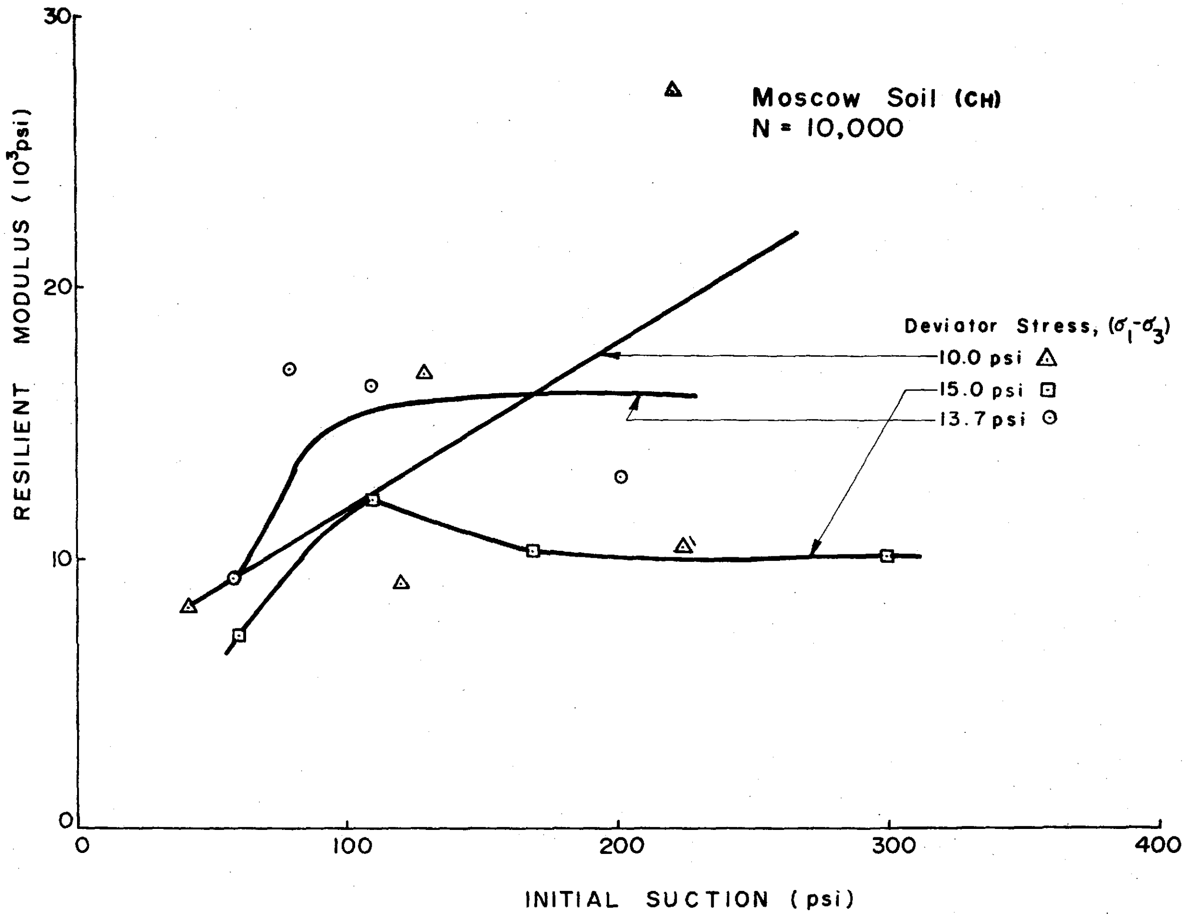


Figure 39. Resilient Modulus of the Moscow Soil (CH) as a Function of the Initial Soil Suction at 10,000 Load Cycles

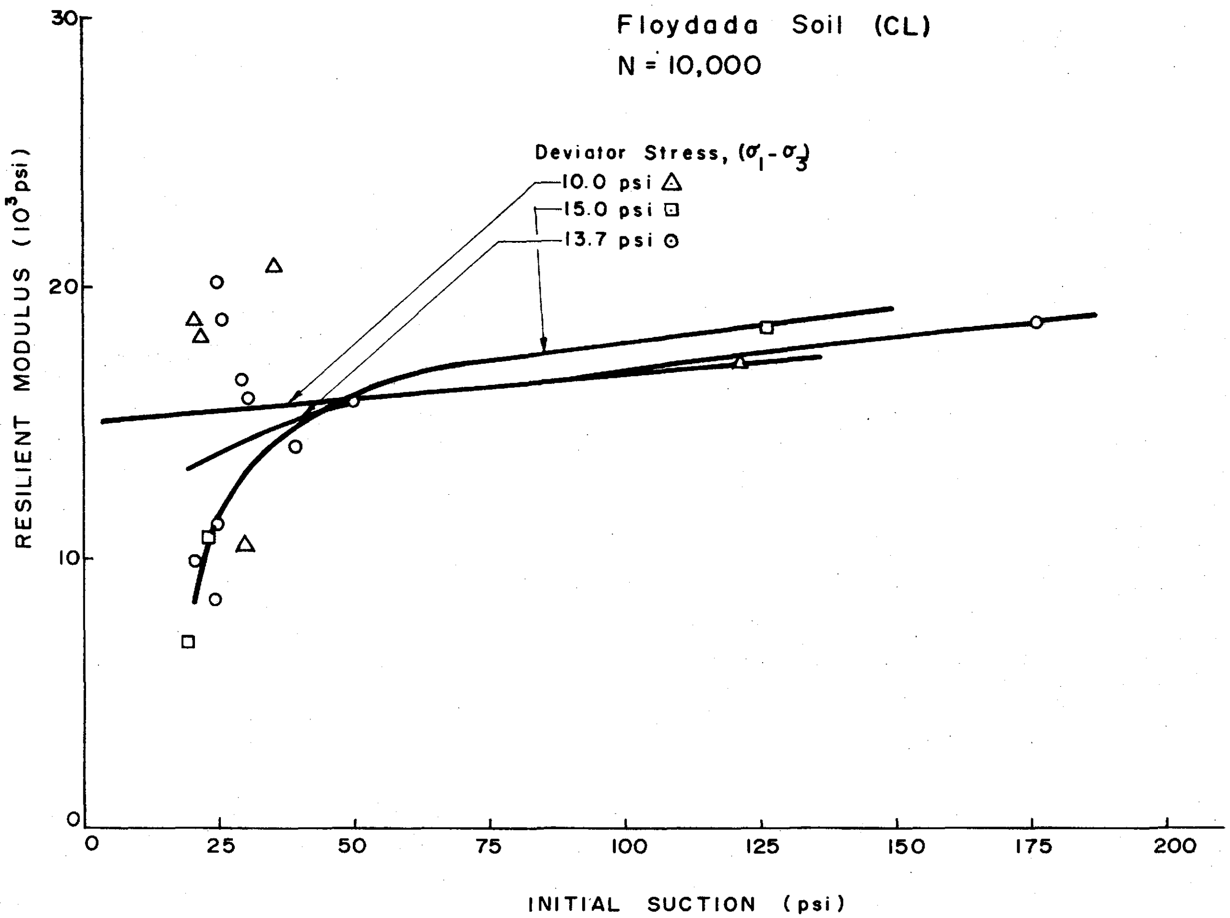


Figure 40. Resilient Modulus of the Floydada Soil (CL) as a Function of the Initial Soil Suction at 10,000 Load Cycles

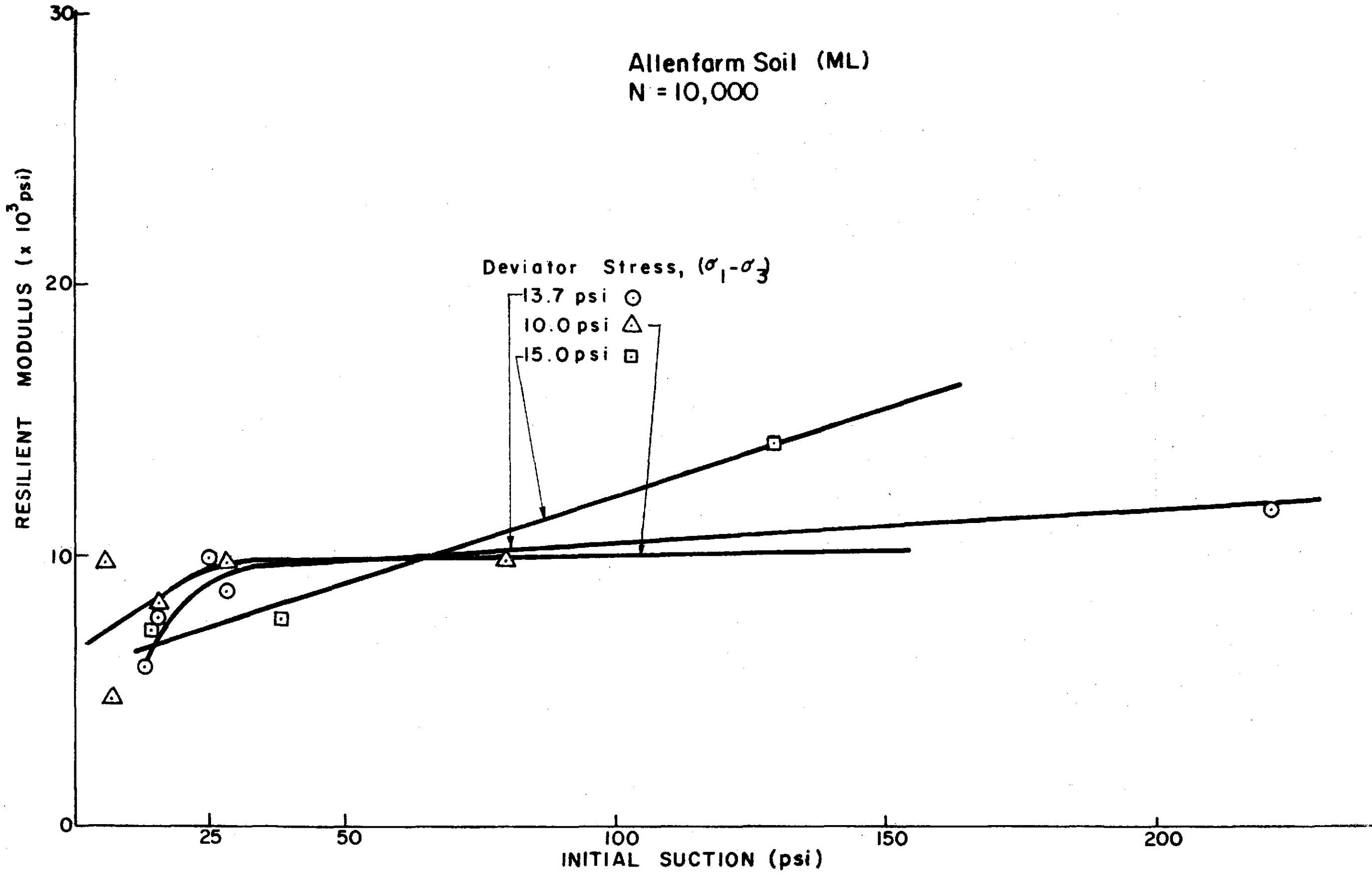


Figure 41. Resilient Modulus of the Allenfarm Soil (ML) as a Function of the Initial Soil Suction at 10,000 Load Cycles

content. The other curves are flatter, with the deviator stress determining the slope of the curve.

Allenfarm Soil (ML). Figure 41 shows that after a suction of 25 psi (172.5 kN/m^2), there is little change in the resilient modulus. The slope of the flat portion of the curve is dependent upon the deviator stress. This being a silty soil with low soil suction, the moisture content changes more than the soil suction when the suction is below 25 psi (172.5 kN/m^2). The suction of 25 psi (172.5 kN/m^2) corresponds to a moisture content that is two percent dry of the optimum moisture content. Because of the low clay content and larger moisture content, the soil structure was weakened. Thus there was a rapid decrease in the resilient modulus with a decrease below the 25 psi (172.5 kN/m^2) suction level. 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.

The effect of the soil type on the resilient modulus - soil suction relationship is shown in Figure 42. The resilient modulus is largest with the CL material, then it decreases for the soils with higher and lower clay contents. 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. Sauer and Monismith (21) showed the same general curve in Figure 13, for a glacial till material. There were several exceptions, the high deviator stress of the Moscow soil that reached a peak, and several curves at the low deviator stress that increase at a nearly constant rate. Even with these exceptions the soil suction will be an important link in any relationship dealing with the resilient modulus.

Residual Strain

The residual deformation has been defined in Chapter 1 on page 7. The residual deformation is used to determine the residual strain which is defined as the ratio of the residual deformation to the sample length. The residual deformation continually increases during

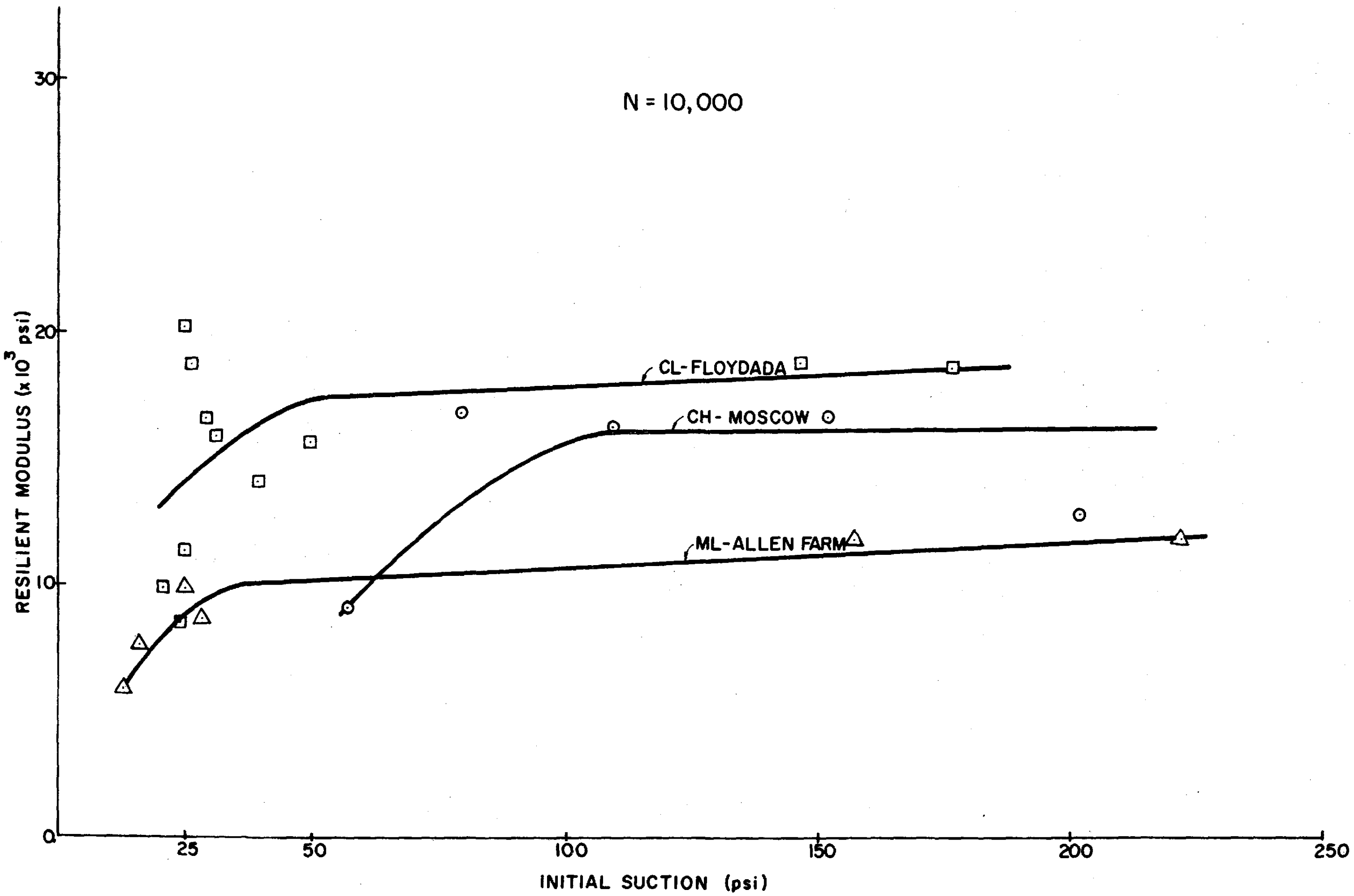


Figure 42. Resilient Modulus of the Three Soils at 10,000 Load Cycles as a Function of the Initial Soil Suction

the test. This increase is not linear; more residual deformation is developed per load cycle in the beginning of the test than as the number of cycles increases.

There was a large range of residual strain that occurred during the first few load cycles. This range is attributed to seating error, because the samples were not pre-loaded. To compensate for this, the residual strain was set to zero at the one hundredth load repetition. Figure 43 shows the residual strain plotted against the number of repetitions before the correction was applied. Figure 44 shows the same plot after the correction was made. In this figure, the differences in the strains are due to differences in the sample, not to the differences caused by the seating error.

The shape of the curves in Figure 44 is similar to the curves presented by Culley in Figure 7 (7), and Sauer and Monismith in Figure 11 (21). Figure 44 is typical of several curves, the curves for the rest of the tests are shown in Appendix IV. The initial suction, saturation, moisture content, and dry density are shown for each curve. Small variations in the dry density does not have a significant effect on the residual strain. From Figure 44 one can see that to predict the residual strain the number of load cycles must be known.

As with the resilient modulus, the residual strain of the samples tested at room temperature is compared with basic moisture properties to determine if a simple relationship or trend can be developed. Unlike the resilient modulus, the volumetric soil content does not show any trend when plotted against the residual strain.

Saturation (S). Figures 45, 46, and 47 show that the residual strain increases as the saturation decreases. In Figures 46 (Floydada Soil) and 47 (Allenfarm Soil), as the saturation reaches the moisture content that is about two percent dry of the optimum moisture content, the residual strain increases rapidly with a small change in saturation. The low deviator stress in the Floydada soil does not show as much of an upward trend as do the other stresses. Also, the same stress in the Allenfarm soil has a rapid increase in the residual strain for a small increase in the saturation. Thus, the

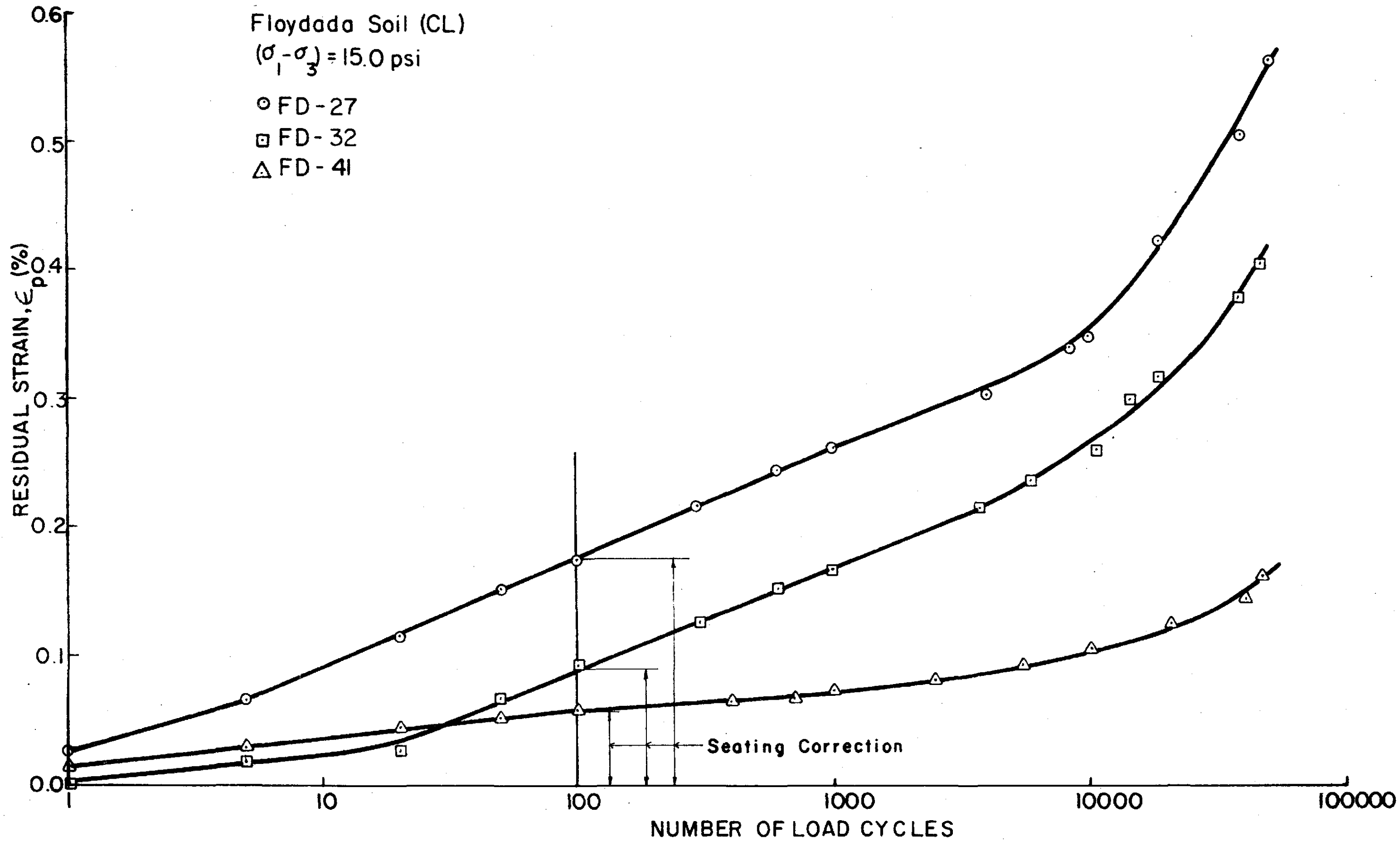


Figure 43. Variation of the Residual Strain With the Number of Load Cycles, Without Seating Correction, Floydada Soil (CL), 15.0 psi Deviator Stress

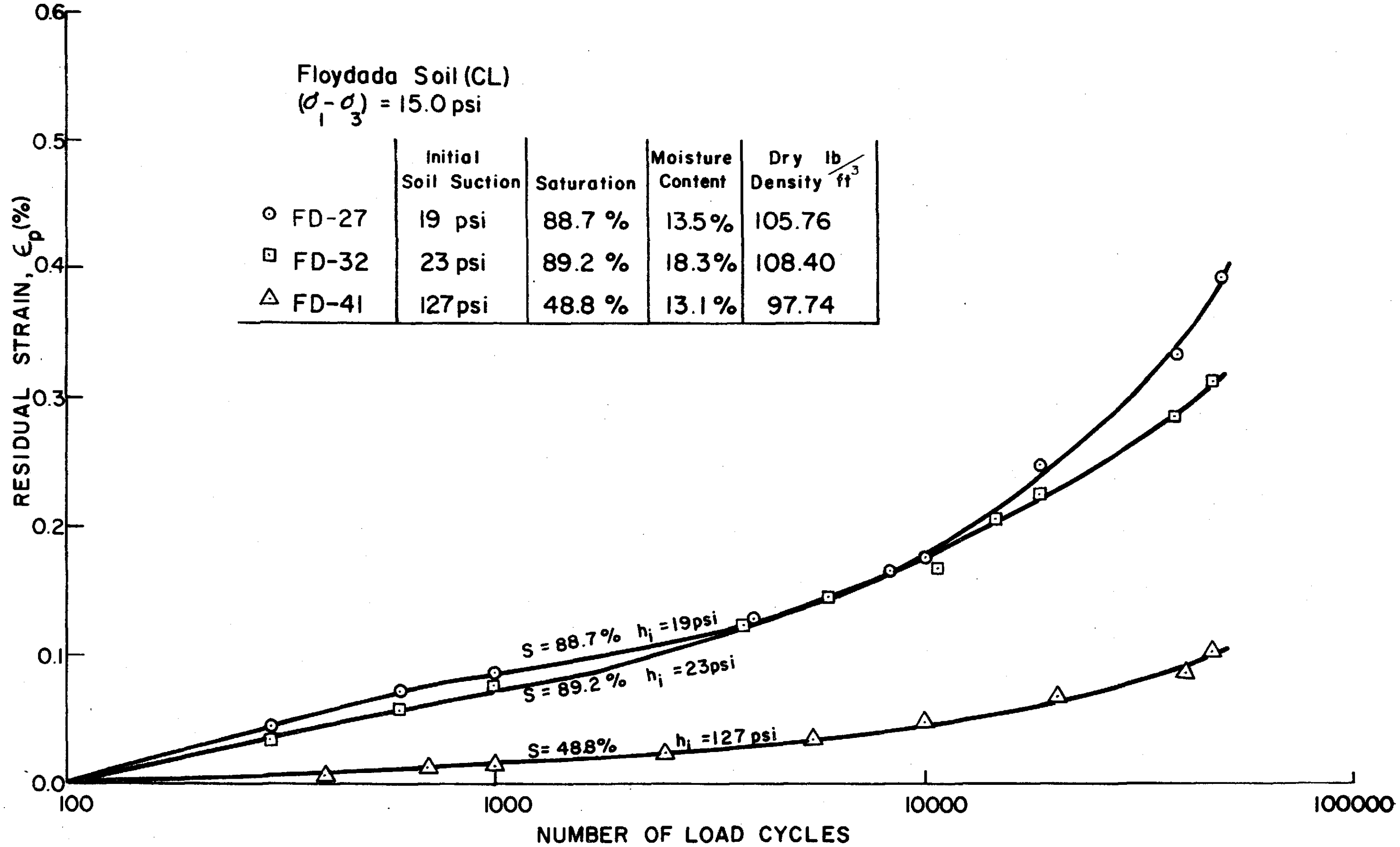


Figure 44. Variation of the Residual Strain With the Number of Load Cycles, With Seating Correction, Floydada Soil (CL) 15.0 psi Deviator Stress

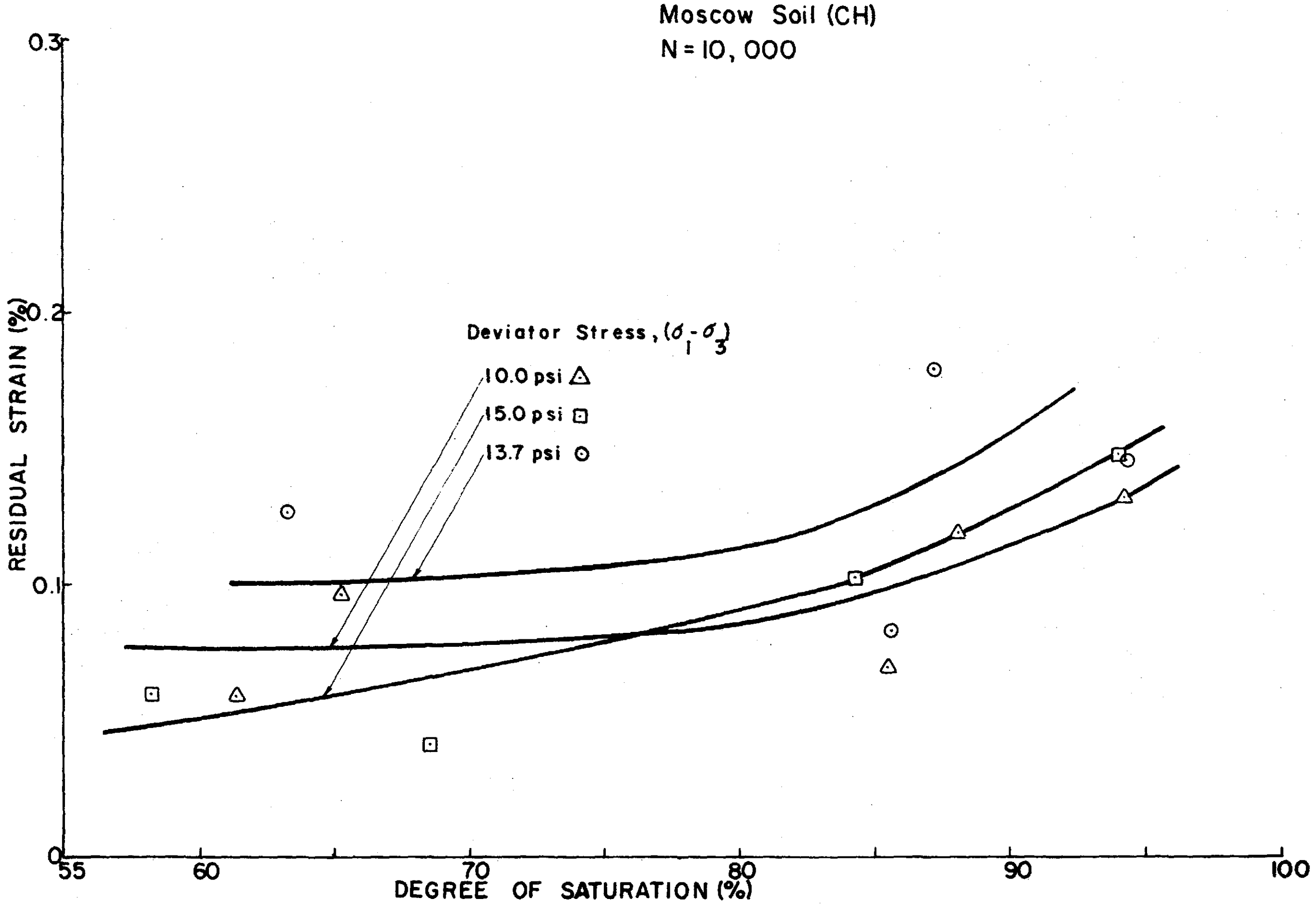


Figure 45. Residual Strain of the Moscow Soil (CH) as a Function of the Degree of Saturation at 10,000 Load Cycles

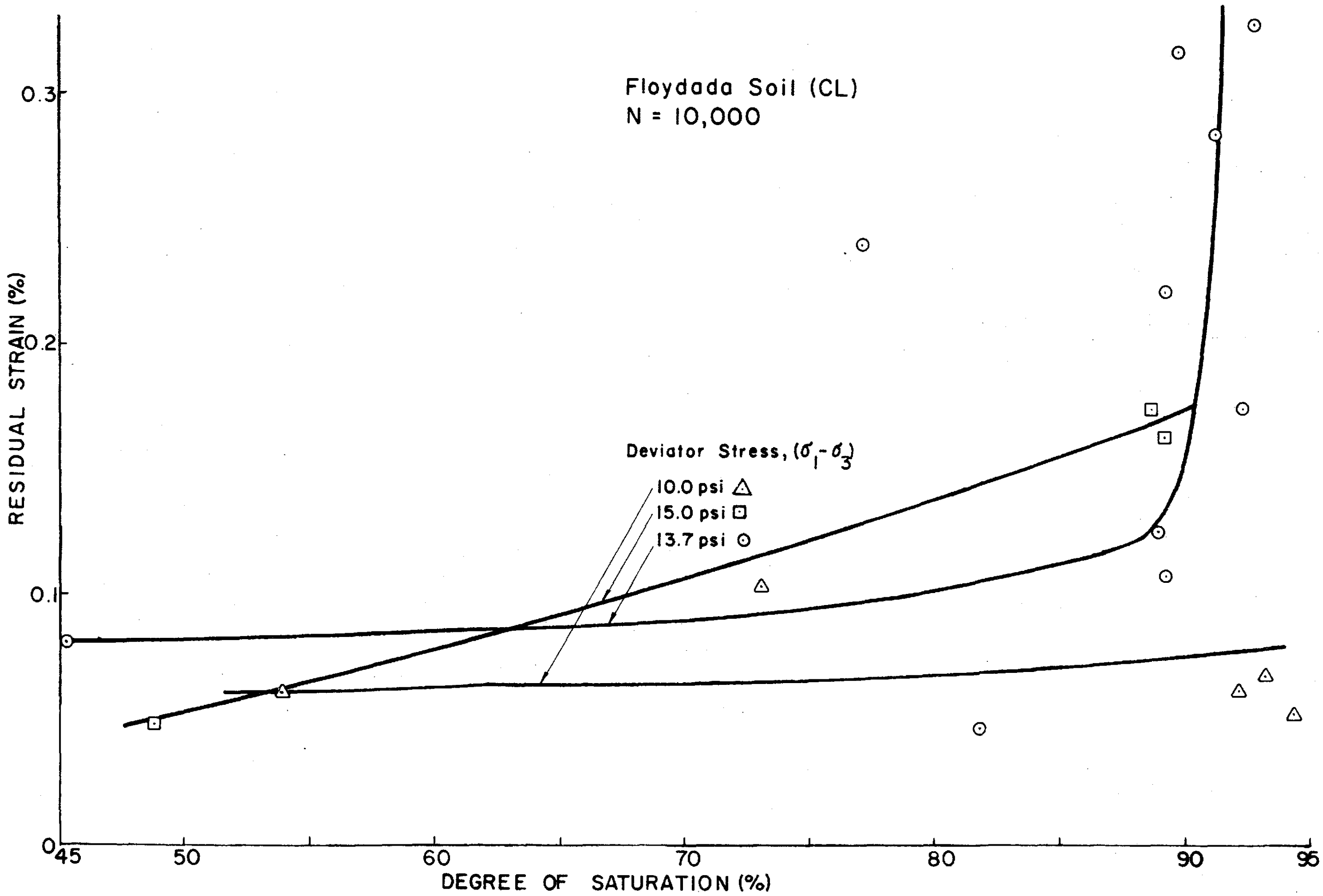


Figure 46. Residual Strain of the Floydada Soil (CL) as a Function of the Degree of Saturation at 10,000 Load Cycles

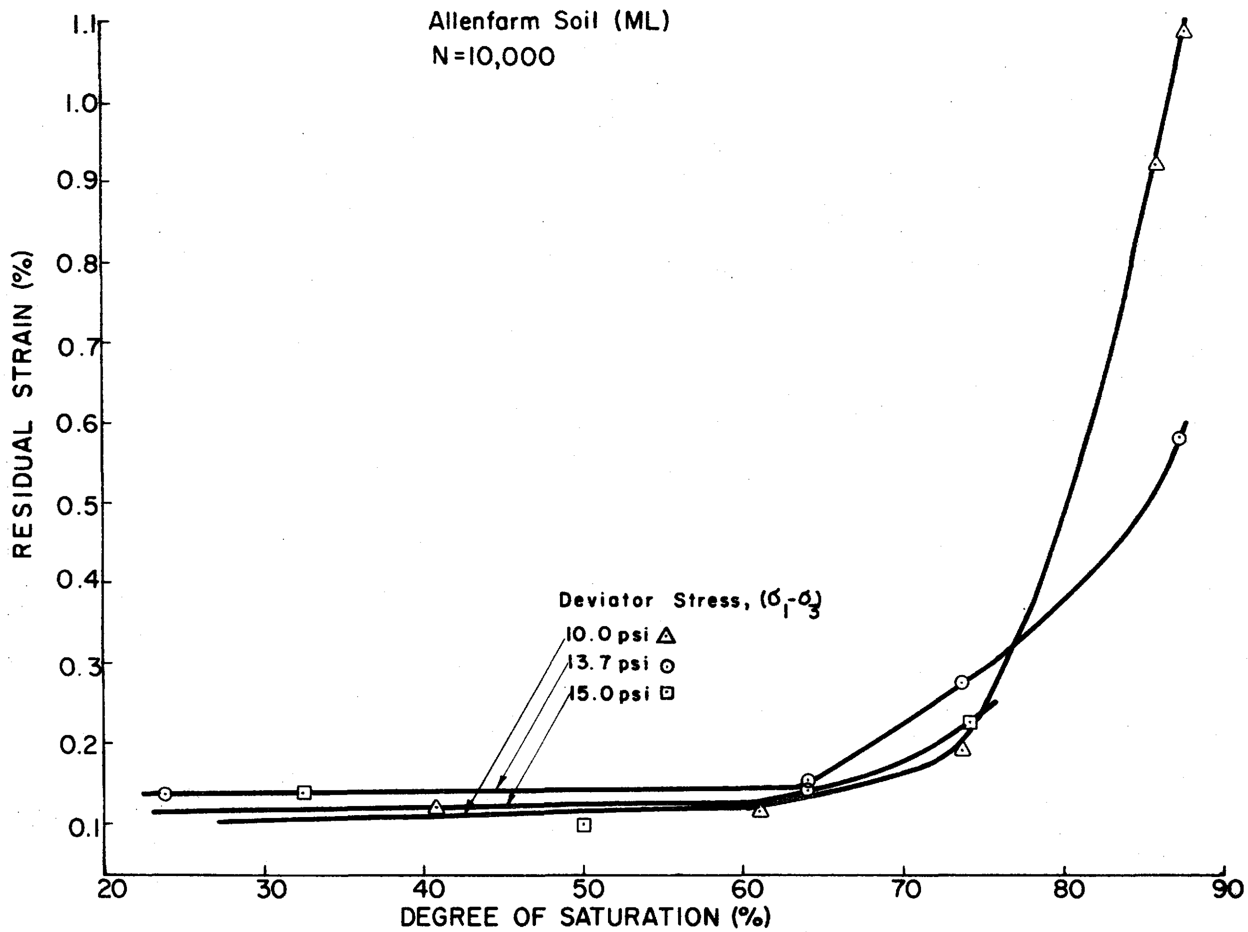


Figure 47. Residual Strain of the Allenfarm Soil (ML) as a Function of the Degree of Saturation at 10,000 Load Cycles

smaller the clay content for a soil that is wetter than two percent dry of the optimum moisture content, the more the residual strain will increase for a small increase in saturation. This would show that the clay tends to hold the samples together. Overall, more residual strain is caused by the stress conditions with higher ratios of deviator stress to mean stress. Thus the middle deviator stress generally caused more strain than the other stress levels. The trend shown in these figures can be used in developing a residual strain relationship.

Volumetric Moisture Content (nS). Figures 48, 49, and 50 show the same trends that were brought out in the previous graphs where the residual strain was plotted against the saturation. It can be seen again in these figures that the general order of deviator stresses that cause more residual strain is 10.0 psi (69 kN/m^2), 15.0 (103.5 kN/m^2) and 13.7 psi (94.5 kN/m^2). As with the saturation graphs, the trend shown can be used to develop a residual strain relationship.

Soil Suction. Since the volumetric moisture content and the saturation curves have the same general shape, these two properties should be expressed by one term. This is done by using soil suction. Figures 51, 52, and 53 shows the graphs of the residual strain and the initial soil suction. When the test and final suctions are plotted with the residual strain, the curves have the same general shape but are shifted slightly from the curves shown in Figures 51, 52, and 53.

Moscow Soil (CH). Figure 51 shows that there is not a rapid 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 largest residual strain is caused by the largest ratio of deviator stress to mean stress. Also the smallest residual strain is generally produced by the smallest ratio of deviator stress to mean stress.

Floydada Soil (CL). In Figure 52, there is a rapid increase in the residual strain as the soil suction decreases below the level

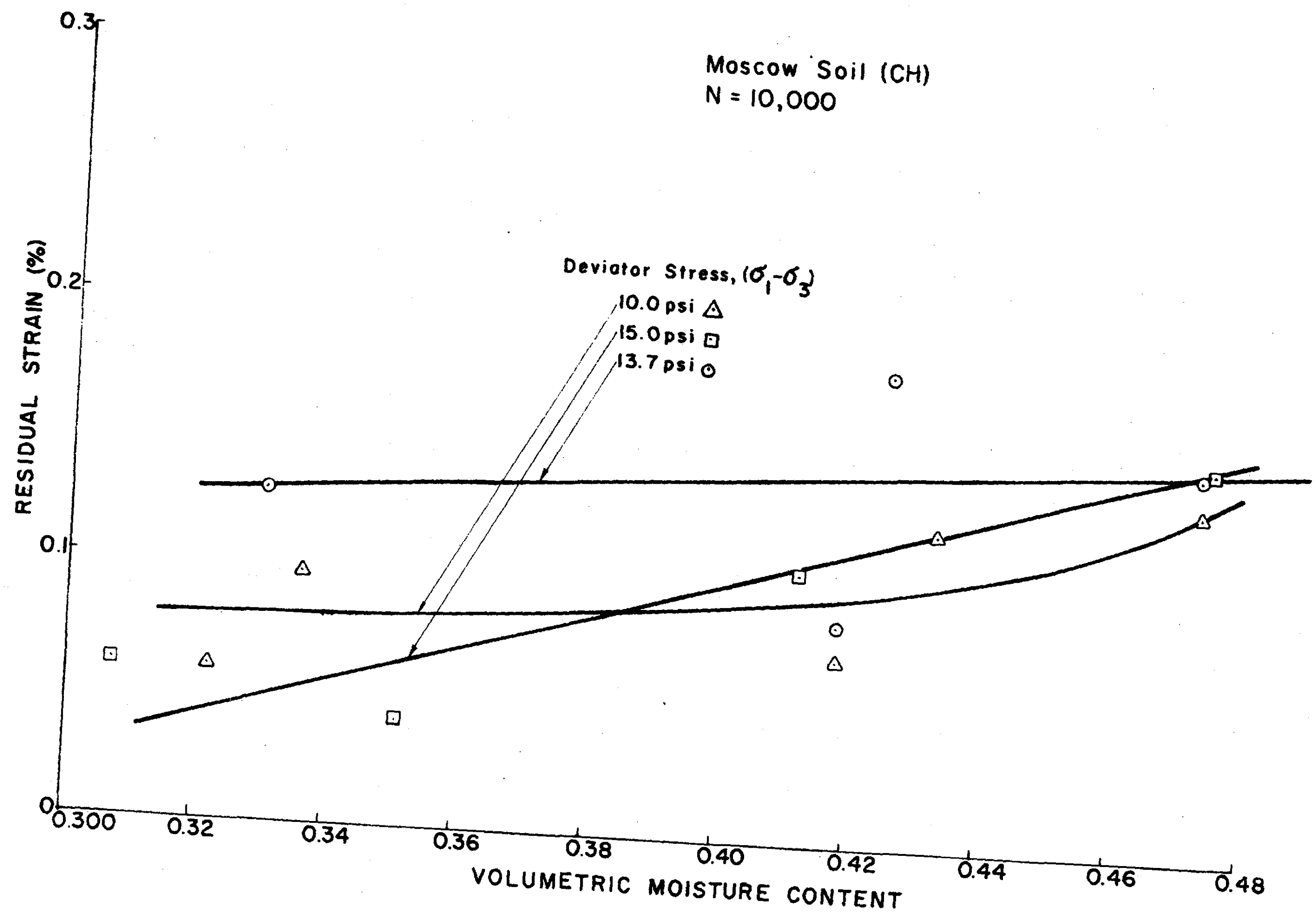


Figure 48. Residual Strain of the Moscow Soil (CH) as a Function of the Volumetric Moisture Content at 10,000 Load Cycles

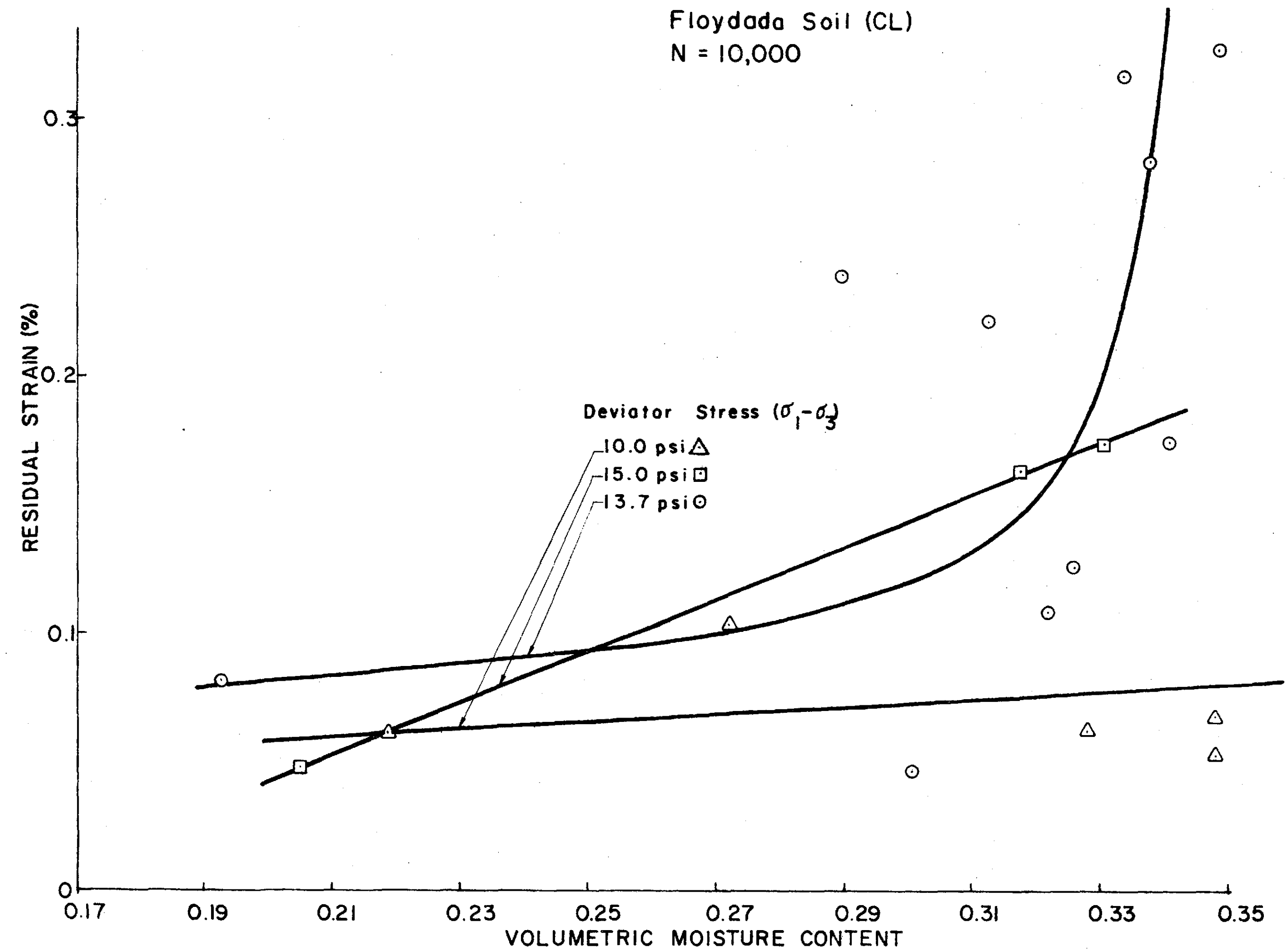


Figure 49. Residual Strain of the Floydada Soil (CL) as a Function of the Volumetric Moisture Content at 10,000 Load Cycles

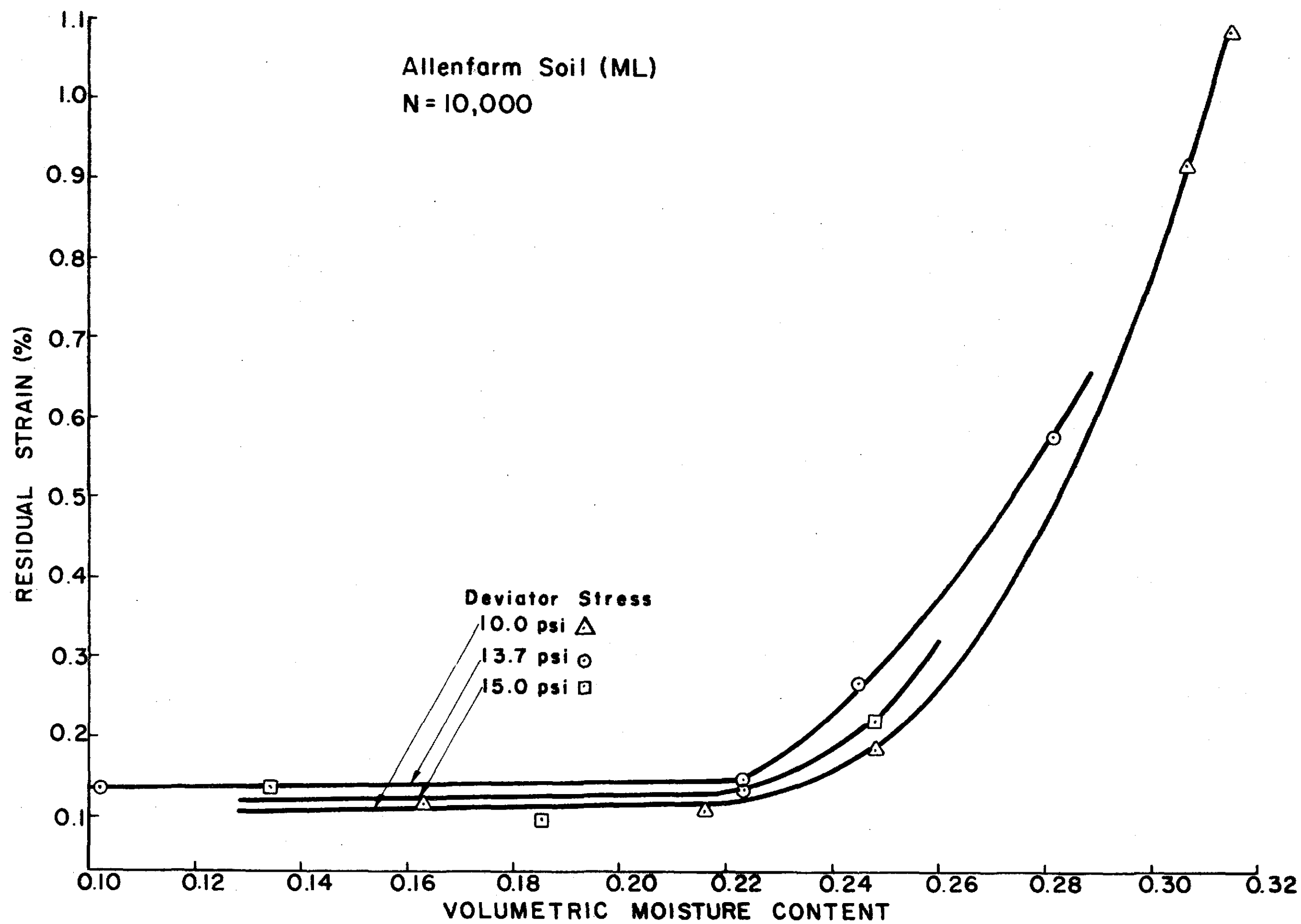


Figure 50. Residual Strain of the Allenfarm Soil (ML) as a Function of the Volumetric Moisture Content at 10,000 Load Cycles

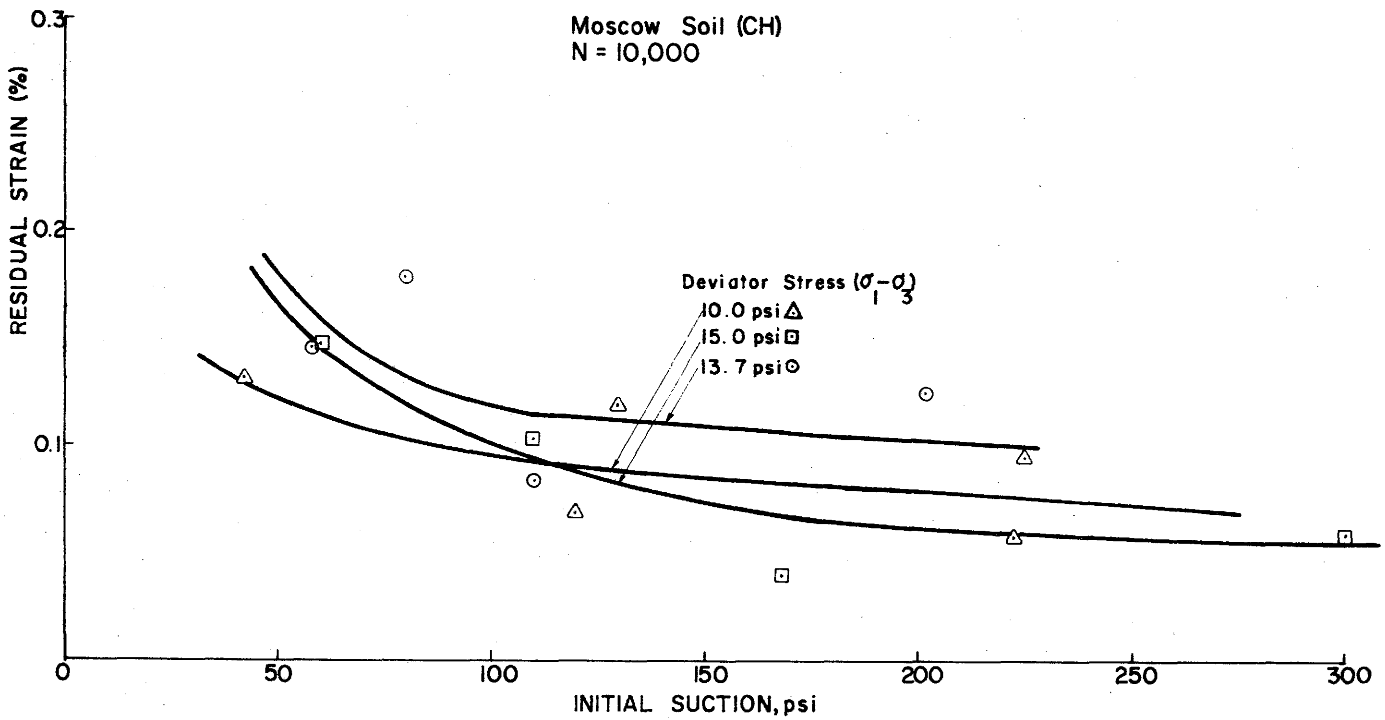


Figure 51. Residual Strain of the Moscow Soil (CH) as a Function of the Initial Soil Suction at 10,000 Load Cycles

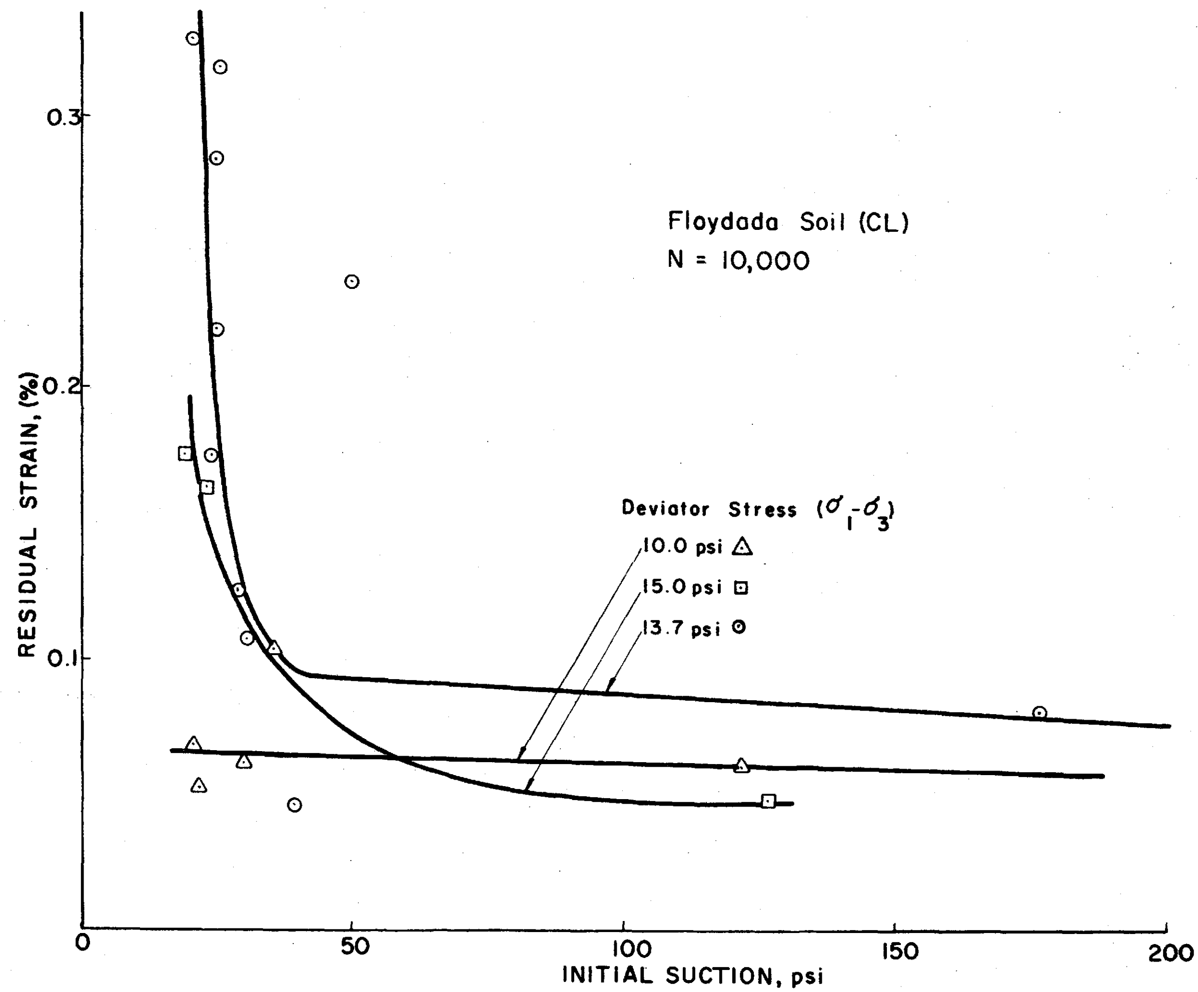


Figure 52. Residual Strain of the Floydada Soil (CL) as a Function of the Initial Soil Suction at 10,000 Load Cycles

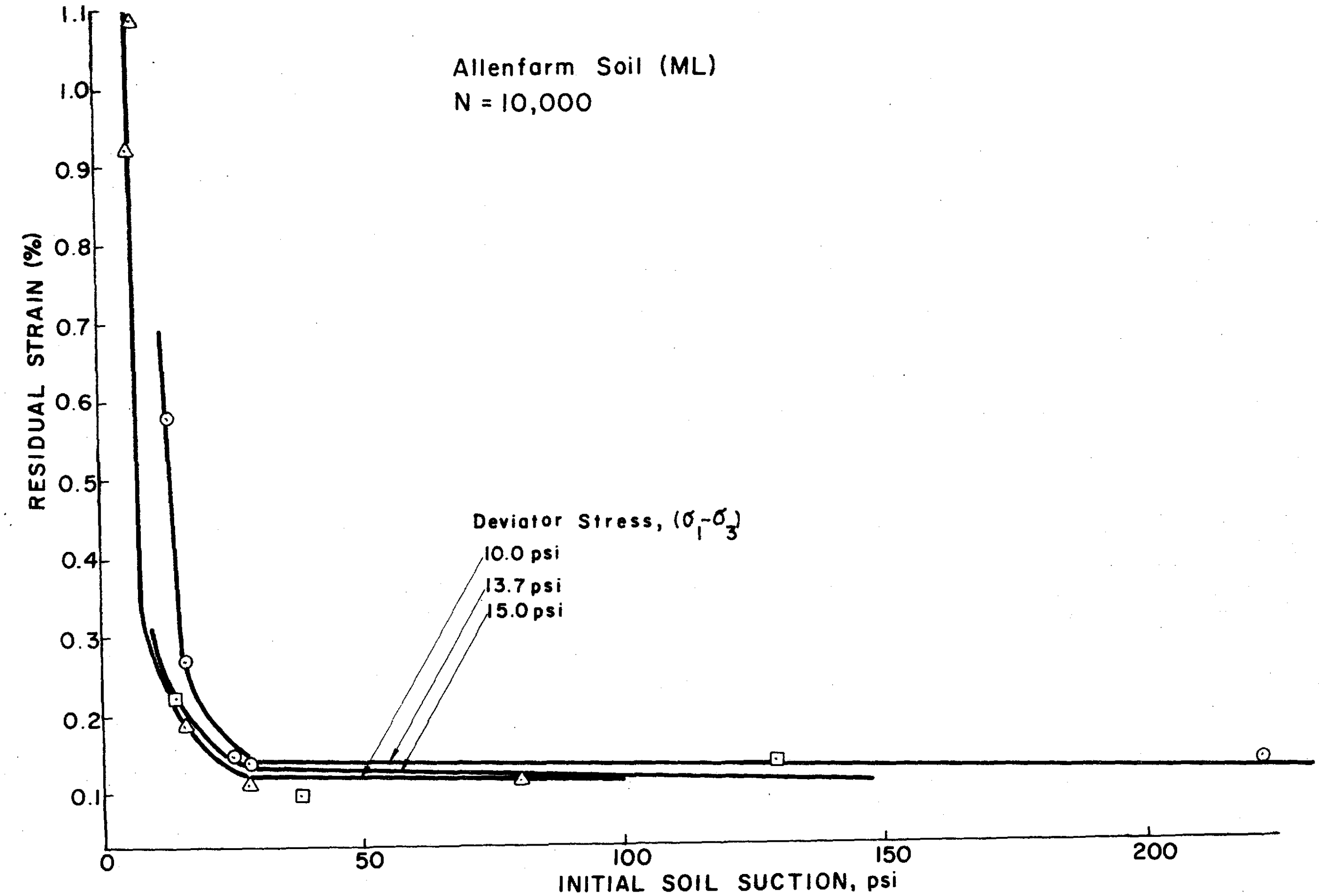


Figure 53. Residual Strain of the Allenfarm Soil (ML) as a Function of the Initial Soil Suction at 10,000 Load Cycles

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 mean stress dictates how much residual strain will be developed. At the higher suction levels, the residual strain in this figure is lower than the residual strain of the Moscow soil. This could be caused by the difference in the clay content of the two soils.

Allenfarm Soil (ML). Figure 53 shows a very rapid increase in the residual strain for a small change in the soil suction below 25 psi (103.5 kN/m^2), which corresponds to about two percent dry of the optimum moisture content. Beyond this point, the curves become very flat. The highest two deviator stresses are represented by the same line. This shows that deviator stresses above 13.7 psi (94.5 kN/m^2) do not produce more residual strain. 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 54. 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 previous figures showed that generally, the mean stress is important in determining the residual strain. As shown in Figure 54, 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. Thus there are two important factors that influence the residual strain that occurs at a particular number of load cycles, they are the clay content and the stress condition.

Temperature Effects on the Resilient Modulus

As mentioned previously, clay behaves viscoelastically, thus the resilient modulus is dependent upon both time and temperature. Generally, the resilient modulus increases when the temperature decreases and vice versa. The change in the resilient modulus is not constant with the change of the temperature. The percent change in the resilient modulus listed in Table 6 was determined by using the initial soil suction as the common factor. Several samples show a decrease in

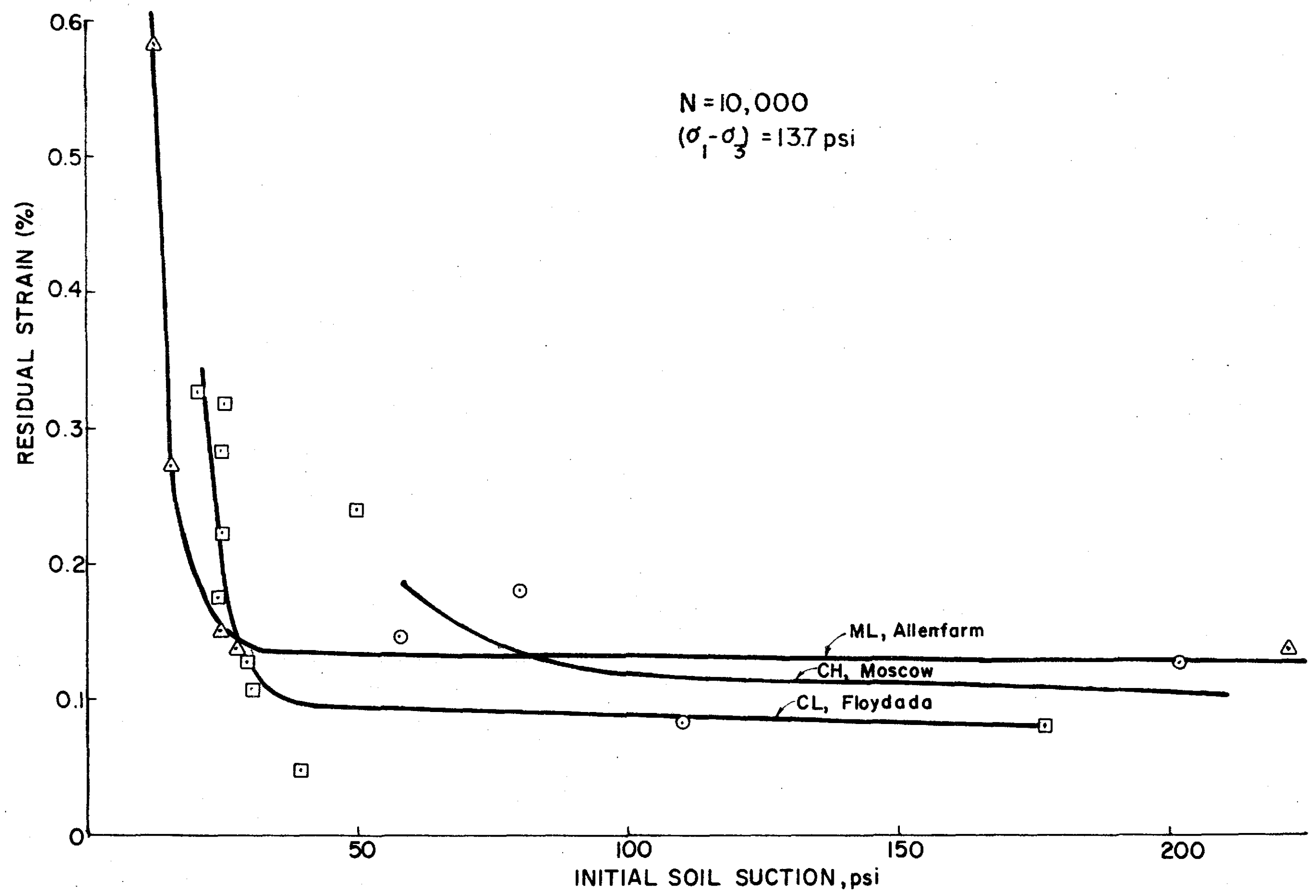


Figure 54. Residual Strain of the Three Soils at 10,000 Load Cycles as a Function of the Initial Soil Suction

TABLE 6

PERCENT CHANGE OF THE RESILIENT MODULUS DUE TO TEMPERATURE CHANGES

Number of Load Cycles	Soil Type	Deviator Stress, psi	Percent Change in the Resilient Modulus	
			Temperature Change from 22° to 0°C	Temperature Change from 22° to 39°C
1000	Moscow Soil	13.7 15.0 10.0	-15.4% & +13.4% +173.1% +24.8%	-52.1% -49.0% -31.2%
	Floydada Soil	13.7 15.0 10.0	+22.9% -19.5% +62.9%	-39.9% -24.3% & -48.1% -47.1%
	Allenfarm Soil	13.7 15.0 10.0	+84.6% +9.6% -32.6%	-11.9% -51.4% -4.5%
10000	Moscow Soil	13.7 15.0 10.0	-24.5% & -13.6% +166.2% -13.2%	-61.5% -50.4% -35.0%
	Floydada Soil	13.7 15.0 10.0	+11.9% -28.4% +46.8%	-44.3% -41.6% &-27.4% -45.6%
	Allenfarm Soil	13.7 15.0 10.0	+87.2% -7.5% -39.8%	-9.4% -47.2% -9.3%
40000	Moscow Soil	13.7 15.0 10.0	-28.4% & -31.5% +162.3% -46.6%	-65.7% -52.1% -35.1%
	Floydada Soil	13.7 15.0 10.0	+0.5% -34.5% +32.1%	-47.9% -8.6% & -45.5% -46.4%
	Allenfarm Soil	13.7 15.0 10.0	+54.4% -27.1% -51.3%	-9.6% -48.2% -14.8%

+ increase in resilient modulus

- decrease in resilient modulus

0°C=32°F
22°C=72°F
39°C=102°F

the resilient modulus instead of the expected increase when the temperature is lowered about 20°C (36°F). This fact, along with the fact that when the temperature was raised all the samples had a decrease in the resilient modulus, shows that a temperature increase will cause more change in the resilient modulus than a temperature decrease of the same amount. Generally, in the range of temperatures considered the resilient modulus is twice as sensitive to an increase of temperature than it is to a temperature decrease.

There are several variables that could relate the change in the resilient modulus with the temperature. The possible group of variables are stress level, number of load cycles and a soil property. There is generally not a significant change of the resilient modulus caused by a variation of the deviator stress. The number of load cycles has a small effect on the percent change when the temperature is increased about 17°C (30°F), but there is a larger effect when the temperature is decreased about 22°C (39.6°F). The effect the number of cycles has on the percent change of the resilient modulus is shown in Figure 55. Of the group of properties that could relate the change of the resilient modulus with temperature, the stress level and number of load cycles do not have a significant effect.

The change in the resilient modulus due to temperature changes must be related to a soil property. The percent change in the resilient modulus as a function of the clay content is shown in Figure 56. For a temperature increase, as the clay content increases the change in the resilient modulus decreases. Also when the temperature decreases a clay content increase causes the change of the resilient modulus to increase. It appears that the clay content can be used in relating the percent change in the resilient modulus to the temperature change.

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. Also the residual strain decreases when the temperature decreases. The increase in the residual strain from 0°C (32°F) to 40°C (104°F) is not constant. The residual strain

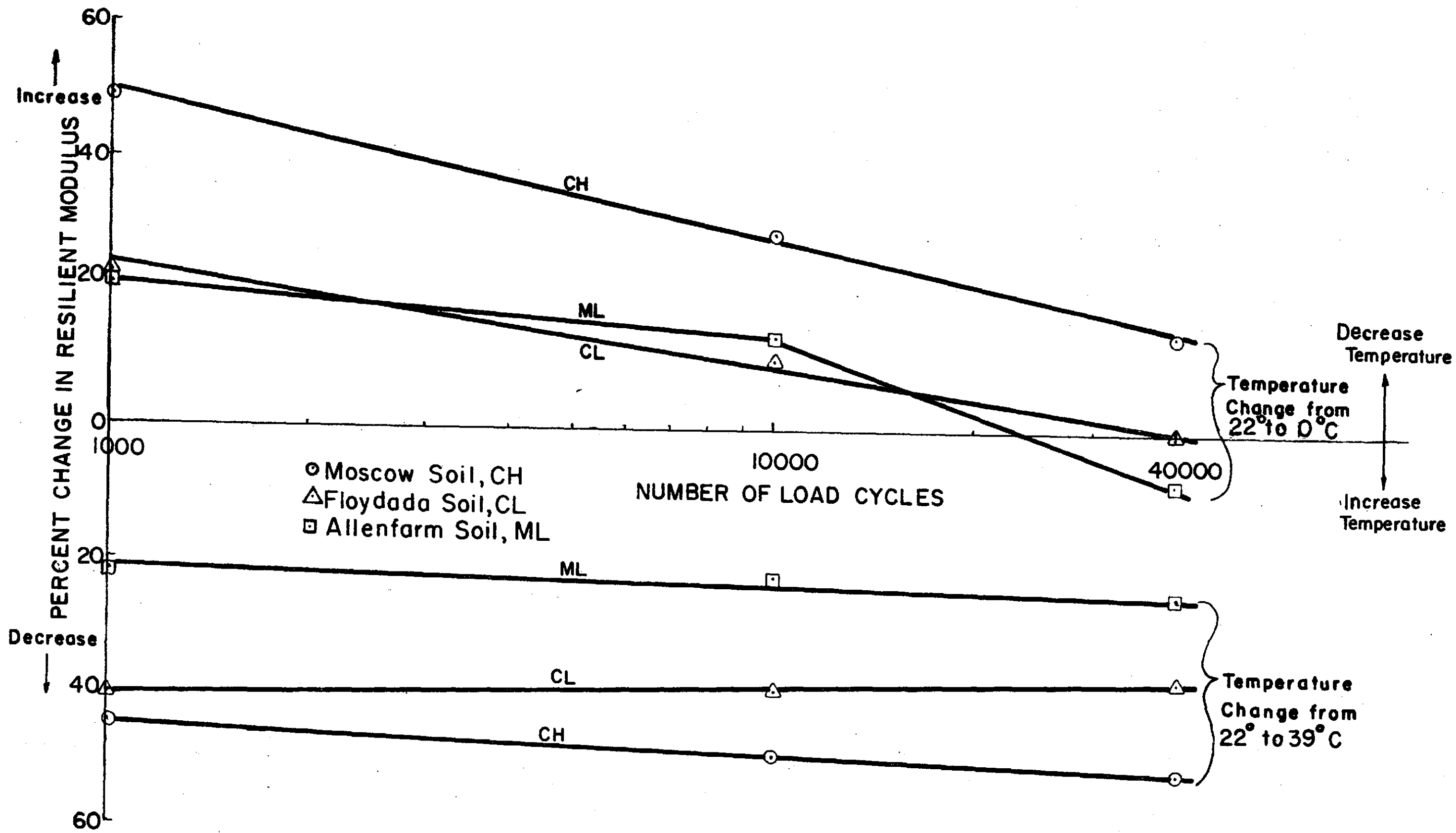


Figure 55. Percent Change in the Resilient Modulus of the Three Soils Due to Temperature Change as a Function of the Number of Load Cycles

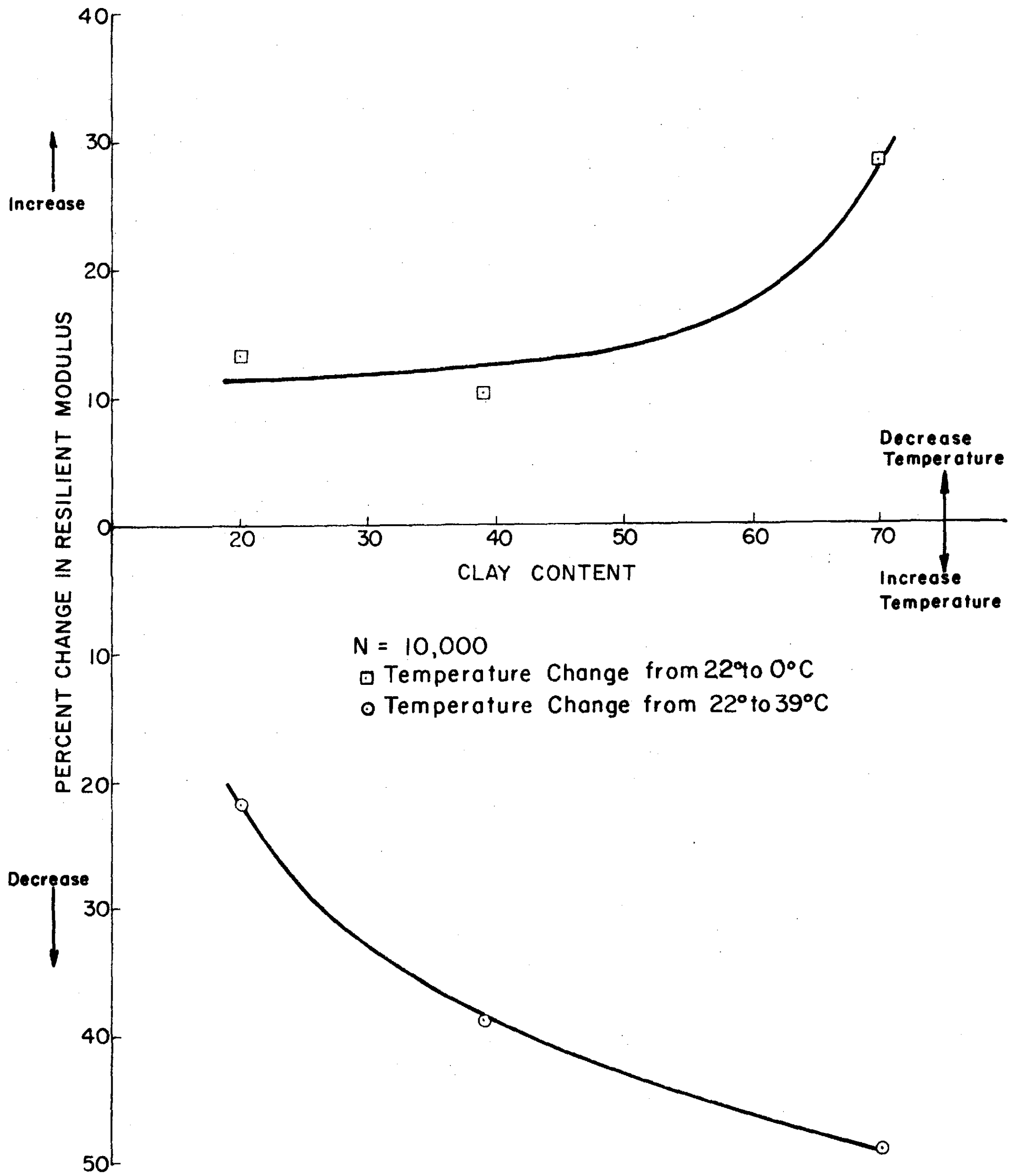


Figure 56. Percent Change in the Resilient Modulus of the Three Soils Due to Temperature Change as a Function of the Clay Content at 10,000 Load Cycles

is about 4.5 times as sensitive to a temperature increase than it is to a temperature decrease. The variation in the residual strain is over twice the variation of the resilient modulus.

The percent change in the residual strain for each sample is listed in Table 7. As with the resilient modulus, the initial soil suction was used as the common factor. The three numbers of load cycles used are 5000, 10000, and 40000 cycles. The five thousand cycle values are used because the seating error affected the one thousand cycle values.

There are several variables that could relate the change in the residual strain with a change in temperature. The group of variables are number of load cycles, stress level, and a soil property. Figure 57 shows how the number of cycles influence the change in the residual strain. For temperatures below room temperature, most of the samples showed that as the number of cycles increases the residual strain decreases slightly. For temperatures above room temperature, as the number of load cycles increases, the residual strain increases slightly.

The clay content comparison with the percent change in the residual strain is shown in Figure 58. When the temperature is decreased, the percent change decreases as the clay content increases. However as the temperature increases the percent change reaches a peak in the middle of the clay content range. Thus the clay content could be used to relate the change in the residual strain when the temperature is below room temperature.

Figure 59 shows how the mean stress compares with the percent change in the residual strain. In this figure, the residual strain increases as the mean stress increases. The increase is not as much when the temperature is decreased to $0^{o}C$ ($32^{o}F$) as when the temperature is raised to $40^{o}C$ ($104^{o}F$). Thus the mean stress can be used to describe the percent change in the residual strain at a particular number of load cycles when the temperature is either increased or decreased.

Summary

The relation of several properties to the resilient modulus has

TABLE 7

PERCENT CHANGE OF THE RESIDUAL STRAIN DUE TO TEMPERATURE CHANGES

Number of Load Cycles	Soil Type	Deviator Stress, psi	Percent Change in the Residual Strain	
			Temperature Change from 22° to 0°C	Temperature Change from 22° to 39°C
5000	Moscow Soil	13.7	-38.2% & -76.2%	-4.1%
		15.0	-46.0%	+410.5%
		10.0	-51.7%	+412.9%
	Floydada Soil	13.7	-85.6%	+97.8%
		15.0	+16.4%	+831.3% & +363.3%
		10.0	-2.0%	+263.8%
	Allenfarm Soil	13.7	-50.0%	-44.8%
		15.0	+51.8%	+257.8%
		10.0	+470.1%	+174.3%
10000	Moscow Soil	13.7	-32.1% & -82.8%	+43.3%
		15.0	-51.0%	+432.9%
		10.0	-59.8%	+370.9%
	Floydada Soil	13.7	-88.3%	+96.7%
		15.0	+8.9%	+637.5% & +254.2%
		10.0	+23.0	+439.3%
	Allenfarm Soil	13.7	-49.3%	-23.2%
		15.0	+11.3%	+229.3%
		10.0	+372.4%	+168.1%
40000	Moscow Soil	13.7	-74.1% & -84.2%	+61.9%
		15.0	-53.7%	+573.3%
		10.0	-57.5%	+234.2%
	Floydada Soil	13.7	-91.0%	+78.0%
		15.0	-25.3%	+668.6& +526.2%
		10.0	-18.9%	+420.0%
	Allenfarm Soil	13.7	-53.9%	+144.8%
		15.0	+37.2%	+164.1
		10.0	+166.8%	+134.1

+ increase in residual strain

- decrease in residual strain

0°C = 32°F
22°C = 72°F
39°C = 102°F

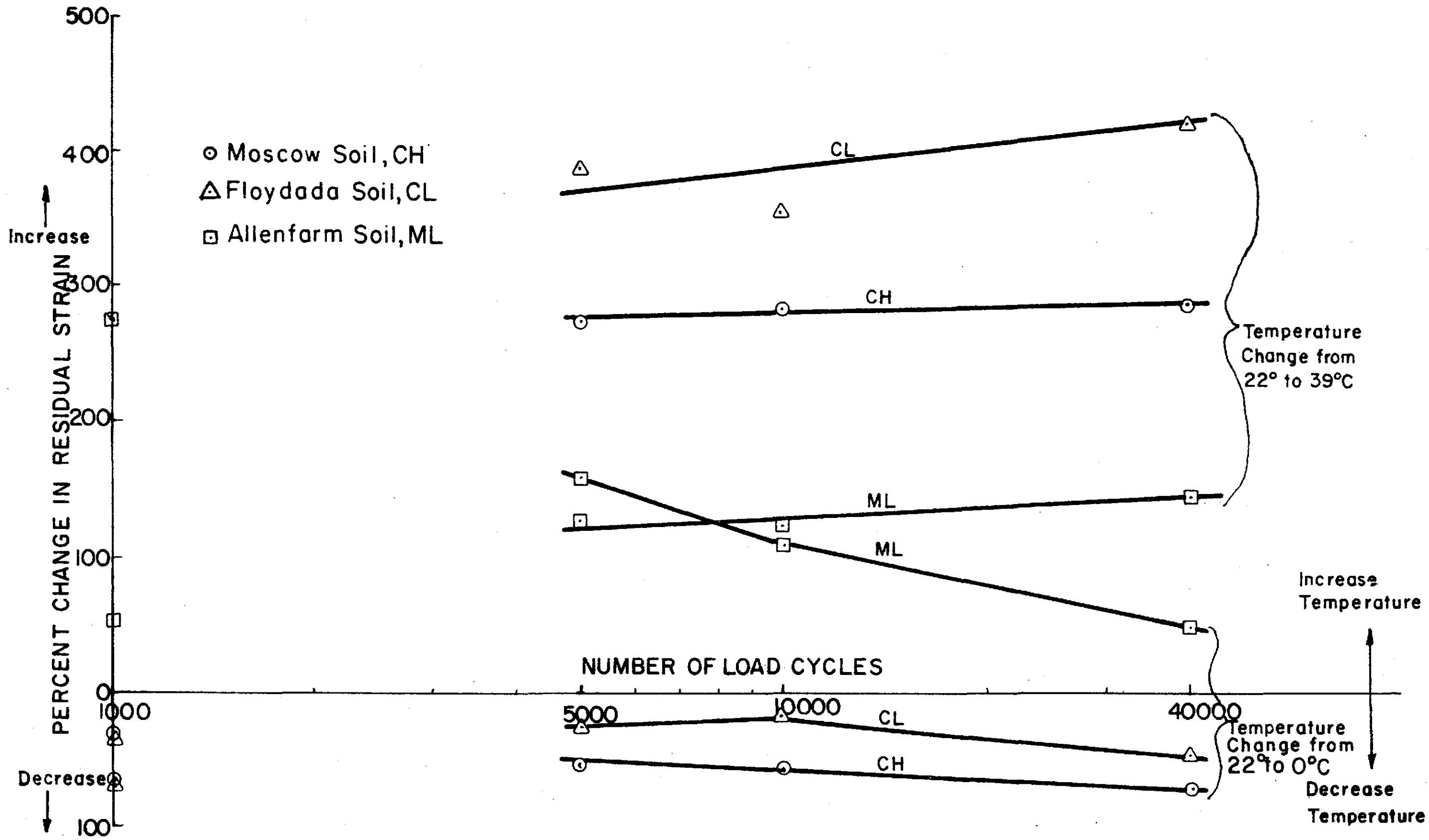


Figure 57. Percent Change in the Residual Strain of the Three Soils Due to Temperature Change as a Function of the Number of Load Cycles

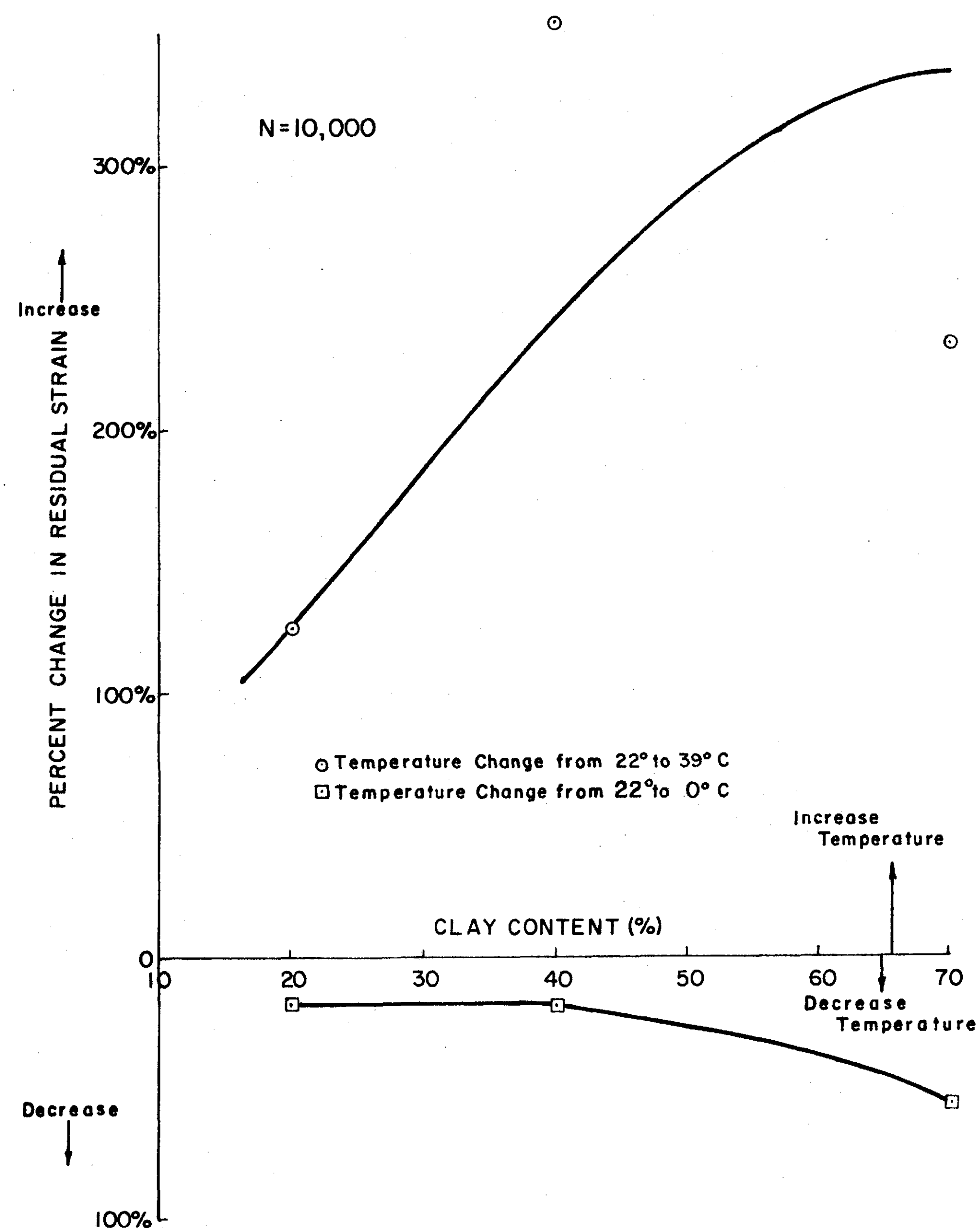


Figure 58. Percent Change in the Residual Strain of the Three Soils Due to Temperature Change as a Function of the Clay Content at 10,000 Load Cycles

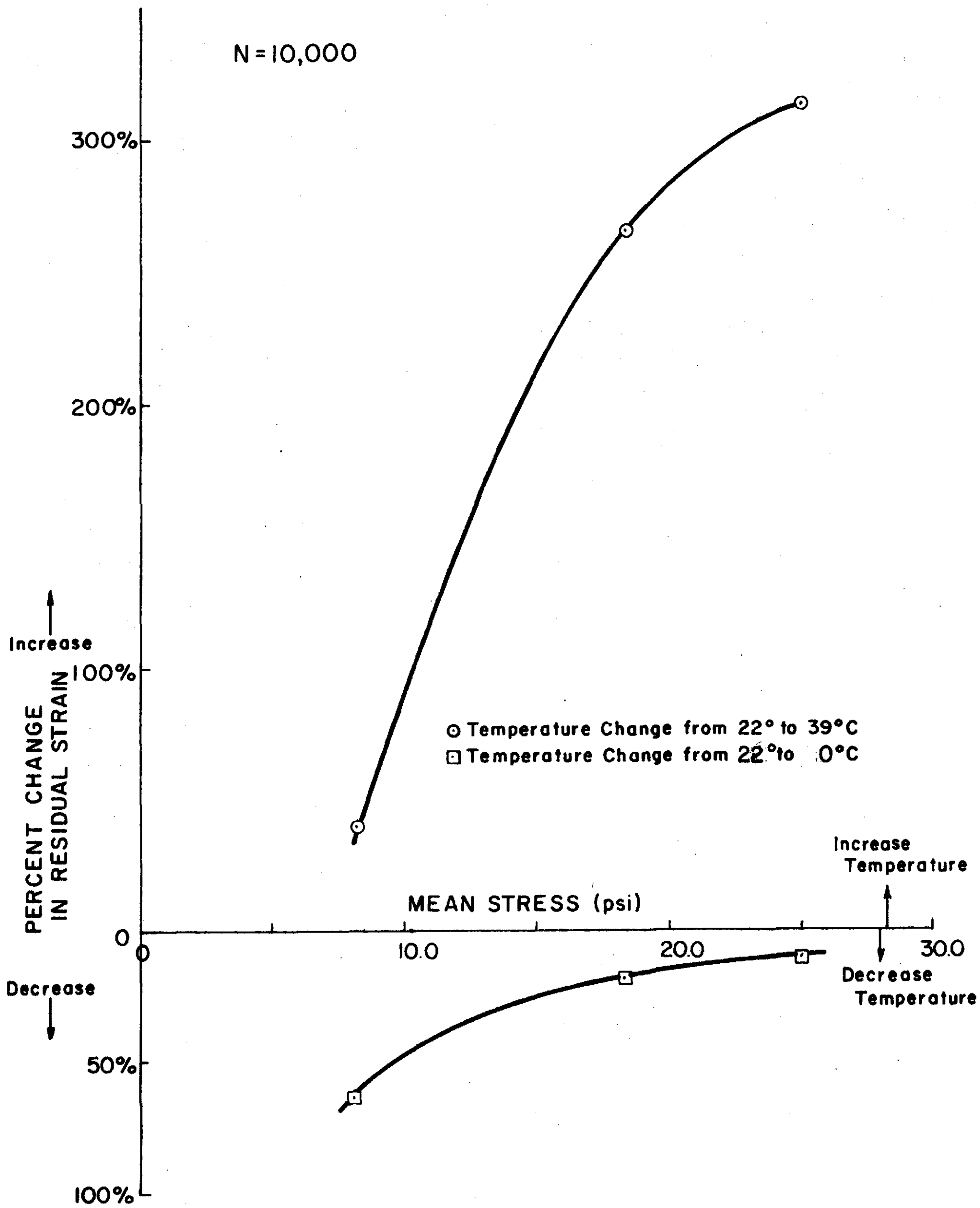


Figure 59. Percent Change in the Residual Strain of the Three Soils Due to Temperature Change as a Function of the Mean Stress at 10,000 Load Cycles

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. The three factors that have the largest influence on the resilient modulus are the number of load cycles, the soil suction, and the deviator stress. To get the best relationship to describe the resilient modulus, most of these terms will have to be combined.

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. The single most important factor in determining the residual strain is the number of load cycles. As with the resilient modulus, the best relationship describing the residual strain will have many terms combined.

The properties that affect the temperature change sensitivity of the resilient modulus and the residual strain have been described. Both dynamic properties are slightly affected by the number of load cycles. But the clay content of the soil affects the change in the resilient modulus, while the change in the residual strain is dependent upon the mean stress. Generally as the temperature increases the resilient modulus decreases and the residual strain increases and conversely for a temperature decrease. The percent change in the dynamic properties is greater as the temperature increases than as it decreases. A method of determining the change in the resilient modulus and residual strain as the temperature changes will be presented in the next chapter.

CHAPTER IV

PREDICTIVE RELATIONSHIP

To develop a relationship that will describe the resilient modulus and the residual strain, it is necessary to determine the important terms. These terms can be divided into three groups of variables, the 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 powers of the terms were determined by taking the anti-log of the results of a log regression using the Select regression program (8). By using the most common terms, groups of terms raised to powers were established. The coefficients of these groups were determined by a linear regression using the same program as before. Using this method to develop the relationships, there is not any pre-set polynomial or power law form and the equation developed has the best correlation with the data.

The soil suction term is divided into three parts, initial suction, test suction, and final suction. The initial suction corresponds to the compacted suction in the lab which corresponds with the field equilibrium suction that can be determined by knowing the Thornthwaite Index and the percent passing the #200 sieve. The test suction is the suction that would develop in the road subgrade as repetitive traffic loads are being applied. In the lab, this suction is greater than the initial suction and generally lower or equal to the final suction. In the field, the test suction is determined by measuring the soil suction under an existing road while it is still in use. The final suction is the suction the soil develops in the lab after repetitive loading has ceased. In the field, this suction is determined by measuring the suction of the subgrade soil under an existing road after traffic loads have been prohibited for a period of time, such as a day. The three soil suction conditions are important in predicting the dynamic behavior of the soil.

Resilient Modulus

The equation determining the resilient modulus (M_R) for each soil is of the same form but the coefficients and powers change:

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

where h_i = initial suction, psi

h_f = final suction, psi

N = number of load cycles

(1-n) = volumetric soil content, decimal form

S = degree of saturation, percent

nS = volumetric moisture content, decimal form

$(\sigma_1-\sigma_3)$ = deviator stress, psi

σ_m = mean stress, psi.

The following table gives the values of the constants. 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 final suction is constant in all the equations at about 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 when the clay content decreases below 40%. The final suction and the number of load cycles have a larger influence on the resilient modulus than does the deviator stress. The coefficients of determination and standard errors of the equation applied to each soil are also given in Table 8.

Figure 60 shows how the resilient modulus of the Moscow Soil (CH) as calculated by Eq. (1) compares with the measured values. Figure 61 shows the same comparison for the Floydada Soil (CL) and Figure 62 shows the comparison for the Allenfarm Soil (ML).

There are several general observations that can be made from the three equations. As the clay content decreases, the power of the volumetric soil content, volumetric moisture content and saturation

Table 8. 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_0	-4791.99	7980.89	-1827.72
a_1	-27272.4	2981.64	171705.
a_2	-45.0169	64.397	0.6566
a_3	-3.733	-4.2008	-4.4849
a_4	1.706×10^{-7}	-2.002×10^{-3}	64.6522
a_5	-5.0763	-3.7228	-1.6108
a_6	-0.1288	-0.1639	-0.001155
a_7	0.05999	-0.1974	-14.8816
a_8	-5.8416	-4.2766	-1.5899
R^2	0.534	0.453	0.766
Standard Error	6522 (psi) 45000 (kN/m^2)	4054 (psi) 27973 (kN/m^2)	1561 (psi) 10771 (kN/m^2)

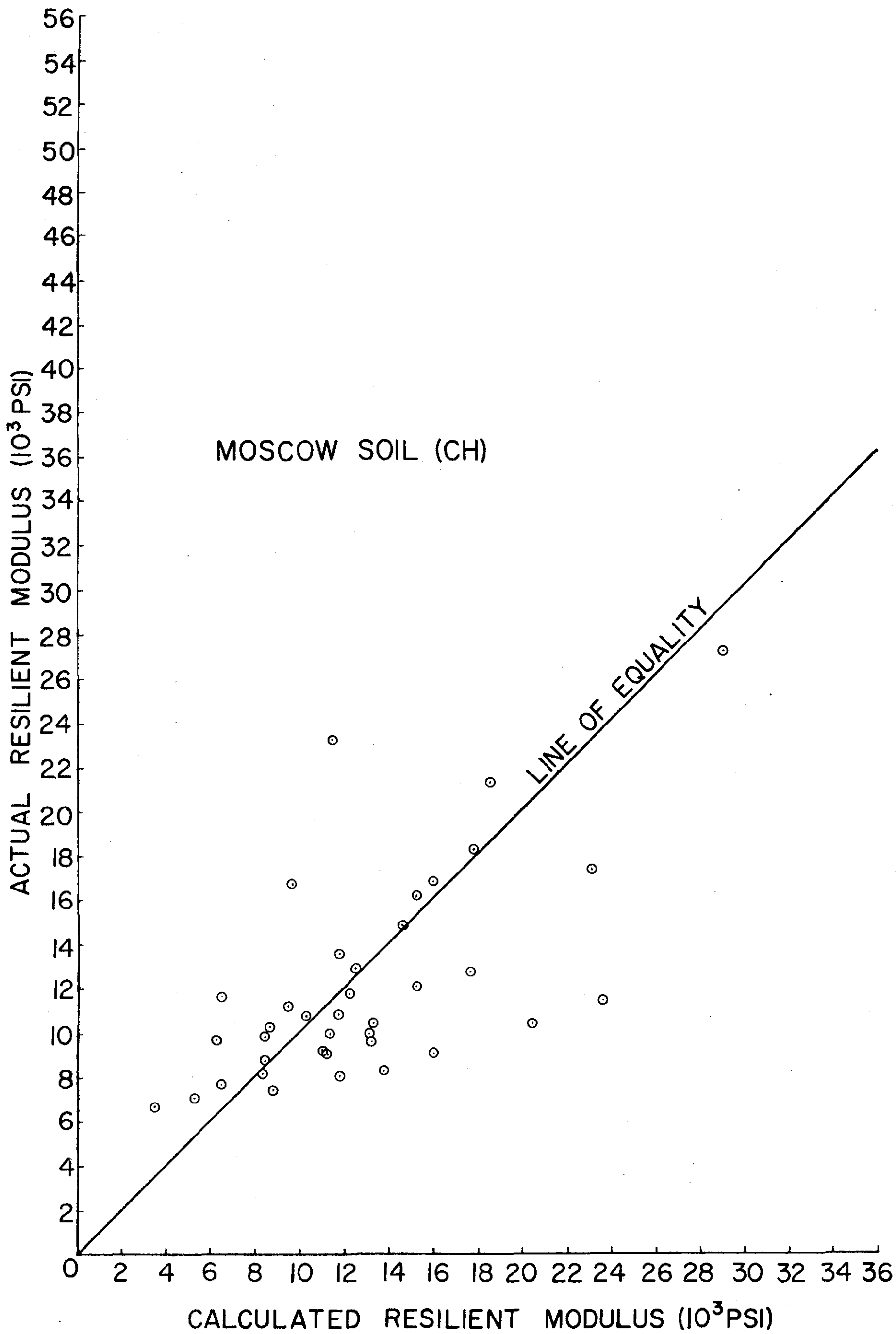


Figure 60. Comparison Between the Actual and the Calculated Resilient Modulus of the Moscow Soil (CH)

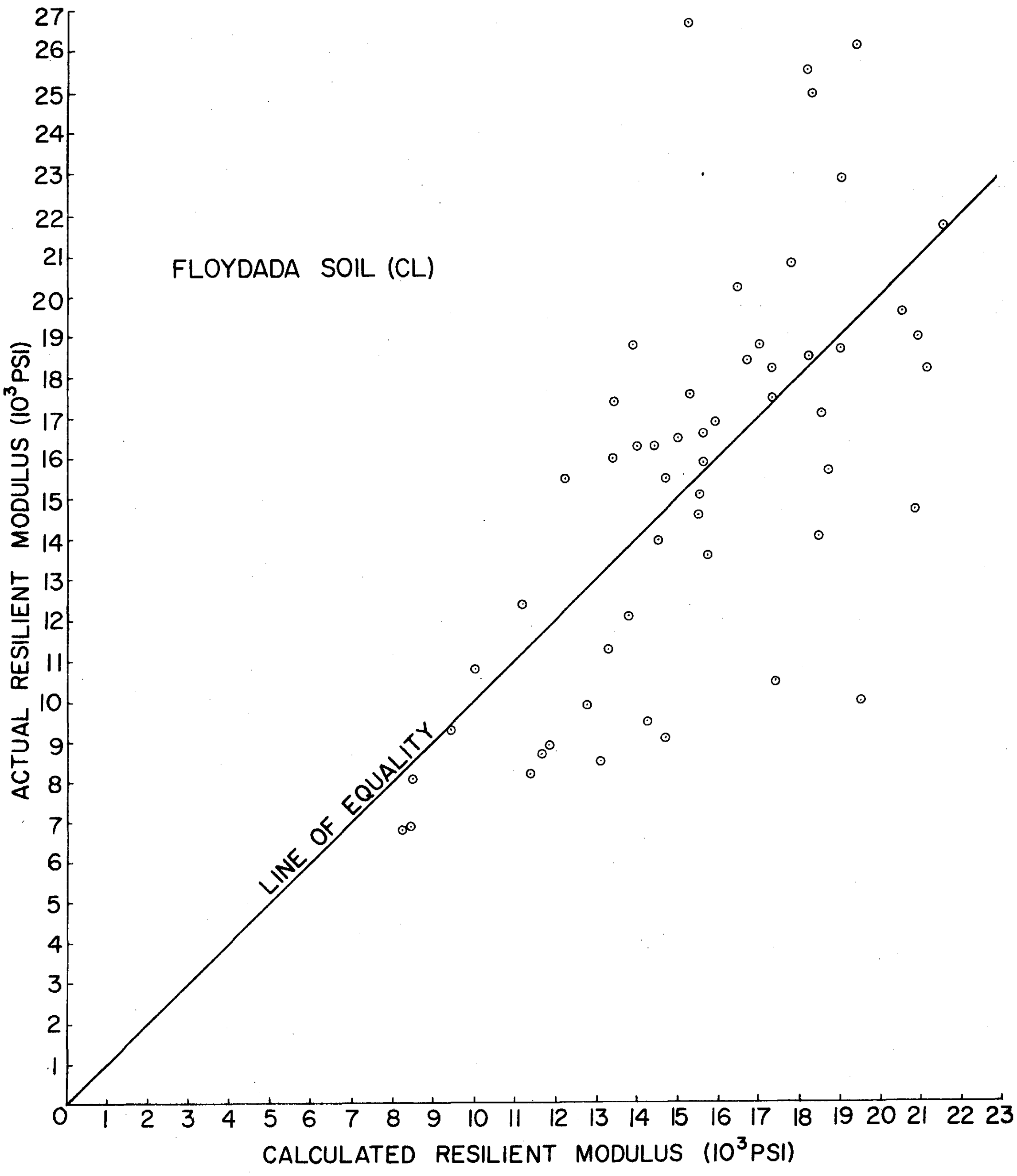


Figure 61. Comparison Between the Actual and the Calculated Resilient Modulus of the Floydada Soil (CL)

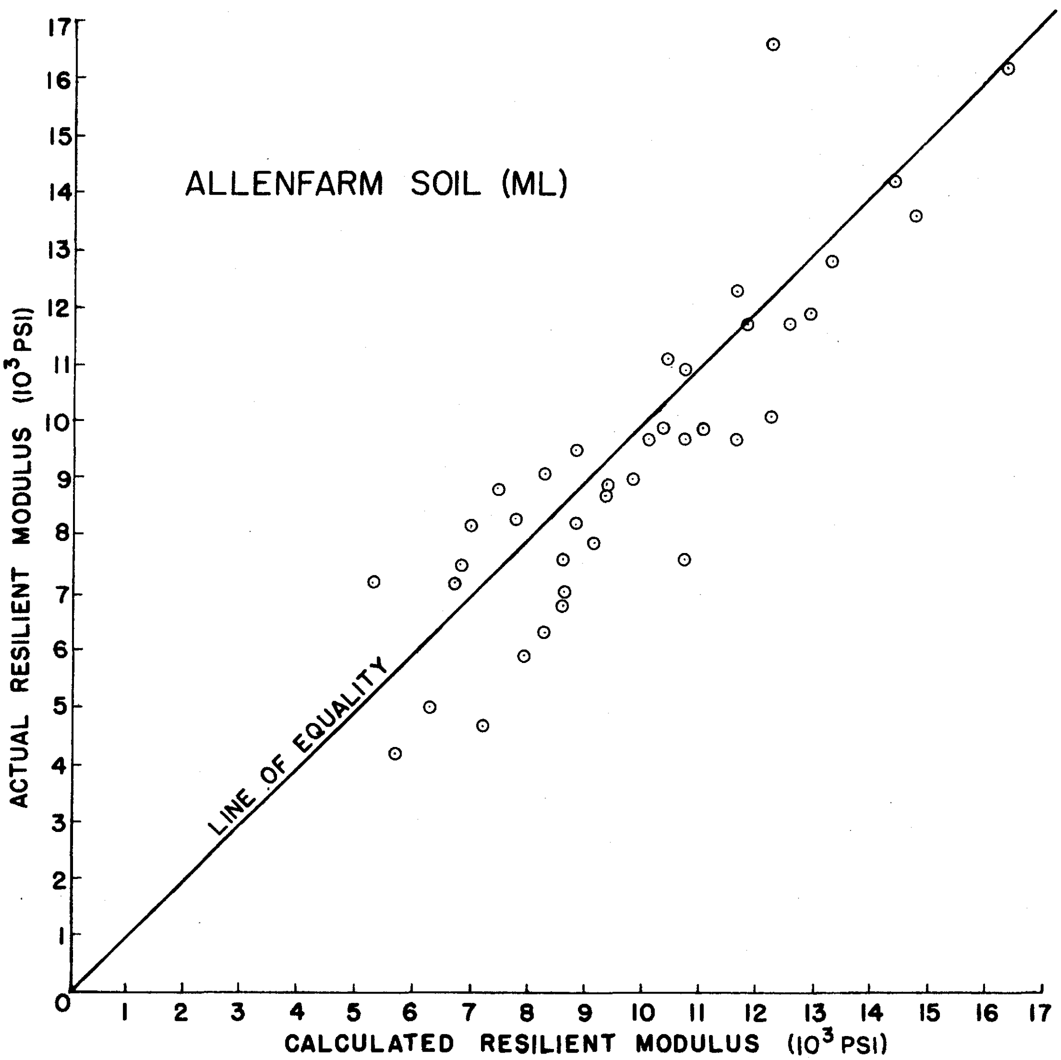


Figure 62. Comparison Between the Actual and the Calculated Resilient Modulus of the Allenfarm Soil (ML)

decrease. However, the decrease is not linear with decreasing clay content. The single most important term in the equations 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 for the residual strain (ε_p) for all soils is:

$$\varepsilon_p(\%) = c_1 \{a_0+a_1 N^b [1+a_2 (\frac{h_t}{h_f})^c \{(\frac{1}{\sigma_3 h_f})^d + a_3(\sigma_1-\sigma_3)^e (\frac{1}{h_f})^f\} + a_4(\frac{1}{\sigma_m h_f})^g + a_5(\sigma_1-\sigma_3)^e (\frac{1}{h_f})^f]\} + c_2 \{-1.2679 [(\frac{1}{h_t})^{0.65} N^{0.395}][1-1.2067\times10^{-15}\{(\frac{S^{5.35}}{nS^{5.10}})(\frac{1}{1-n})^{10.4}\}]+0.04076\} \quad (2)$$

where h_t = test suction, psi

σ_3 = confining stress, psi

$c_1 = 1-c_2$

$$c_2 = \frac{1}{1+e^{46(clay-0.3)}}$$

clay = clay fraction of the soil, decimal form

and all other terms have been defined previously. The values of the constants are given in Table 9.

The coefficients of determination and standard errors of the equation applied to each soil are also given in Table 9.

Figure 63 shows a comparison between the residual strains calculated by Eq. (2) for the Moscow Soil (CH) and those actually measured. Figure 64 gives the same comparison for the Floydada Soil (CH) and Figure 65 shows the comparison for the Allenfarm Soil (ML).

Of the three stress terms, the deviator stress is directly proportional and 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 power of the number of load cycles is highest

Table 9. 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_0	-0.000186	0.01519	0.07915
a_1	-0.000443	-0.000254	0.01995
a_2	-63.0264	-24.62205	-10.44812
a_3	-0.09398	-0.01297	-0.35852
a_4	123.8399	61.1811	15.9875
a_5	-5.9323	-0.52205	-4.7278
R^2	0.830	0.802	0.900
Standard Error	0.042(%)	0.083(%)	0.106(%)

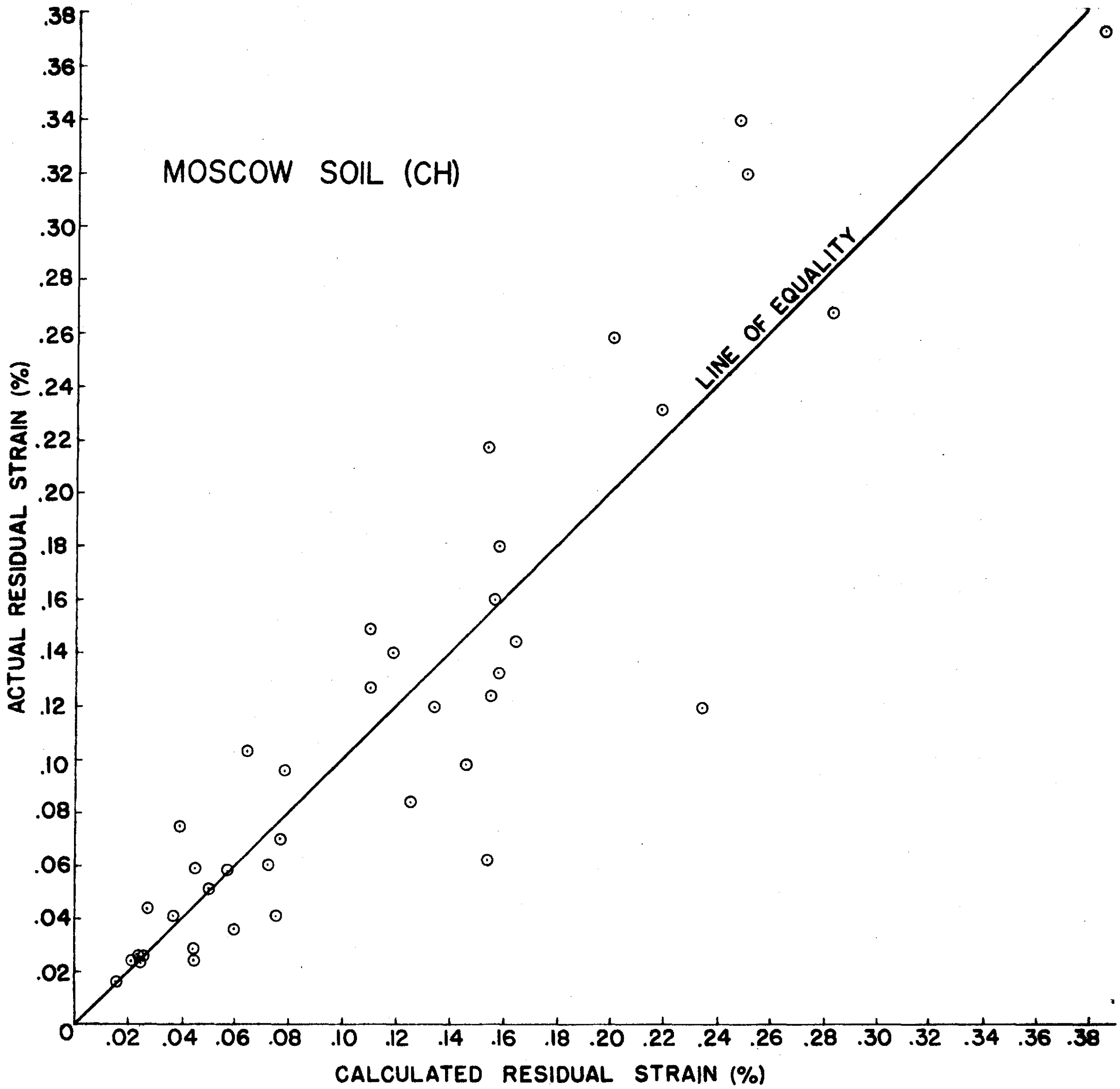


Figure 63. Comparison Between the Actual and the Calculated Residual Strain of the Moscow Soil (CH)

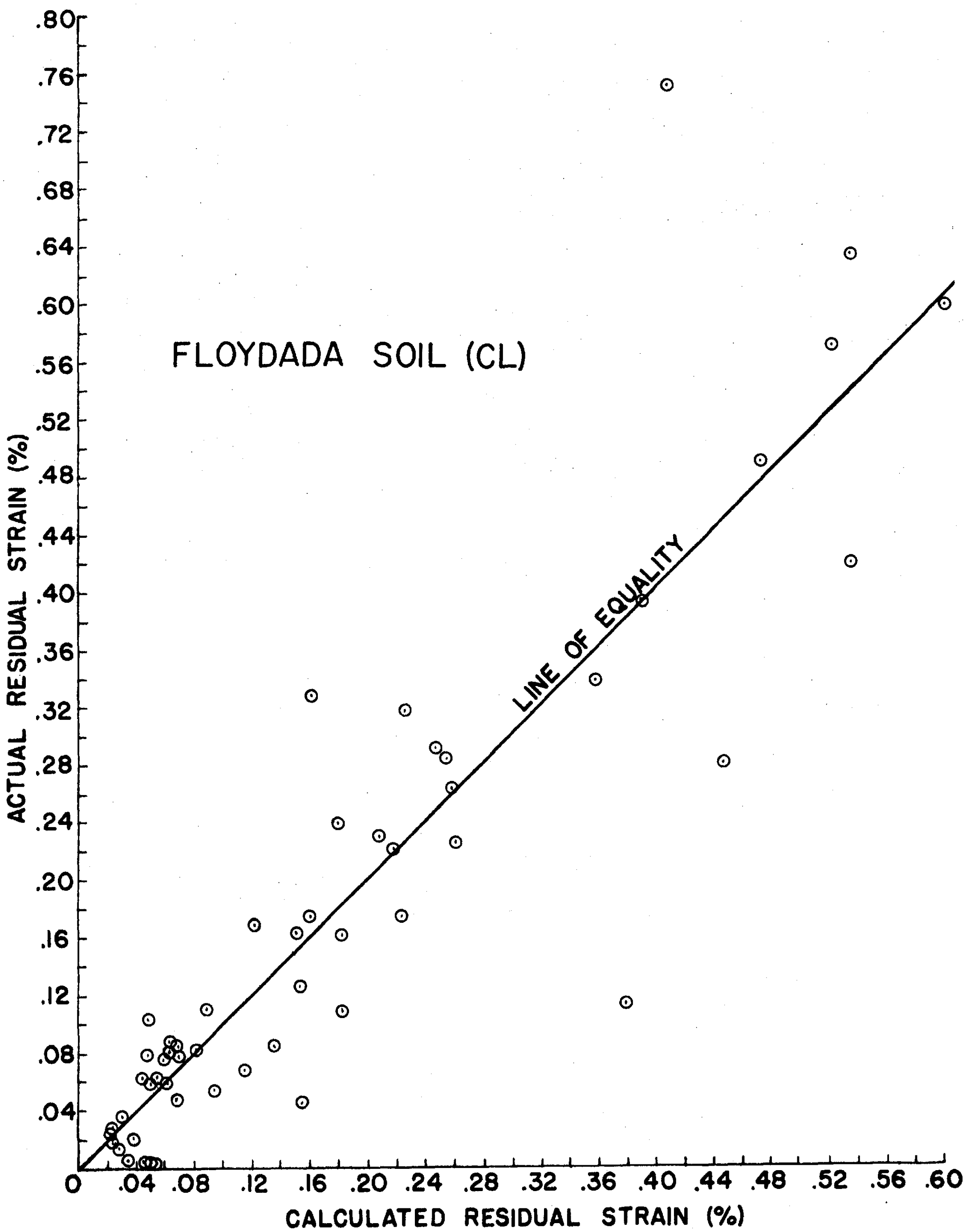


Figure 64. Comparison Between the Actual and the Calculated Residual Strain of the Floydada Soil (CL)

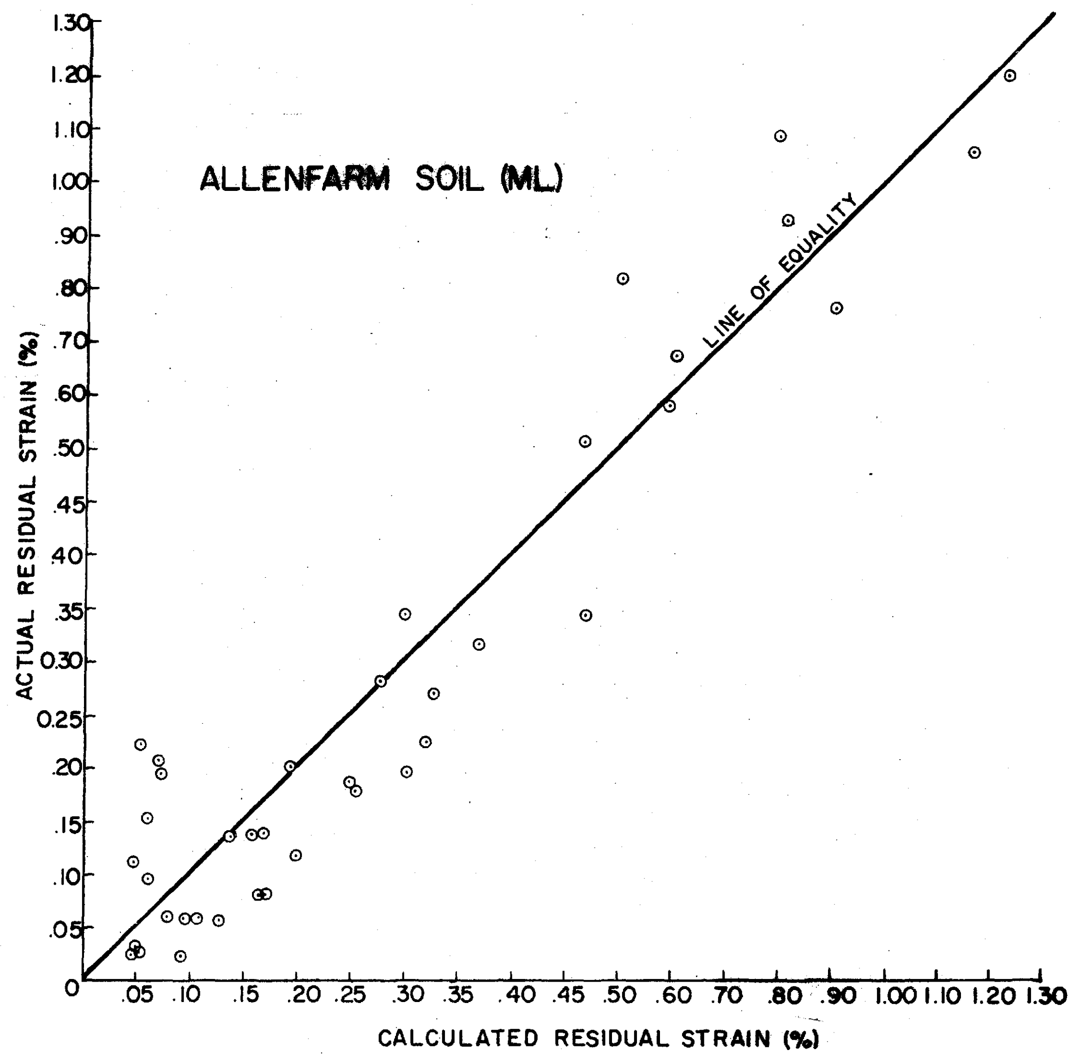


Figure 65. Comparison Between the Actual and the Calculated Residual Strain of the Allenfarm Soil (ML)

for the CL material (0.63) and decreases with either higher or lower clay content.

There are several general observations to be made concerning the residual strain equations. The number of load cycles is the single most important term in the three equations. This is due to the residual strain increasing as the number of cycles increase as has been shown in Figure 44 (p. 70). As the clay content increases, the residual strain is more dependent on the stress conditions and the soil suction rather than the volumetric soil and water properties. The coefficient of determination is higher for the soil with the low clay content, however there is not much difference in the coefficients of the three soils. As the clay content increases the standard error decreases. The coefficients of determination are higher for the residual strain equations than they were for the resilient modulus equations. Thus the residual strain is more predictable than the resilient modulus.

Method of Predicting Resilient Modulus and Residual Strain

With the developed equations, and the clay content it is possible to predict the dynamic properties of any soil with a clay content between 20 and 70 percent, as shown in Figure 66. The procedure is as follows:

1. First calculate the resilient modulus or residual strain for each of the known soils which have clay contents of 0.20, 0.39, and 0.70 for the ML, CL, and CH soils respectively.
2. Secondly, determine the constants in the parabolic interpolation formula

$$y = a + b(\text{clay}) + c(\text{clay})^2 \quad . . . (3)$$

where

y = the dynamic property of interest

a,b,c = the constants to be determined.

The constants are found by solving the following three simultaneous equations written in matrix form:

$$\begin{bmatrix} 1 & 0.20 & 0.04 \\ 1 & 0.39 & 0.1521 \\ 1 & 0.70 & 0.49 \end{bmatrix} \begin{Bmatrix} a \\ b \\ c \end{Bmatrix} = \begin{Bmatrix} M_R(ML) \\ M_R(CL) \\ M_R(CH) \end{Bmatrix} \text{ or } \begin{Bmatrix} \varepsilon_p(ML) \\ \varepsilon_p(CL) \\ \varepsilon_p(CH) \end{Bmatrix} . . (4)$$

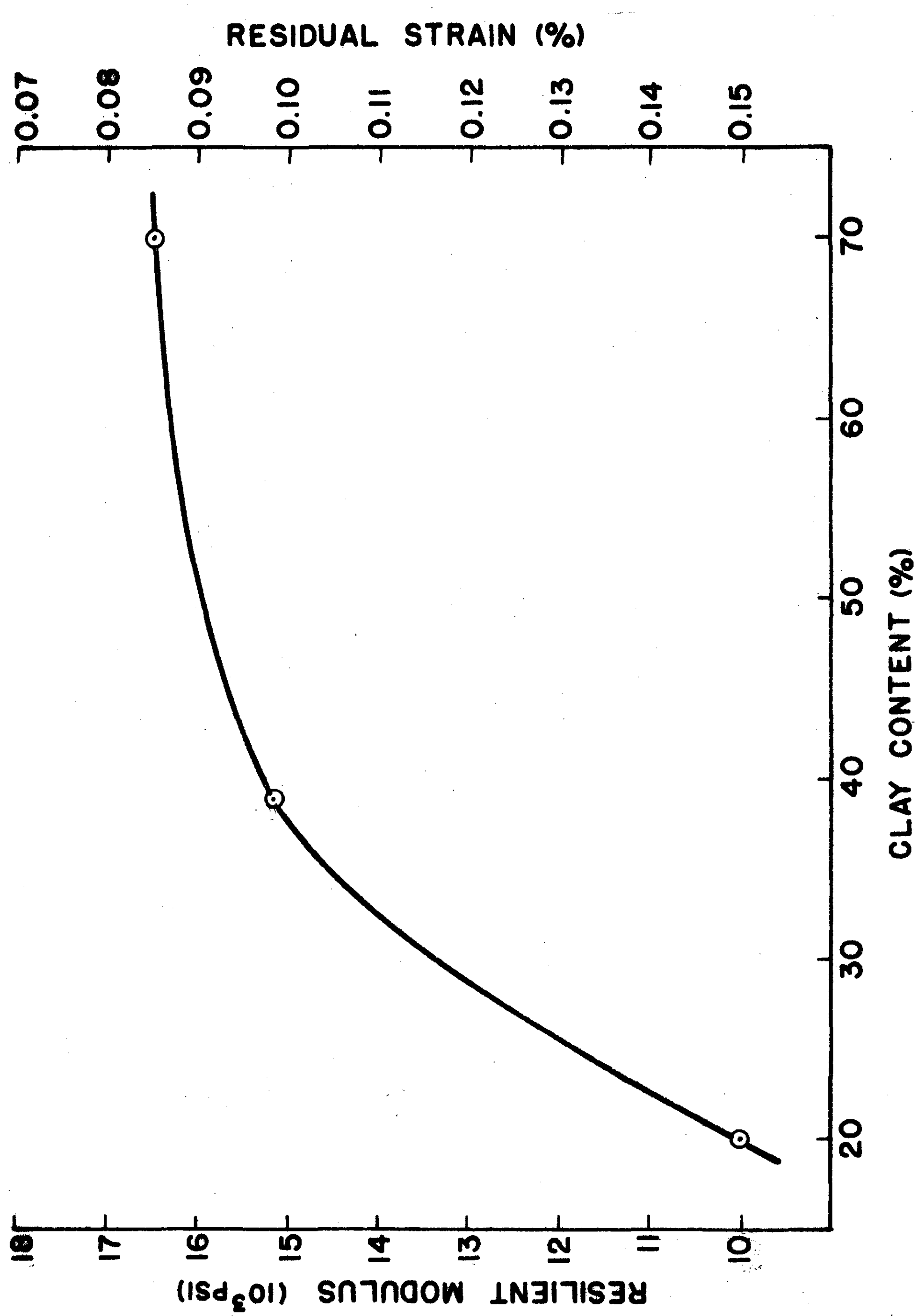


Figure 66. The Parabolic Interpolation Scheme for the Resilient Modulus and the Residual Strain Using the Clay Content

3. Thirdly, use the constants to predict the desired dynamic property using Eq. (3).

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 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 2 (p. 4) knowing the climatic index and the percent passing the #200 sieve. The final suction is found by making field observations. The ratio of final suction to initial suction along with the ratio of test suction to final suction can be estimated from Figures 67 and 68. Figure 67 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%. Figure 68 shows the ratio of test suction to final suction as a function of the number of load cycles. The ratio for the Floydada soil increases more than the other soils, while the ratio for the Moscow soil increases slightly as the number of cycles increases. Thus, by performing laboratory tests and knowing the design criteria, the terms necessary to calculate the dynamic properties may be established.

<u>Predicting the Effect of Temperature</u>

When trying to predict the effect of a temperature change, there are several factors other than the temperature that must be considered. As shown previously the number of cycles influences the soil behavior differently at varied temperature levels. The soil suction will generally change inversely as the temperature changes. The temperature does not effect the stress intensity, but as the temperature increases there is more deformation developed with the same stress as has been shown in the preceding chapter. 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 must be referenced to a single state. The reference state that was

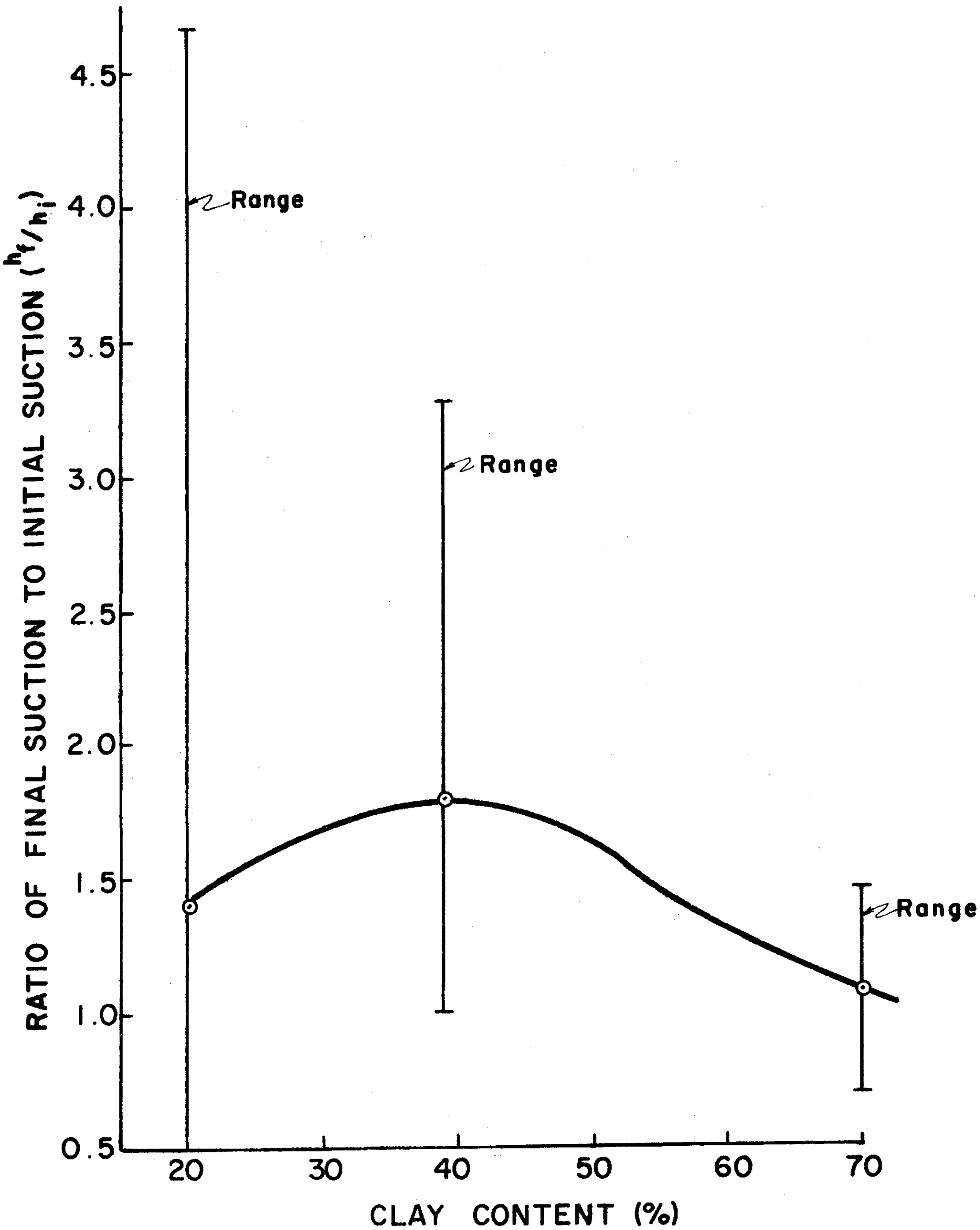


Figure 67. The Ratio of the Final Suction to the Initial Suction as a Function of the Clay Content

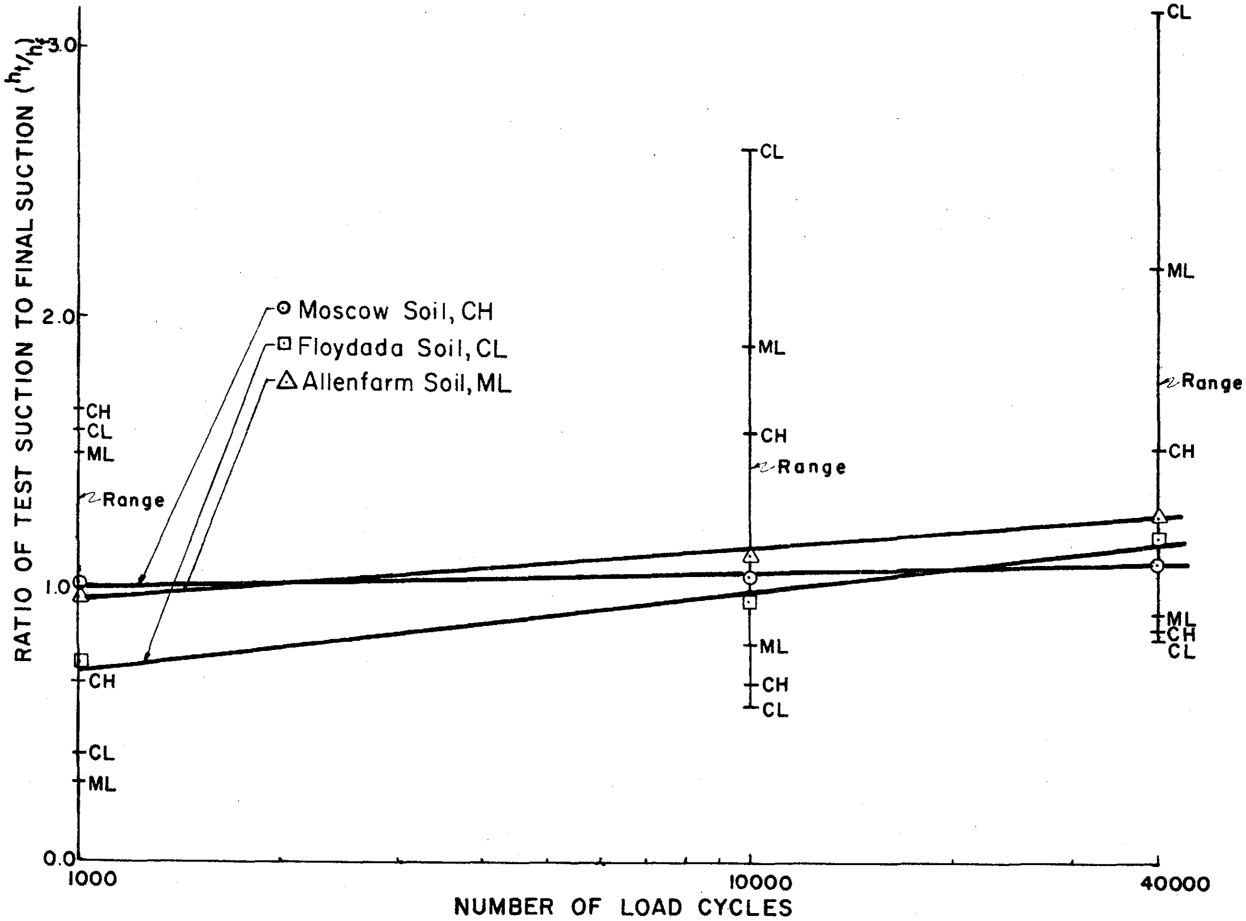


Figure 68. The Ratio of the Test Suction to the Final Suction as a Function of the Number of Load Cycles

chosen consisted of 72°F (22°C) temperature, 13.7 psi (94.5 kN/m^2) 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. The soil suction level was chosen because there seems to be a change in behavior of the soils at this point. Using this reference state, the fractions developed for each soil are listed in Appendix V. Generally the fractions for the resilient modulus and the residual strain were inversely related to the temperature change.

The same procedure was used to develop these equations as was used to develop the previous equations. Without losing very much of the optimum correlation, the same form of the equation was chosen for all three soils. Thus the only differences in the equations are the coefficients and the powers of each variable. Each of the coefficients and powers is in turn, related with a soil property.

<u>Resilient Modulus</u>

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

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

$$[1 - a_6\left(\frac{h}{h_0}\right)^c + a_8\left(\frac{h}{h_0}\right)^c\left(\frac{D}{D_0}\right)^b - a_7\left(\frac{D}{D_0}\right)^b]\} \quad . . . (7)$$

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)

$c = 0.0271 - 0.2873 \log$ (clay)

$d = 0.0697 - 0.9846$ (clay)

$e = 0.0582 - 0.00226$ (1/clay)

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

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

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

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

$a_4 = 0.8088 + 0.3006\ (clay)$

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

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

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

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

clay = clay fraction in decimal form

LL = liquid limit

PL = plastic limit

SL = shrinkage limit

The coefficients of determination along with the standard error of the equations of the three soils are listed in Table 10. Figure 69 shows how the actual correction factors compare with the calculated correction factors.

The powers of the ratios have an excellent relationship with soil properties. All except the deviator stress ratio are related with the clay content of the soil. The coefficients of determination for the power relationships are listed in Table 10. The power of the deviator stress is related to the plastic limit. The values of this power are small positive numbers, except the Floydada soil where the power was a minus six tenths. The positive powers indicate that the ratio and the resilient modulus are directly related. The power of the soil suction ratio is related to the logarithm of the clay content. The values of the powers range from 0.074 for the Moscow soil to 0.230 for the Allenfarm soil. The power of the temperature ratio is directly related to the clay content. The powers are negative values ranging from -0.620 for Moscow to -0.128 for Allenfarm. The negative power indicates that the ratio and the resilient modulus are inversely related. The number of load cycle ratio has a power that is a small positive number. The small variations of the power from soil to soil are inversely related with the clay content. As with the deviator stress ratio, the soil suction and number of load cycle ratio changes are directly related with the resilient modulus changes.

TABLE 10

COEFFICIENTS OF DETERMINATION FOR THE TERMS IN THE RESILIENT MODULUS TEMPERATURE CORRECTION EQUATION, EQUATION (7)

	Term	Coefficient of Determination	Standard Error
Powers	b	0.993	
	c	0.998	
	d	0.999	
	e	0.996	
Coefficients	a_0	1.00	
	a_1	1.00	
	a_2	0.999	
	a_3	0.999	
	a_4	0.993	
	a_5	1.00	
	a_6	1.00	
	a_7	1.00	
	a_8	1.00	
Equations for the Different Soils	Moscow Soil	0.496	0.212
	Floydada Soil	0.751	0.185
	Allenfarm Soil	0.628	0.276

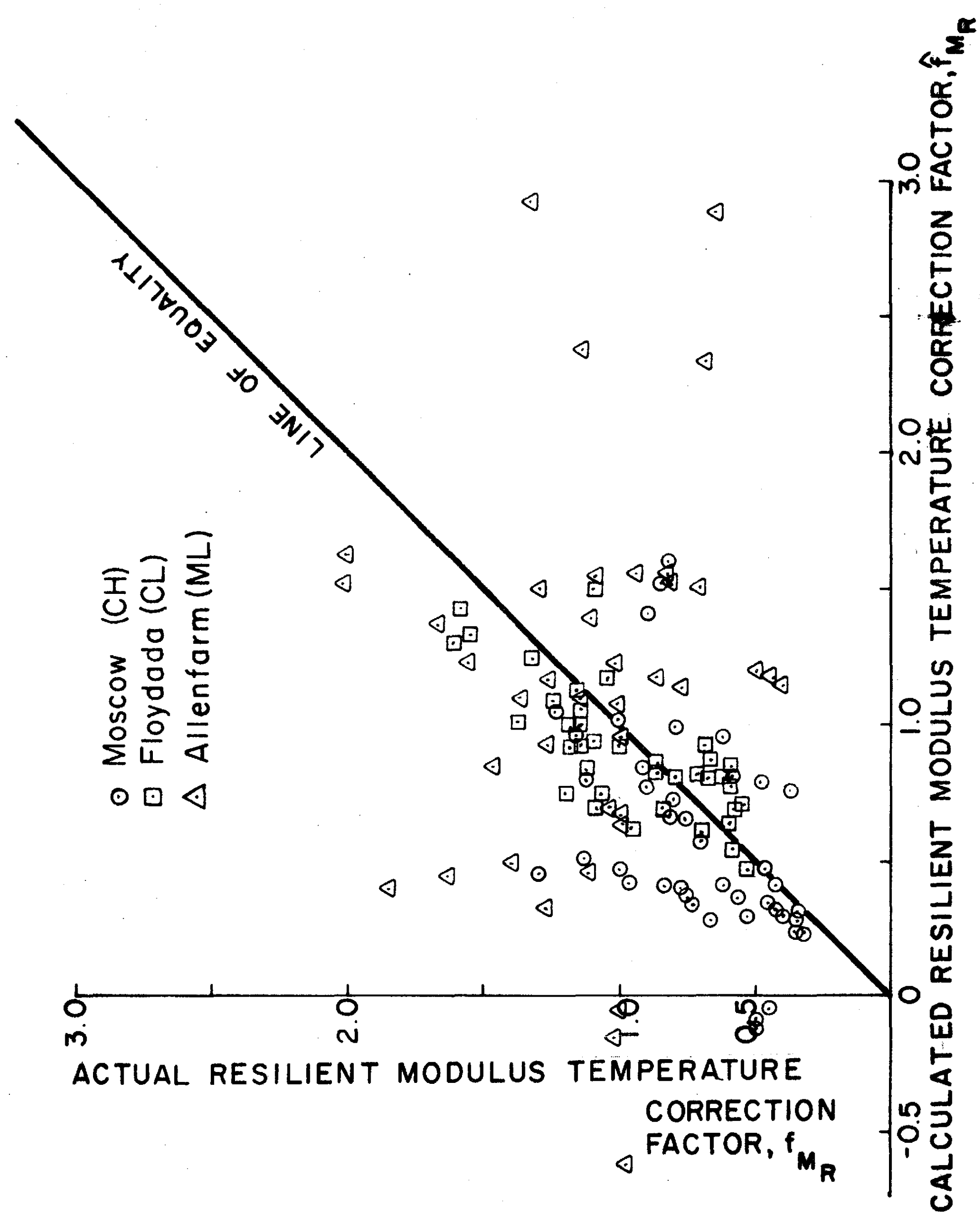


Figure 69. Comparison Between the Actual and the Calculated Temperature Correction Factor for the Resilient Modulus of the Three Soils

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 listed in Table 10. The fourth coefficient is the only one that is related to the clay content. Of the parts of the Atterberg limits, the liquid limit is used with only two coefficients, one of which also contains the plastic limit. The shrinkage limit along with the plastic limit are used in all the other relationships. Adding or multiplying two limits does not make any physical sense, but to develop a relation with a small error, it was necessary to use both of the limits along with the product. The sum of the terms within the brackets is a very small number that greatly influences the result of the equation. As the clay content increases these terms can be factored to $[1-a_6(\frac{h}{h_0})^c][1-a_7(\frac{D}{D_0})^b]$. The first four coefficients of the Floydada soil differ from the coefficients of the other soils. This could be due to the power of the deviator stress ratio. From the coefficient relationships, the resilient modulus temperature correction factor is dependent upon the plasticity of the soil.

Residual Strain

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

$$f_{\varepsilon_p} = a_0+a_1(\frac{h}{h_0})^c+a_2(\frac{T}{T_0})^d(\frac{N}{N_0})^e\{1-a_3(\frac{h}{h_0})^c+a_4(\frac{h}{h_0})^c(\frac{D}{D_0})^b -a_5(\frac{D}{D_0})^b\} \quad . . . (8)$$

where $b = 0.6761 - 0.2384$ (1/clay)

$c = -1.7043 + 1.9130$ (#200 sieve)

$d = 2.3620 - 0.4128$ (1/clay)

$e = 0.3716 + 0.1700$ (clay)

$a_0 = -114.111 + 159.212$ (#200 sieve)

$a_1 = 119.823 - 166.053$ (#200 sieve)

$a_2 = -81.345 - 41.866$ (1/log)

$a_3 = 0.7882 + 1.4700$ (SL)

$a_4 = -0.0663 + 1.5124$ (#200 sieve)

$a_5 = -0.2791 + 1.7426$ (#200 sieve)

#200 sieve = fraction of soil passing the #200 sieve, in decimal form

other terms have been previously defined.

The coefficients of determination along with the standard error of the equation developed for the three soils are listed in Table 11. Also Figure 70 shows how the calculated correction factors compare with the actual correction factor.

The powers of the ratios have a good relationship 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. Two of the soil suction ratio powers were around -0.33 while the Moscow soil had a small positive number. The negative power indicates that the suction ratio and the residual strain are inversely related, which is what would be expected. The power of the temperature ratio is directly related with the clay content of the soil. The values range from 1.697 for the Moscow soil to 0.263 for the Allenfarm soil. This is the largest range of values for any of the powers, thus the temperature ratio is the most important ratio. Besides the temperature ratio, the power of the deviator stress is directly related with the clay content. Two values were positive fractions while the Allenfarm soil had a power of minus one half. The positive values of the powers indicate that the residual strain increases when the deviator stress increases, which is what would be anticipated. The number of load cycle ratio is directly related with the clay content. The value of the power does not vary much and the average is 0.44. All the coefficients of determination of the power relationships are listed in Table 11. The temperature, deviator stress and number of load cycle ratios are directly related with the residual strain while the soil suction ratio is inversely related.

As with the powers, the coefficients are generally related to part of the soils grain size distribution. The third coefficient is the only one that is related to part of the Atterberg limits, the shrinkage limit. The second coefficient is related to the inverse of the logarithm of the clay content. This coefficient has the largest range of all the coefficients, ranging from 190 for Moscow

TABLE 11

COEFFICIENTS OF DETERMINATION FOR THE TERMS IN THE RESIDUAL STRAIN TEMPERATURE CORRECTION EQUATION, EQUATION (8)

	Term	Coefficient of Determination	Standard Error
Powers	b	0.994	
	c	0.989	
	d	0.983	
	e	0.993	
Coefficients	a_0	0.999	
	a_1	0.998	
	a_2	0.999	
	a_3	0.995	
	a_4	0.956	
	a_5	0.973	
Equations for the Different Soils	Moscow Soil	0.888	0.878
	Floydada Soil	0.718	0.449
	Allenfarm Soil	0.432	1.205

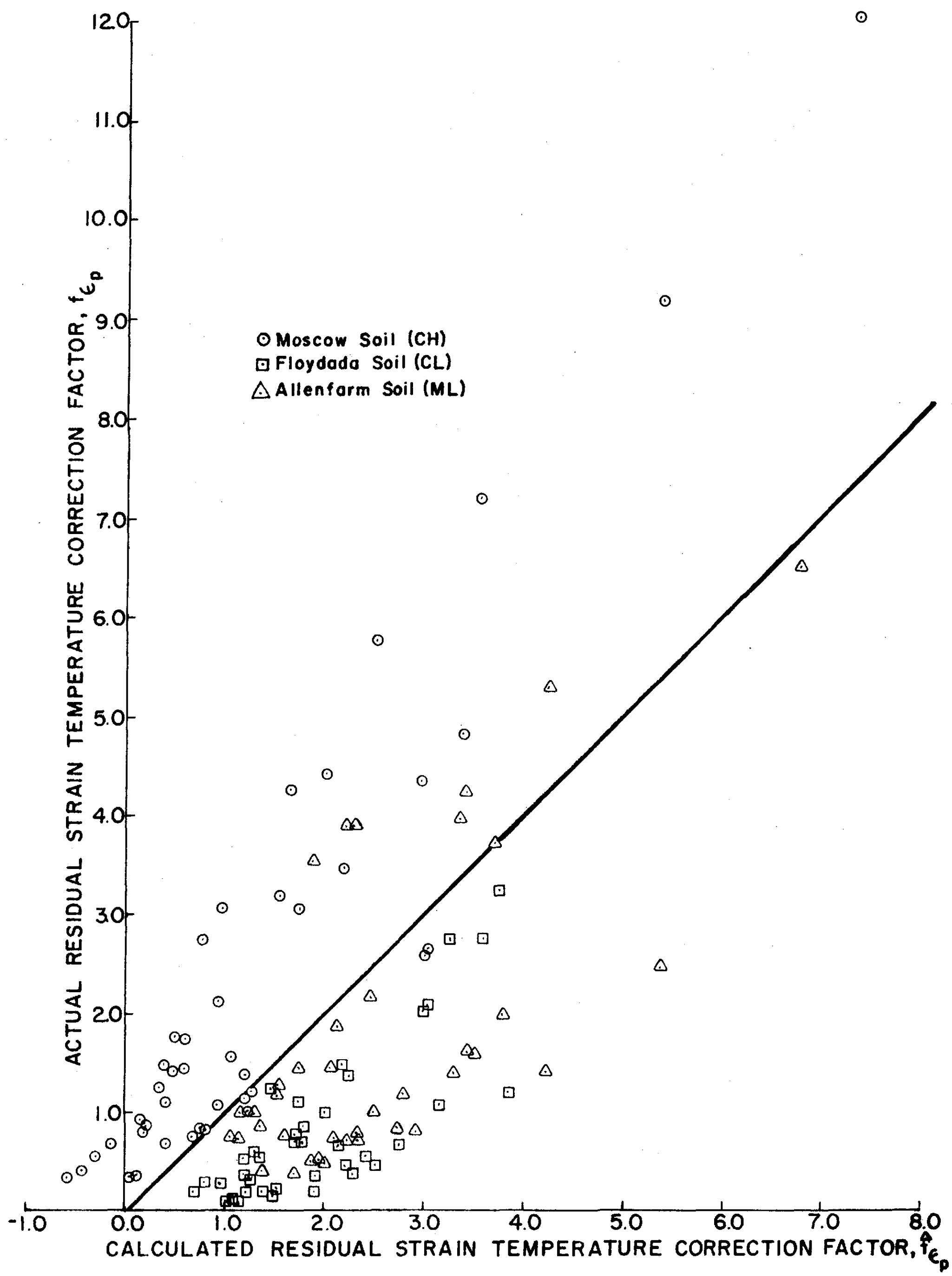


Figure 70. Comparison Between the Actual and the Calculated Temperature Correction Factor for the Residual Strain of the Three Soils

to -18 for Allenfarm. The remainder of the coefficients are directly related with the portion passing the #200 sieve. The coefficients of determination for the coefficient relationships are listed in Table 11. The coefficient relationship for the residual strain temperature correction factor are very dependent upon the particle distribution of the soil.

The equations to determine the change in the resilient modulus and the residual strain caused by temperature variations have been presented. The results of these equations 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.

CHAPTER V

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:

$h = 21.4807 + 181.1435\ (\text{clay})$ and $pF = 3.0693 + 1.1803\ (\text{clay})$

where: clay = clay fraction of soil in decimal form

h = soil suction in psi

pF = soil suction expressed as the log (cm. of water).

By knowing the soil suction in pF at the point where the soil behavior changes, the Thornthwaite Moisture Index can be determined for each soil using Figure 2 (p. 4). Figures 71, 72, and 73 are the same as Figure 1 except that the Thornthwaite Index that corresponds to the change in behavior of each soil has been added. Generally, anywhere the index is larger 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 resilient modulus can be predicted using the soil suction degree of saturation, volumetric moisture and soil contents, stress intensity, and the number of load cycles. As the clay content increases, the importance of the soil suction increases along with the power of the soil suction.

3) The residual strain can be predicted using the soil suction, degree of saturation, volumetric moisture and soil contents, stress intensity, and the number of load cycles. As the clay content increases, the soil suction and stress intensity terms gain importance.

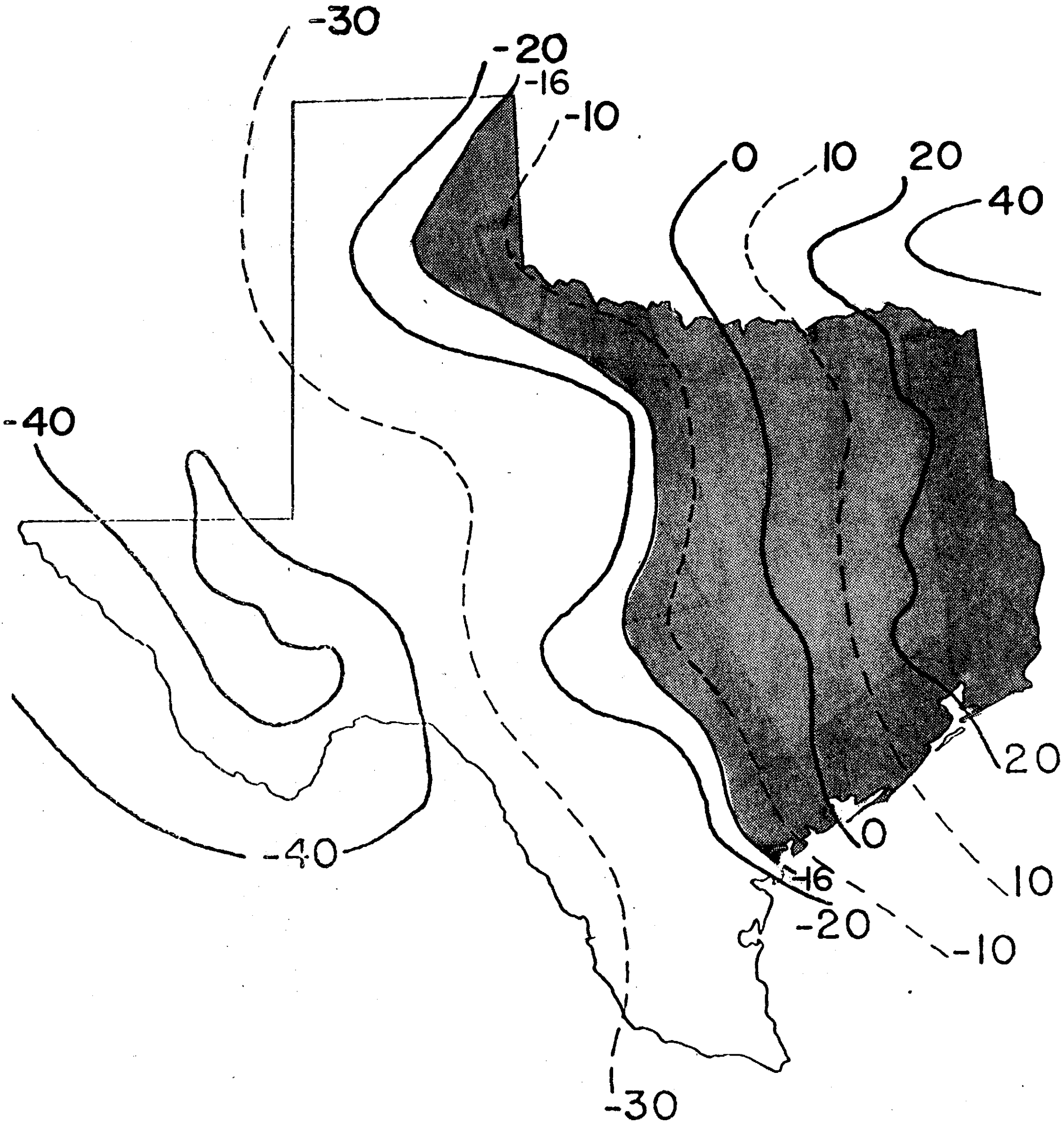


Figure 71. Thornthwaite Moisture Index in Texas Including the Index Where CH Soils Change Behavior. The Shaded Area Corresponds to the Possible Need of Stabilizing CH Soils

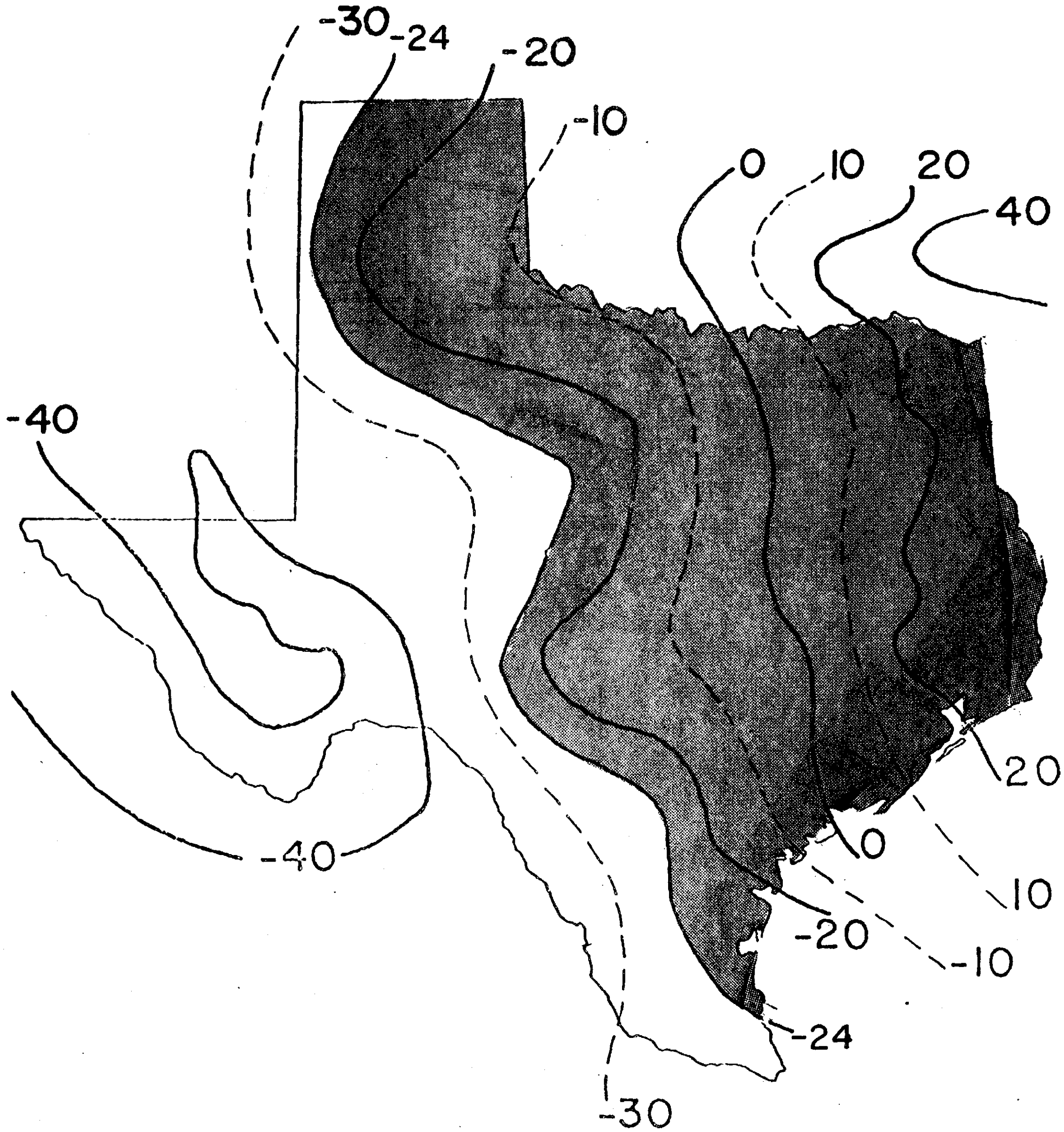


Figure 72. Thornthwaite Moisture Index in Texas Including the Index Where CL Soils Change Behavior. The Shaded Area Corresponds to the Possible Need of Stabilizing CL Soils

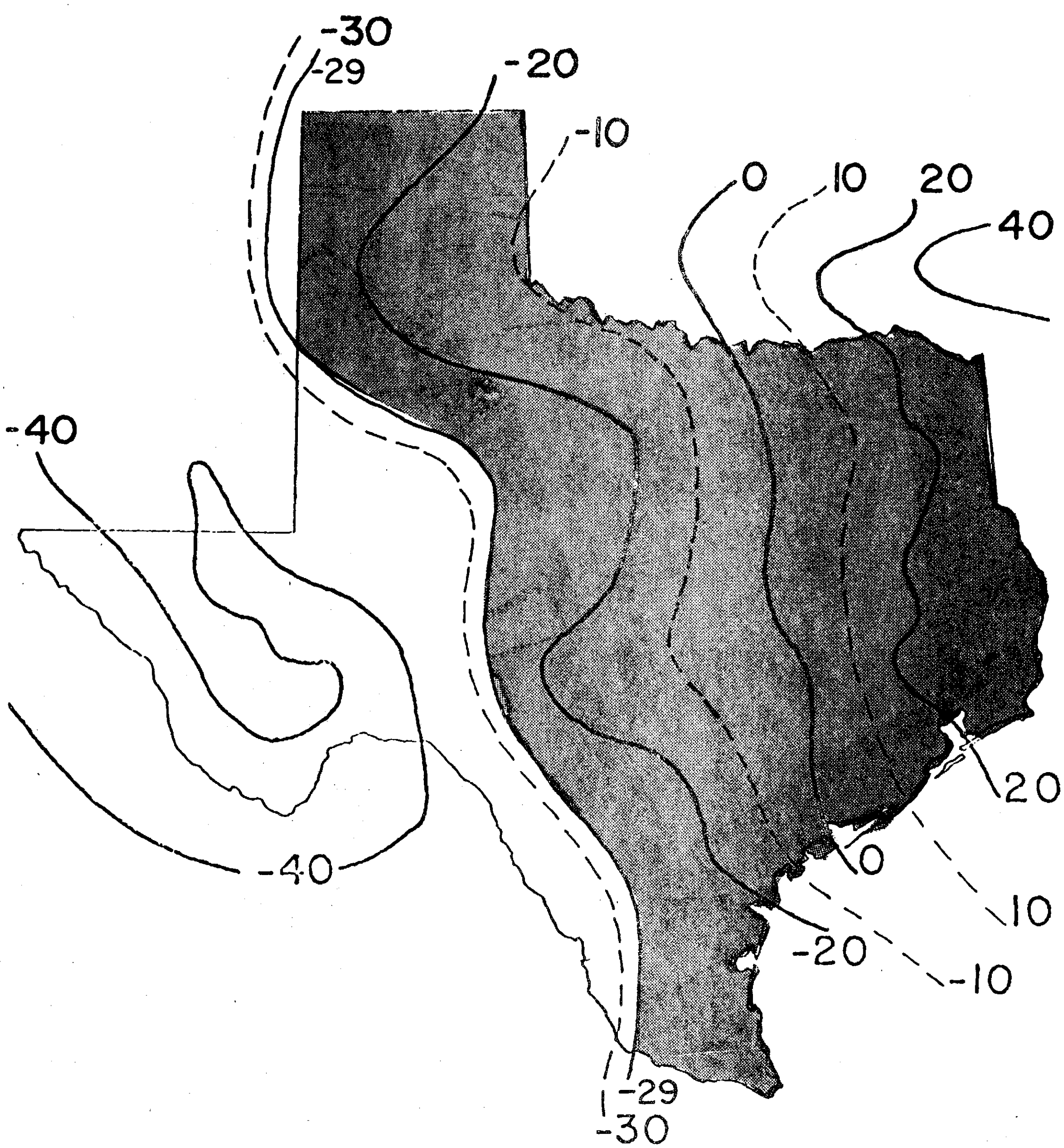


Figure 73. Thornthwaite Moisture Index in Texas Including the Index Where ML Soils Change Behavior. The Shaded Area Corresponds to the Possible Need of Stabilizing ML Soils

The power of the soil suction and the stress terms decrease as the clay content decreases.

4) The temperature correction factor for the resilient modulus is developed. The powers of the factor in this equation are generally related to the clay content while the coefficients are generally related to the plastic limit of the soil.

5) The temperature correction factor for the residual strain is developed. The powers and coefficients are generally related to either the clay content or to the percent passing the #200 sieve.

6) 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 0.40 and 0.63.

7) The coefficients of determination for all but one equation are above 0.50. This is better than any other published results to date.

Using the methods presented in this paper it is possible to calculate the resilient modulus and the residual strain. Instead of needing a large, expensive repetitive loading apparatus, the soil properties necessary to use the developed equations can be performed using standard laboratory tests (Atterberg limits and grain size distribution). Thus many more engineers are able to use the resilient modulus and residual strain in designing highway pavements, railroad grade crossings, and bridge approaches.

Recommendations - The following recommendations concerning further work in this area are:

1) Additional repetitive load tests are needed on different soil types to ascertain the validity of the interpolated values presented.

2) The effect on the dynamic properties of different compactive efforts needs to be investigated.

3) Determine if the properties of the clay mineralogy of the soil could be related to some of the powers or coefficients in place of the clay content.

4) Use the electron microscope to determine how much particle reorientation occurs during loading.

5) Determine if the resilient modulus and the residual strain are affected by freeze-thaw action.

APPENDIX I - REFERENCES

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APPENDIX II - NOTATIONS

The following symbols are used in this paper:

a_0-a_8 = coefficients of equation (7) and (8)
a, b, K_m, K_p, w, x, y = constants
b,c,d,e = powers of ratios in equation (7) and (8)
d = yearly deficit of water
$(\frac{D}{D_0})$ = ratio of deviator stress in equation (7) and (8)
E_p = yearly potential evapo-transpiration
g = gravitational force
h = total suction
h_i = initial suction
h_f = final suction
h_t = test suction
$(\frac{h}{h_0})$ = ratio of initial suctions in equation (7) and (8)
I = Thornthwaite Moisture Index
LL = liquid limit
m = molecular weight of water
M_R = resilient modulus
n = porosity
nS = volumetric moisture content
N = number of load cycles
$(\frac{N}{N_0})$ = ratio of number of load cycles in equation (7) and (8)
P = vapor pressure of soil water
P_0 = vapor pressure of free water
pF = soil suction expressed as the log (cm. of water)
PI = plasticity index
PL = plastic limit
R = gas constant
r^2 = coefficient of determination
S = degree of saturation
S_0 = yearly surplus of water
SL = shrinkage limit

T = temperature

$(\frac{T}{T_0})$ = ratio of temperature in equation (7) and (8)

w = gravitational moisture content

$(1-n)$ = volumetric soil content

ε_p = residual strain

ε_R = resilient strain

γ_D = dry unit weight

σ_{oct} = octahedral normal stress

σ_m = mean stress = $\frac{\sigma_1+2\sigma_3}{3}$

σ_1 = largest principal stress

σ_3 = smallest principal stress

$(\sigma_1-\sigma_3)$ = deviator stress

τ_{oct} = octahedral shear stress

APPENDIX III - SOIL SUCTION MEASURING DEVICE AND TECHNIQUE

Of the various instruments to measure the soil suction, the thermocouple psychrometer is chosen. Carpenter (22) shows a cross section view of a psychrometer in Figure A-3-1. This device consists of two small diameter dissimilar metal wires welded together. The wires are copper and constantan. This tip acts like a thermocouple in that an electro-motive force (emf) is developed when there is a temperature change. This force is in the microvolt range. Thus by measuring this force, the temperature of the junction can be determined. Since the wire leads are small, fragile, and easily contaminated, they are protected by a ceramic tip which allows moisture only in the vapor state to pass them.

As mentioned in the text, the soil suction is related to the relative humidity of the soil. So by using the thermocouple psychrometer to measure the humidity of the soil, the soil suction can be determined. Originally the thermocouple psychrometer was used like a sling psychrometer. The initial emf is the dry bulb reading. Passing a cooling current thru the tip causes condensation of moisture on the tip. Stopping the cooling current will cause the tip to equilibrate at the dew point temperature, which is the wet bulb reading. Thus the relative humidity and in turn the soil suction is determined.

Recently a new measuring method called the dew point method has been developed. This is the technique used in this program to measure the soil suction. One of the differences in the method is that the dew point temperature is maintained at the tip by a cooling current. The procedure is as follows:

1) A cooling coefficient, which is determined when the psychrometer is constructed because it is a function of the tip geometry, is set in the measuring instrument.

2) The microvoltmeter is zeroed and a cooling current is passed through the tip to condense a bead of water.

3) The instrument is set to dew point. This maintains the cooling current such that heat is removed from the tip and the surroundings

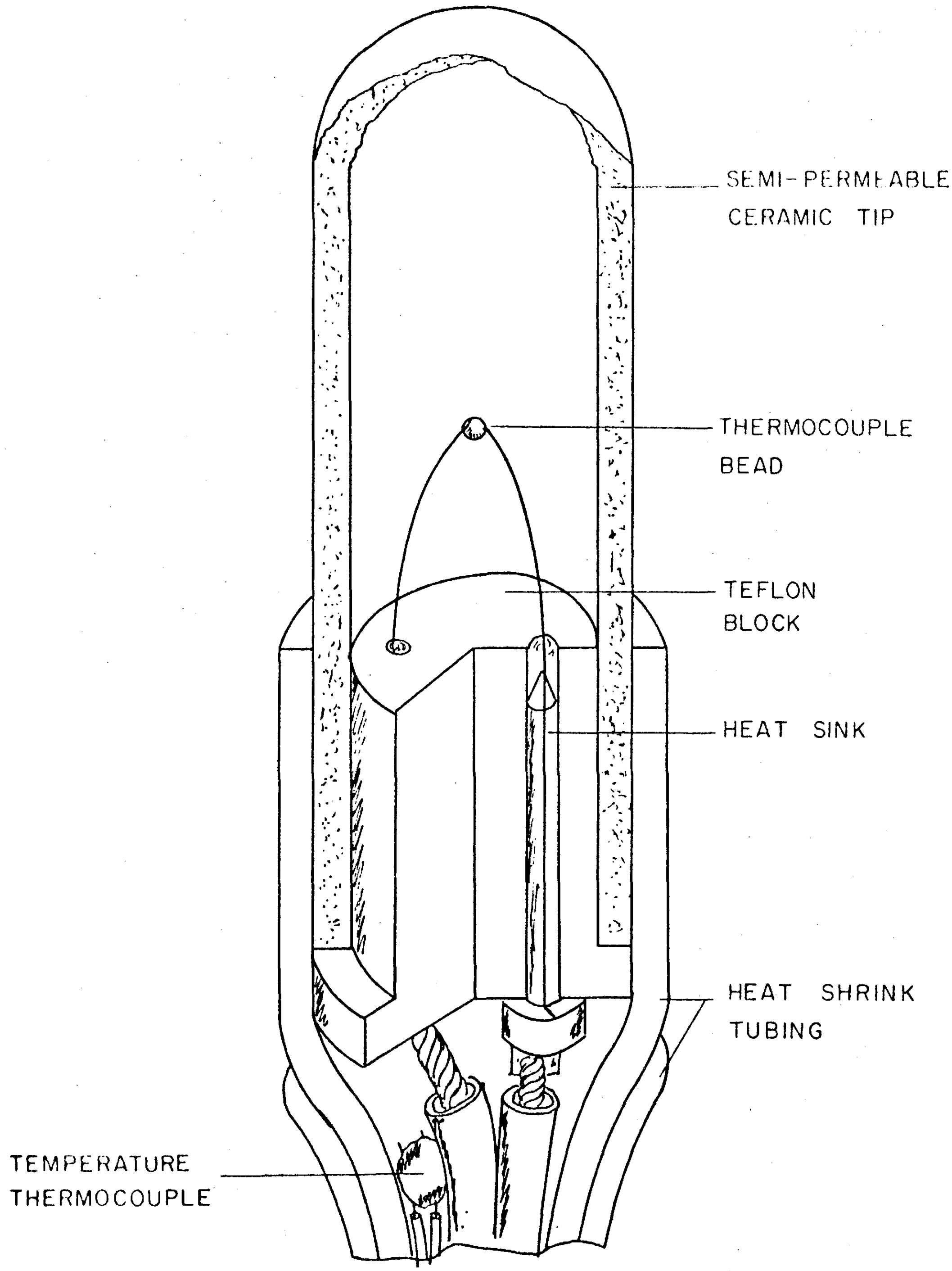

Figure A-3-1. Cross-Section View of a Thermocouple Psychrometer at the same rate. This process continues until the tip temperature reaches the dew point, where evaporation stops and the tip temperature remains constant.

The current necessary for the tip to stay at the dew point temperature is proportional to the relative humidity. This method is superior to the psychrometric technique in that the results are more reliable and there is a larger range of linear operation.

Temperature changes effect both methods of soil suction measurement. To make the correction for the psychrometric technique requires several calculations after the reading is made. Whereas the dew point method can correct for temperature differences electronically by changing the cooling coefficient. Thus, the dew point method is easier to use than the psychrometric method.

As has been mentioned several times, the relative humidity is related to the soil suction. This is done by using potassium chloride salt solutions, where the humidity and soil suction can be calculated. Table 3-1 lists the soil suction for different salt concentrations. Thus by calibrating the psychrometers in salt solutions of known concentrations, a calibration curve such as the one in Figure A-3-2 is developed. The psychrometers are individually calibrated, thus the accuracy is ±5 percent of the reading.

Soil suction, which is defined as a negative quantity, is discussed as a positive magnitude in this paper for ease of discussion.

Table 3-1

Soil Suction of KCl Solutions at 25^{o}C (39)

KCl	Soil Suction	
Molarity	Bars	Psi
0.05	-2.29	-33.2
0.1	-4.59	-66.6
0.2	-9.03	-131.0
0.3	-13.48	-195.5
0.4	-17.88	-259.3
0.5	-22.28	-323.1
0.7	-31.13	-451.4
1.0	-44.49	-645.2
1.2	-53.45	-775.1

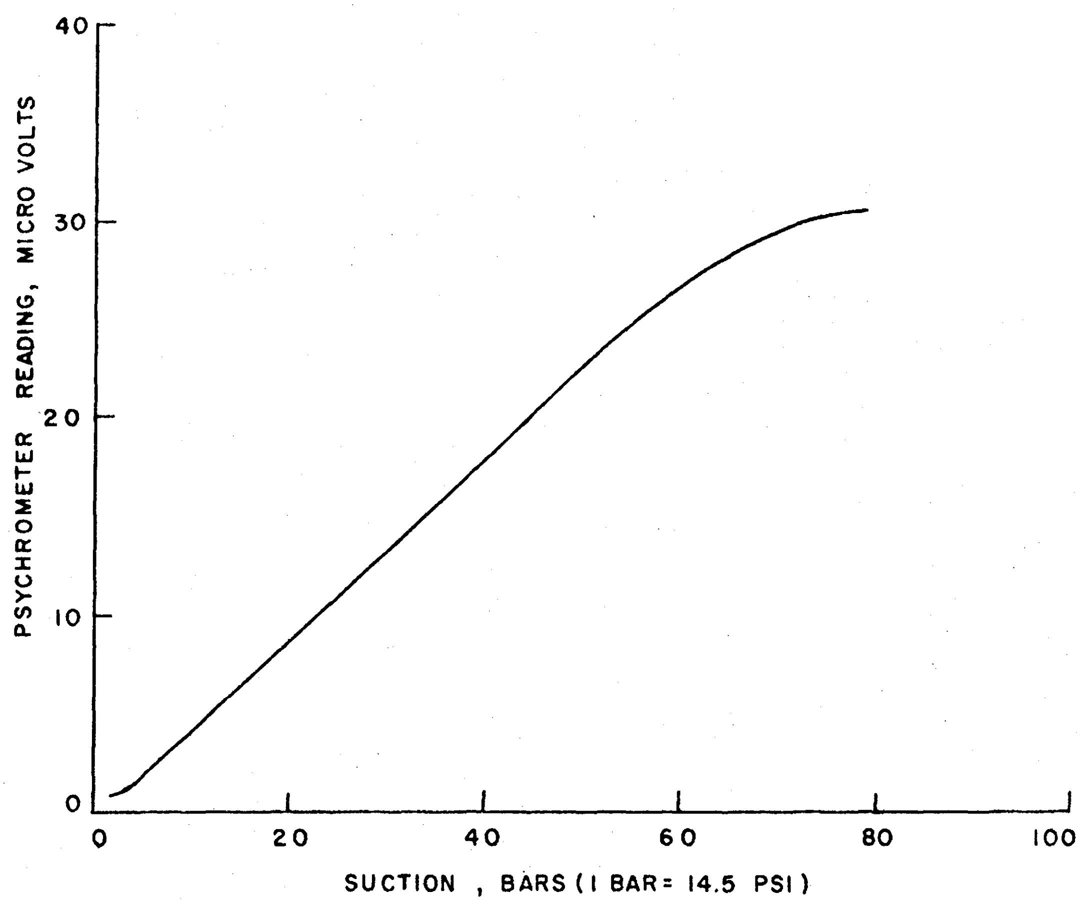

Figure A-3-2. Thermocouple Psychrometer Calibration Curve

APPENDIX IV

GRAPHS OF RESILIENT MODULUS AND RESIDUAL STRAIN VS. NUMBER OF LOAD CYCLES

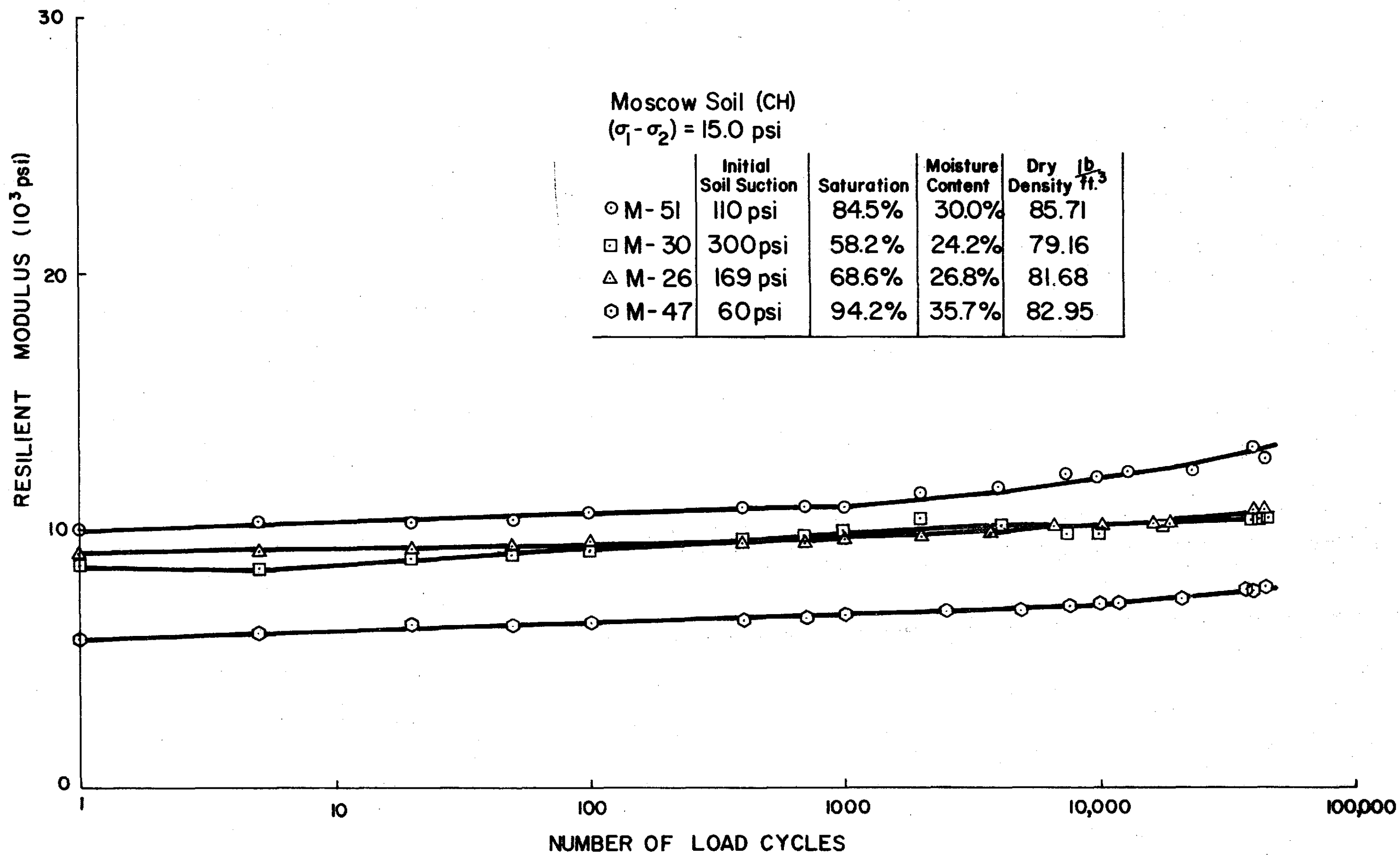

Figure A-4-1. Variation of the Resilient Modulus with the Number of Load Cycles, Moscow Soil (CH), 15.0 psi Deviator Stress

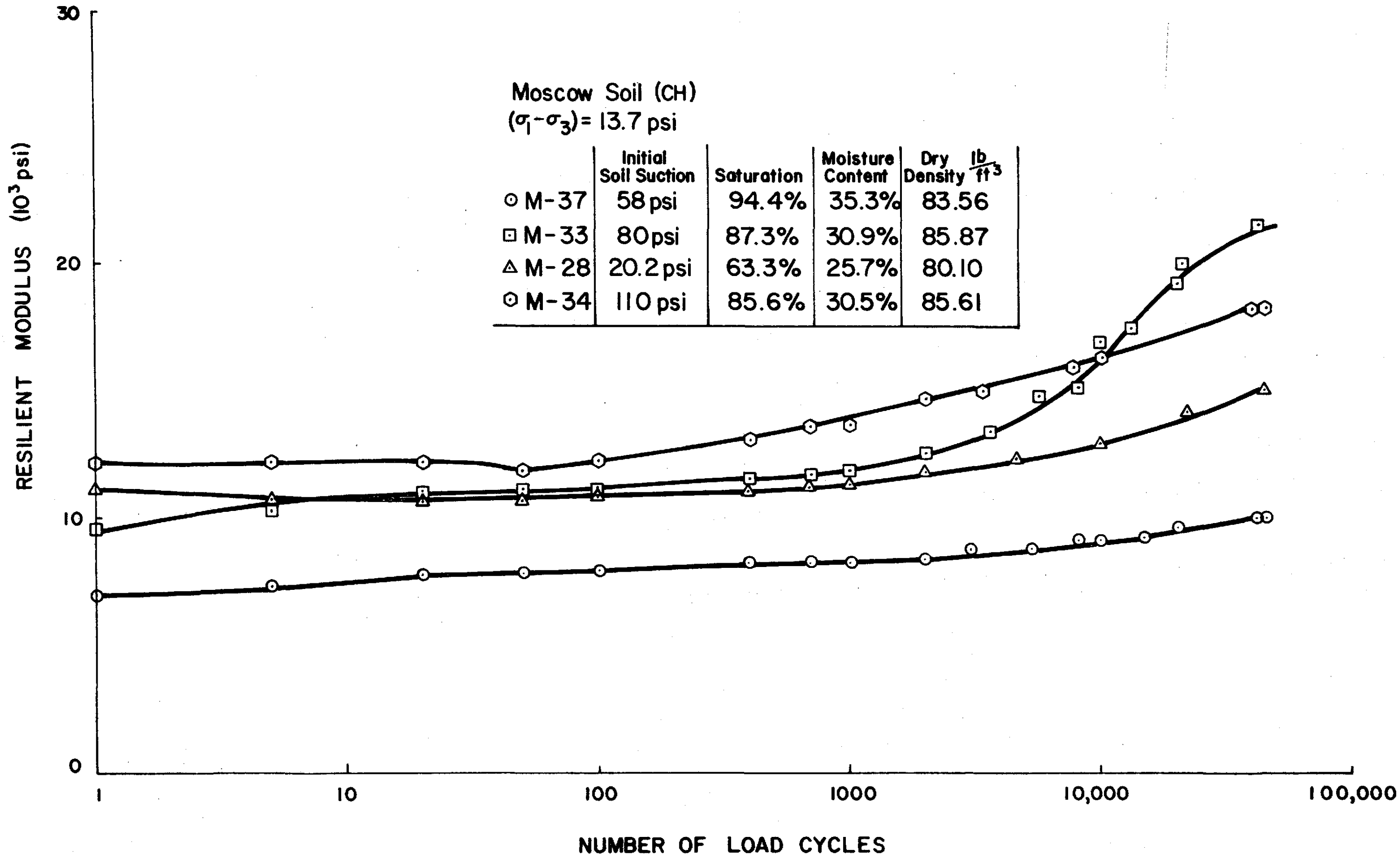

Figure A-4-2. Variation of the Resilient Modulus with the Number of Load Cycles, Moscow Soil (CH), 13.7 psi Deviator Stress

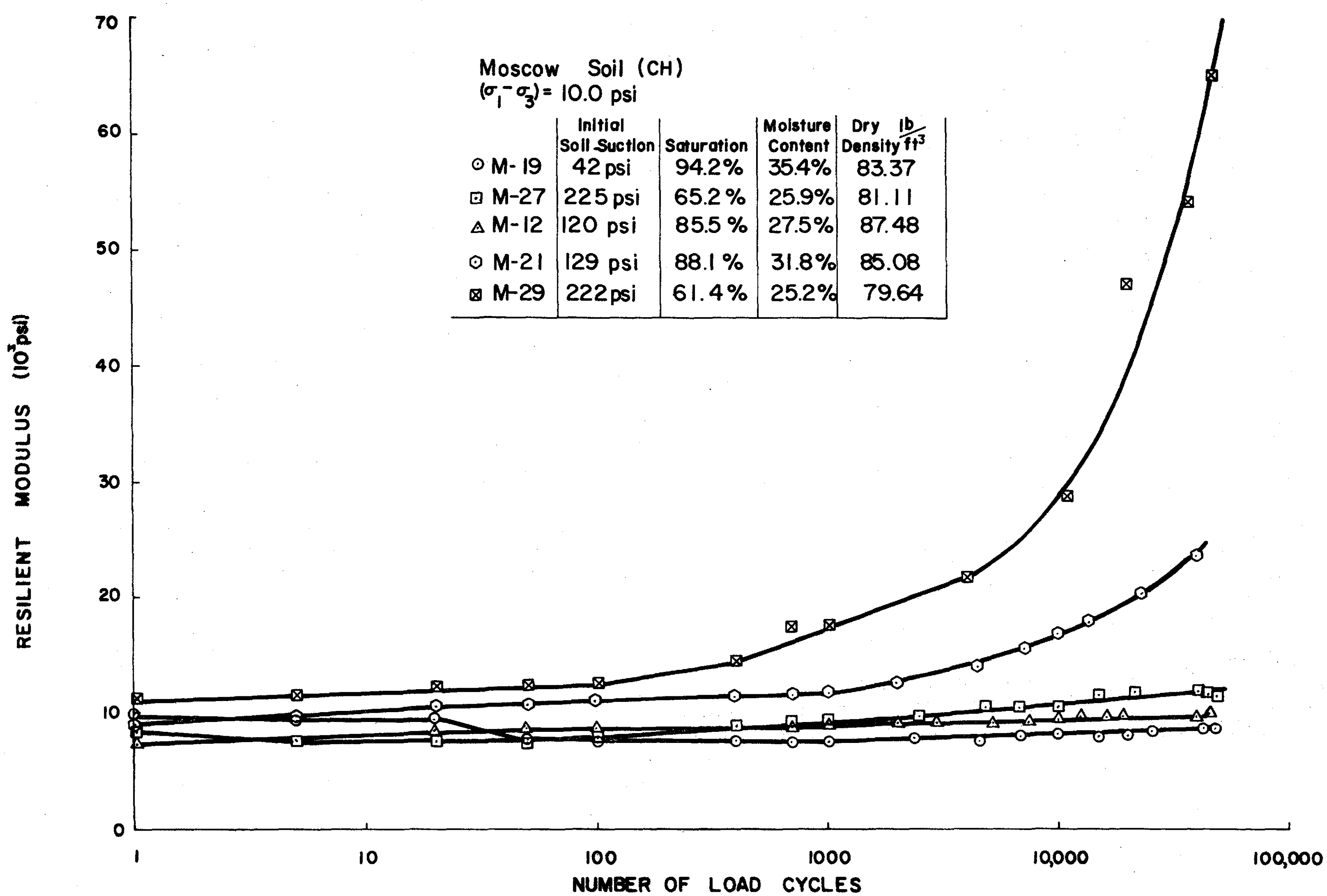

Figure A-4-3. Variation of the Resilient Modulus with the Number of Load Cycles, Moscow Soil (CH), 10.0 psi Deviator Stress

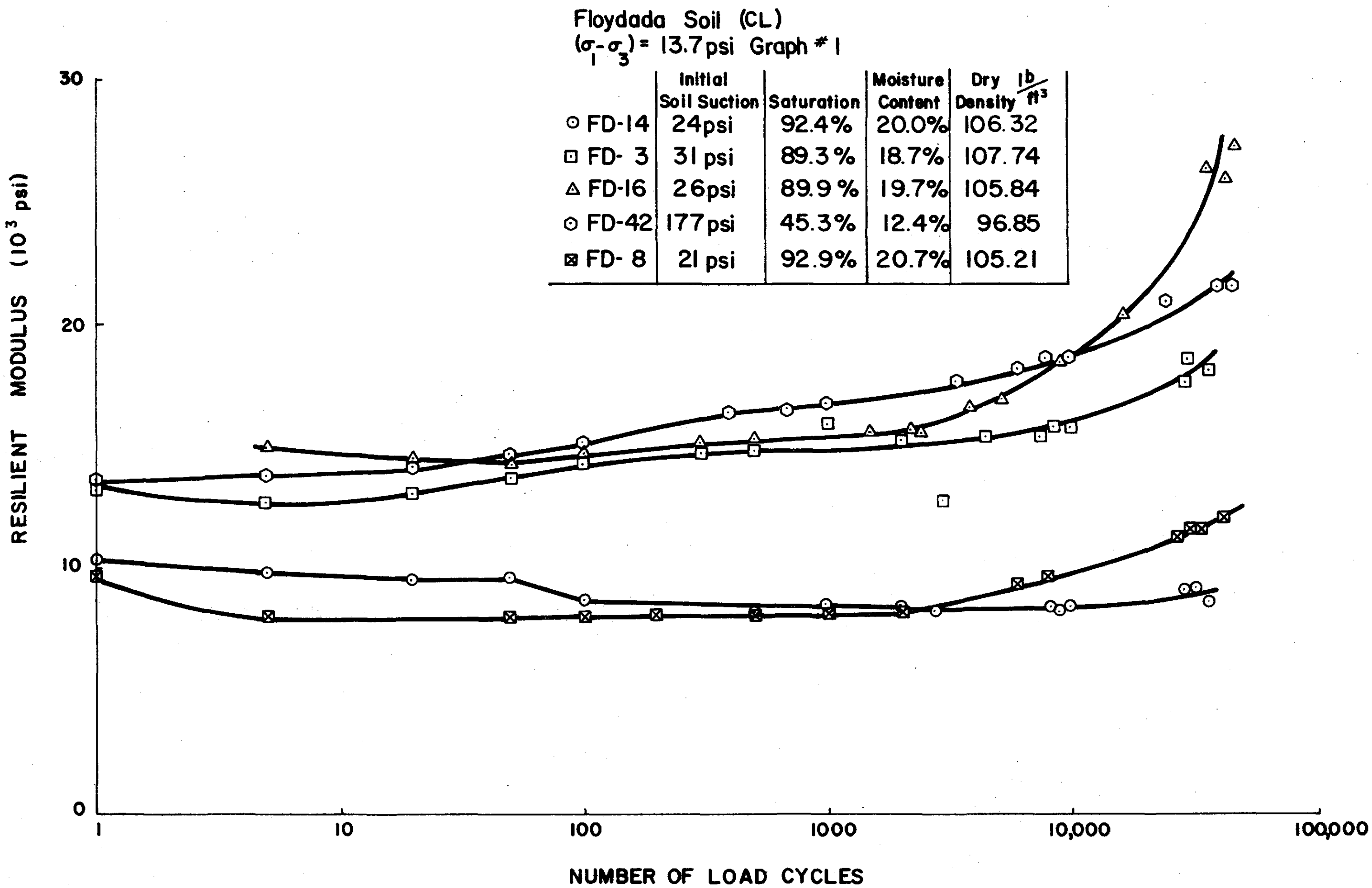

Figure A-4-4. Variation of the Resilient Modulus with the Number of Load Cycles, Floydada Soil (CL), 13.7 psi Deviator Stress, Graph #1

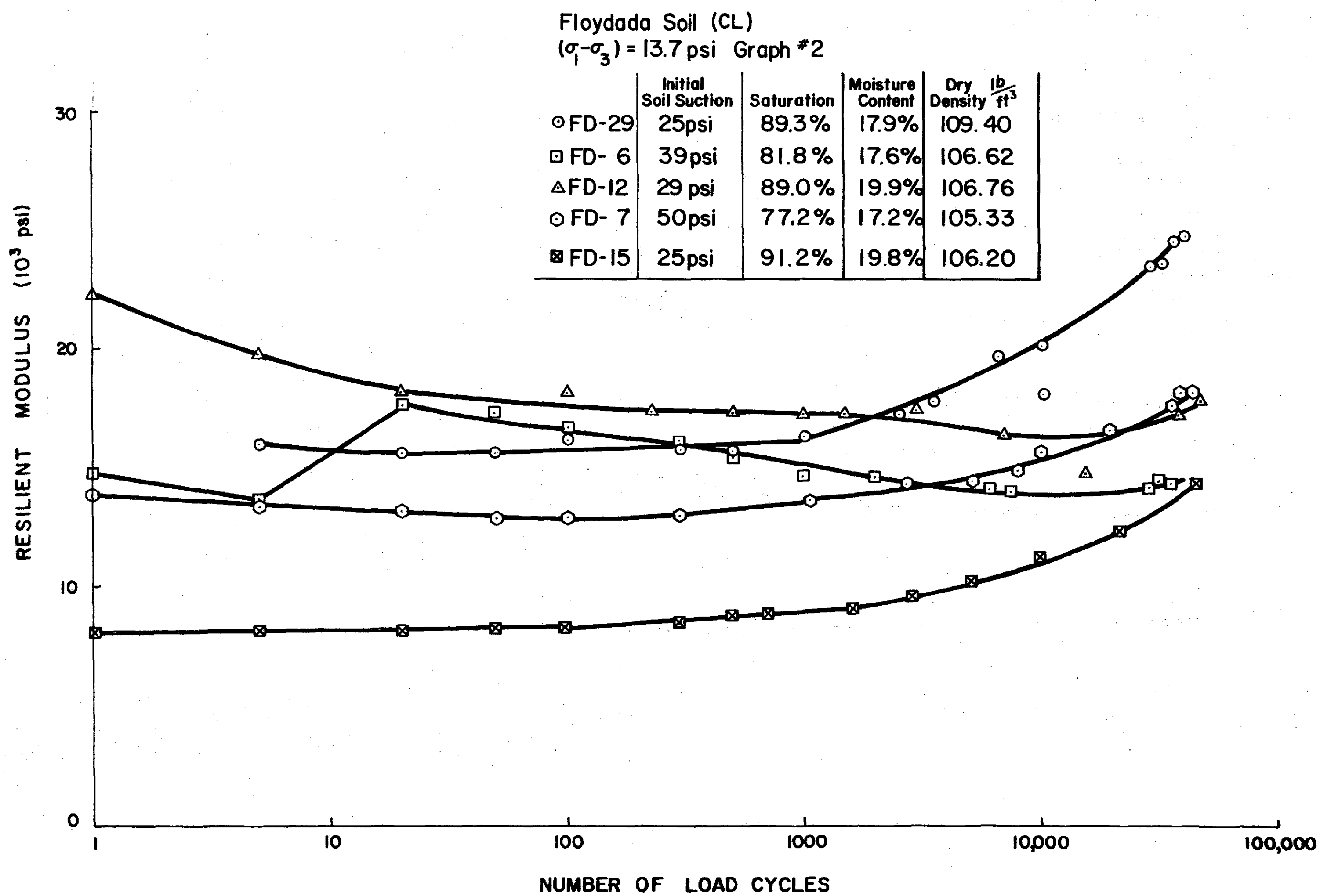

Figure A-4-5. Variation of the Resilient Modulus with the Number of Load Cycles, Floydada Soil (CL), 13.7 psi Deviator Stress, Graph #2

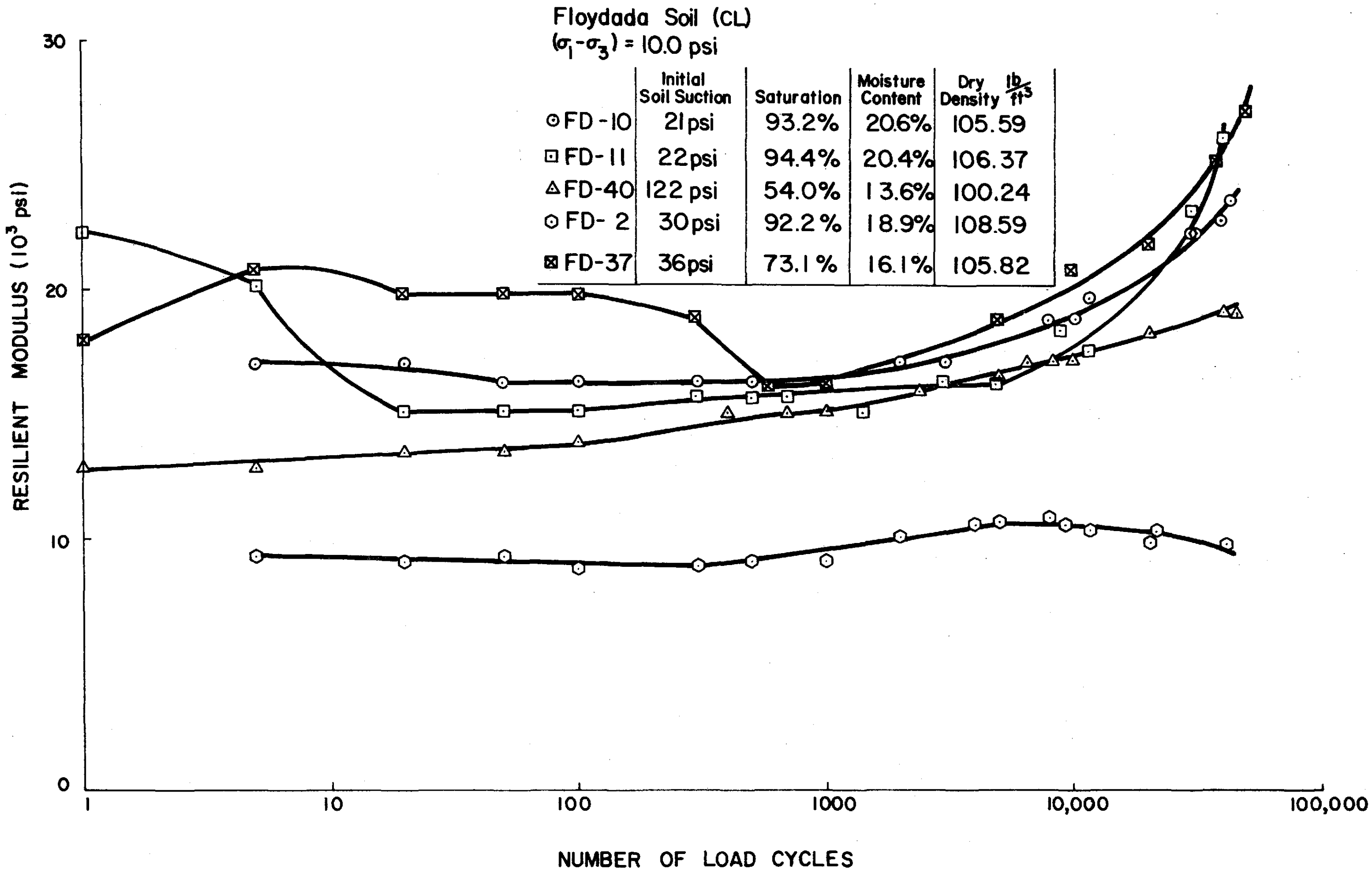

Figure A-4-6. Variation of the Resilient Modulus with the Number of Load Cycles, Floydada Soil (CL), 10.0 psi Deviator Stress

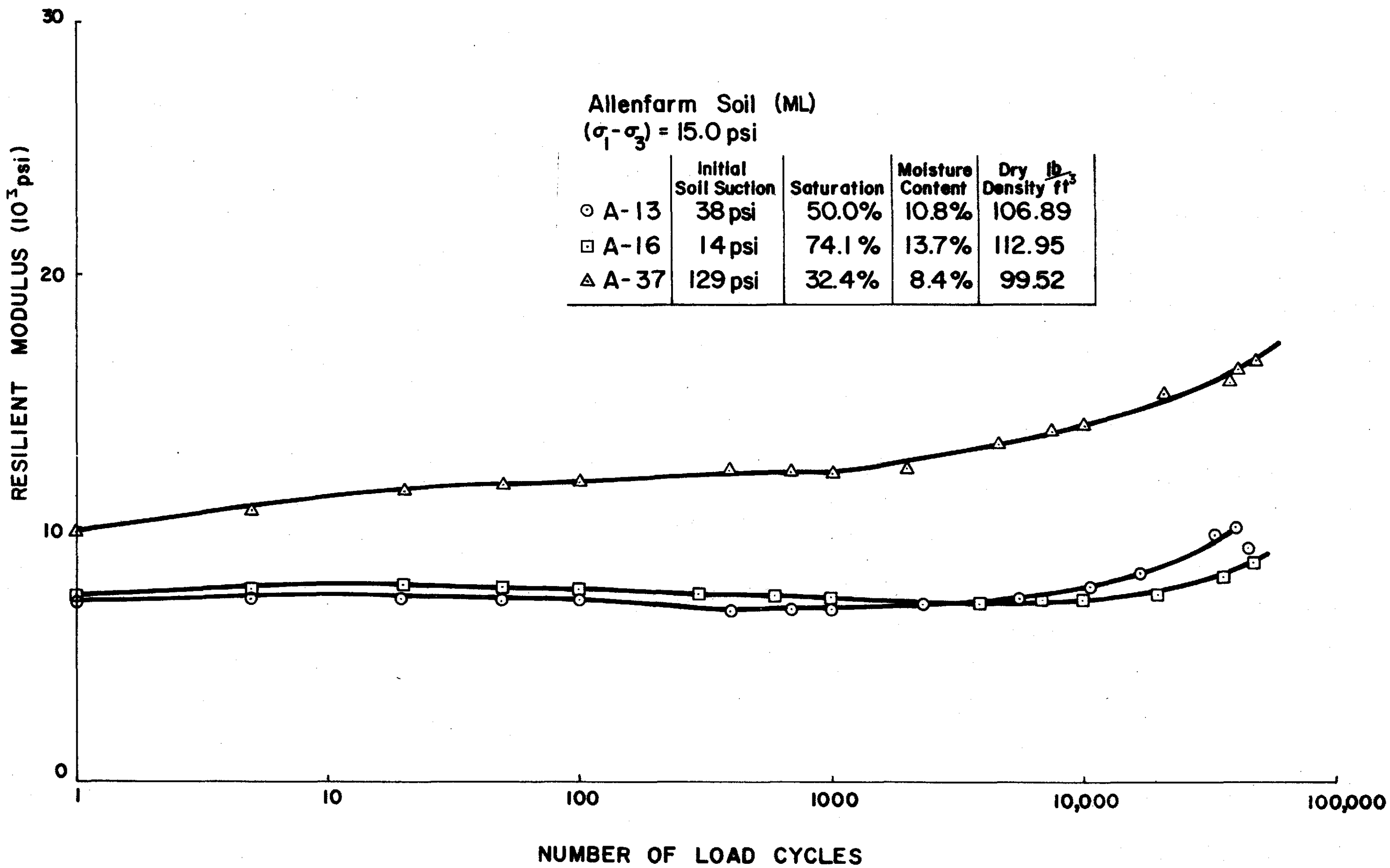

Figure A-4-7. Variation of the Resilient Modulus with the Number of Load Cycles, Allenfarm Soil (ML), 15.0 psi Deviator Stress

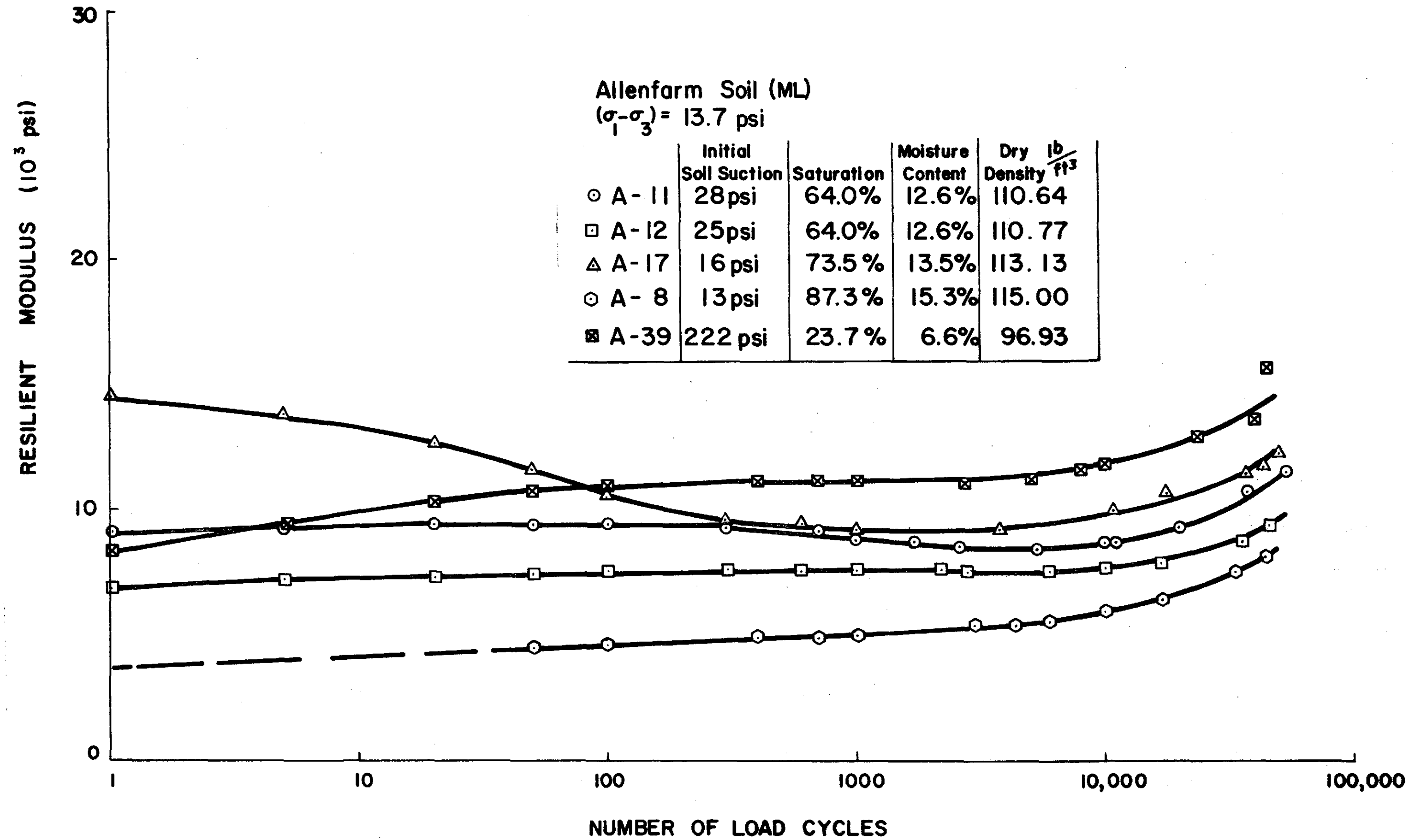

Figure A-4-8. Variation of the Resilient Modulus with the Number of Load Cycles, Allenfarm Soil (ML), 13.7 psi Deviator Stress

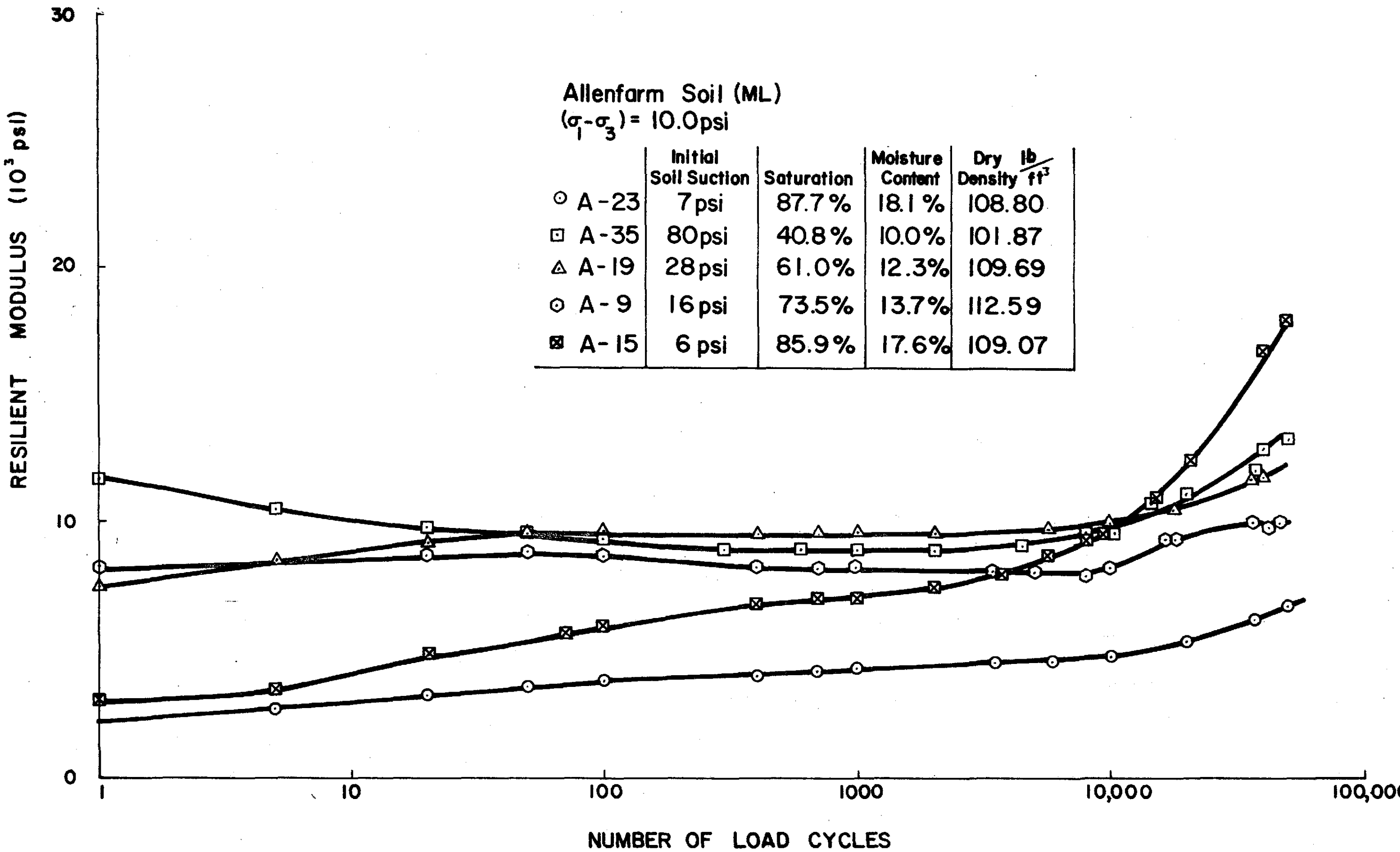

Figure A-4-9. Variation of the Resilient Modulus with the Number of Load Cycles, Allenfarm Soil (ML), 10.0 psi Deviator Stress

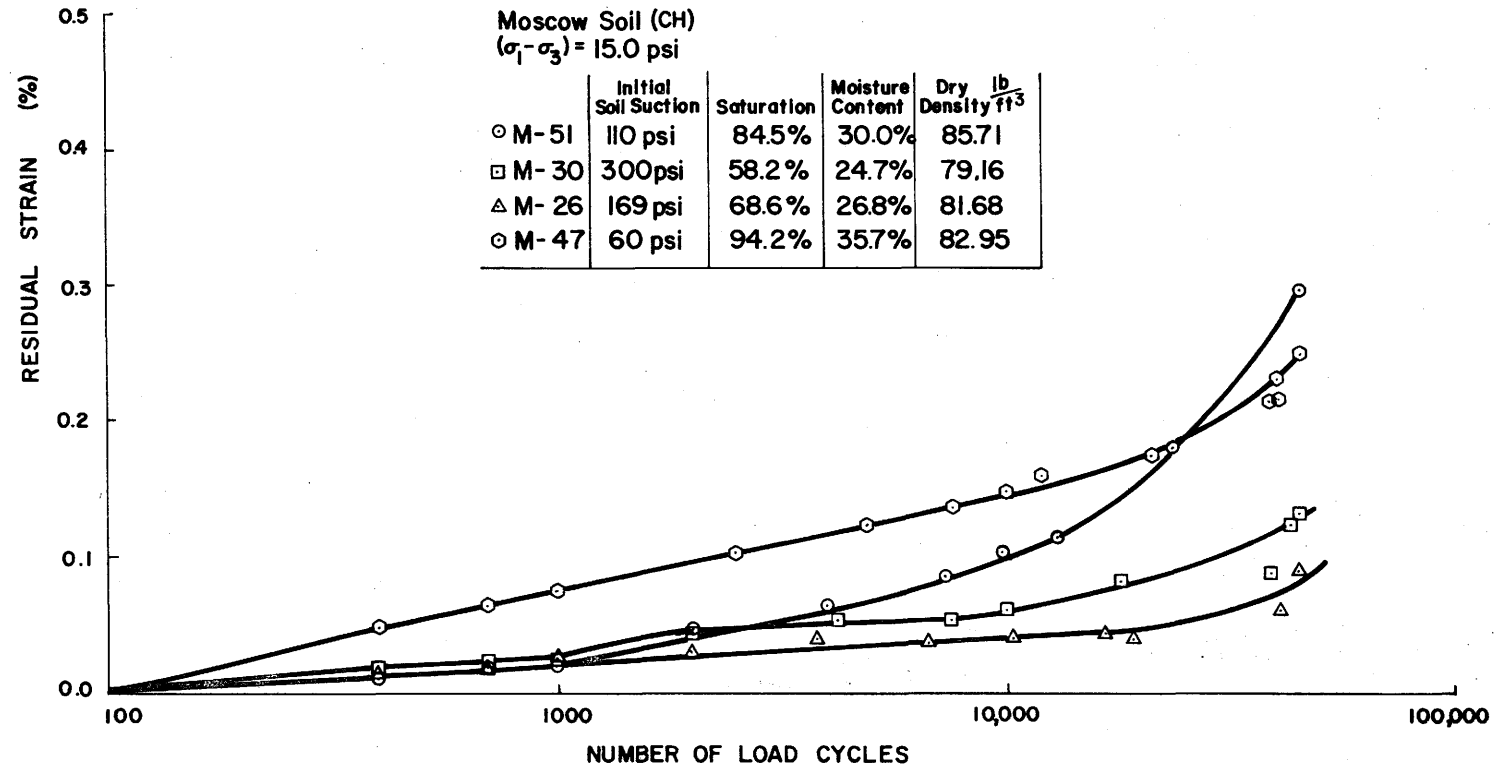

Figure A-4-10. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Moscow Soil (CH), 15.0 psi Deviator Stress

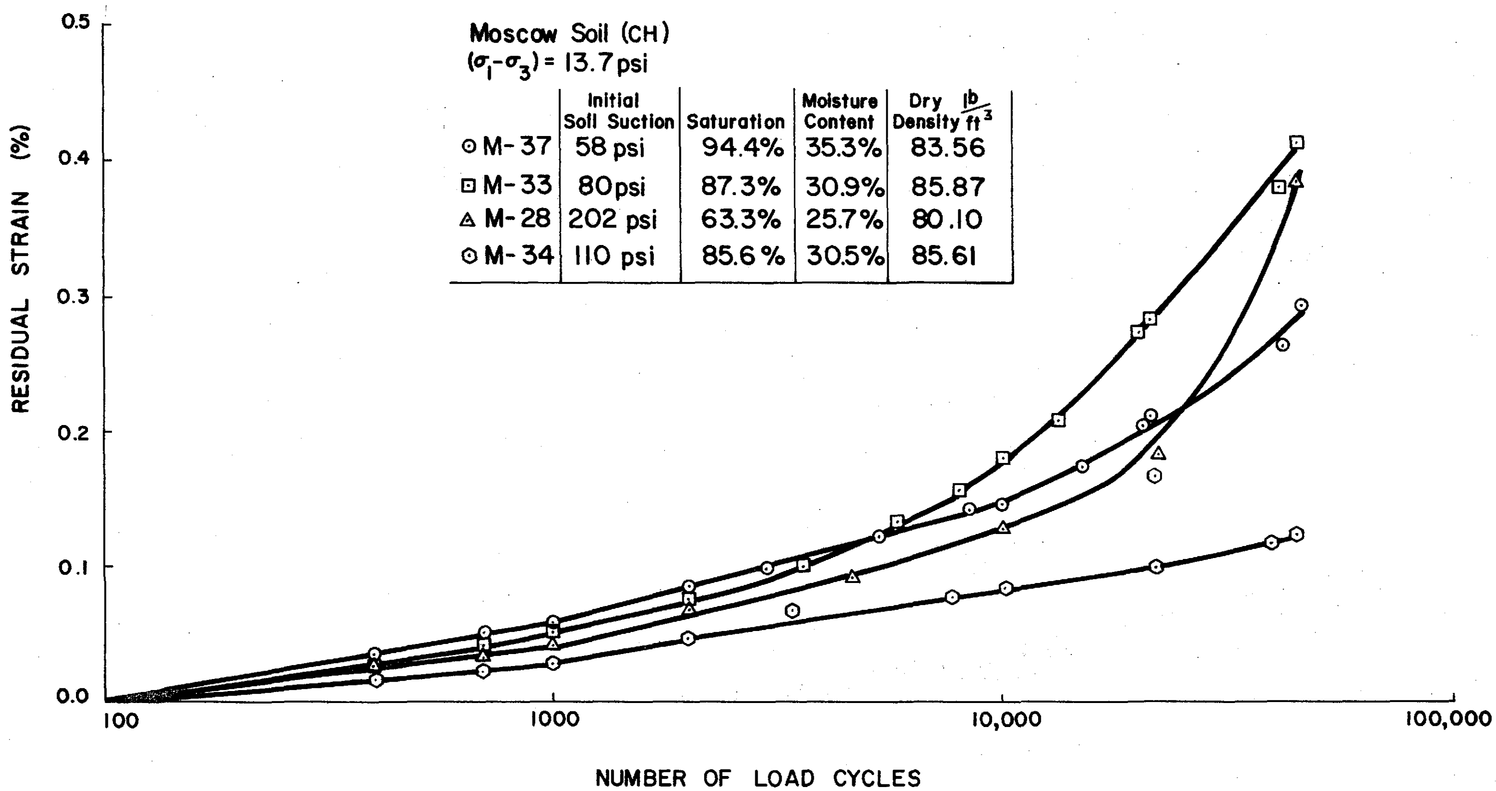

Figure A-4-11. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Moscow Soil (CH), 13.7 psi Deviator Stress

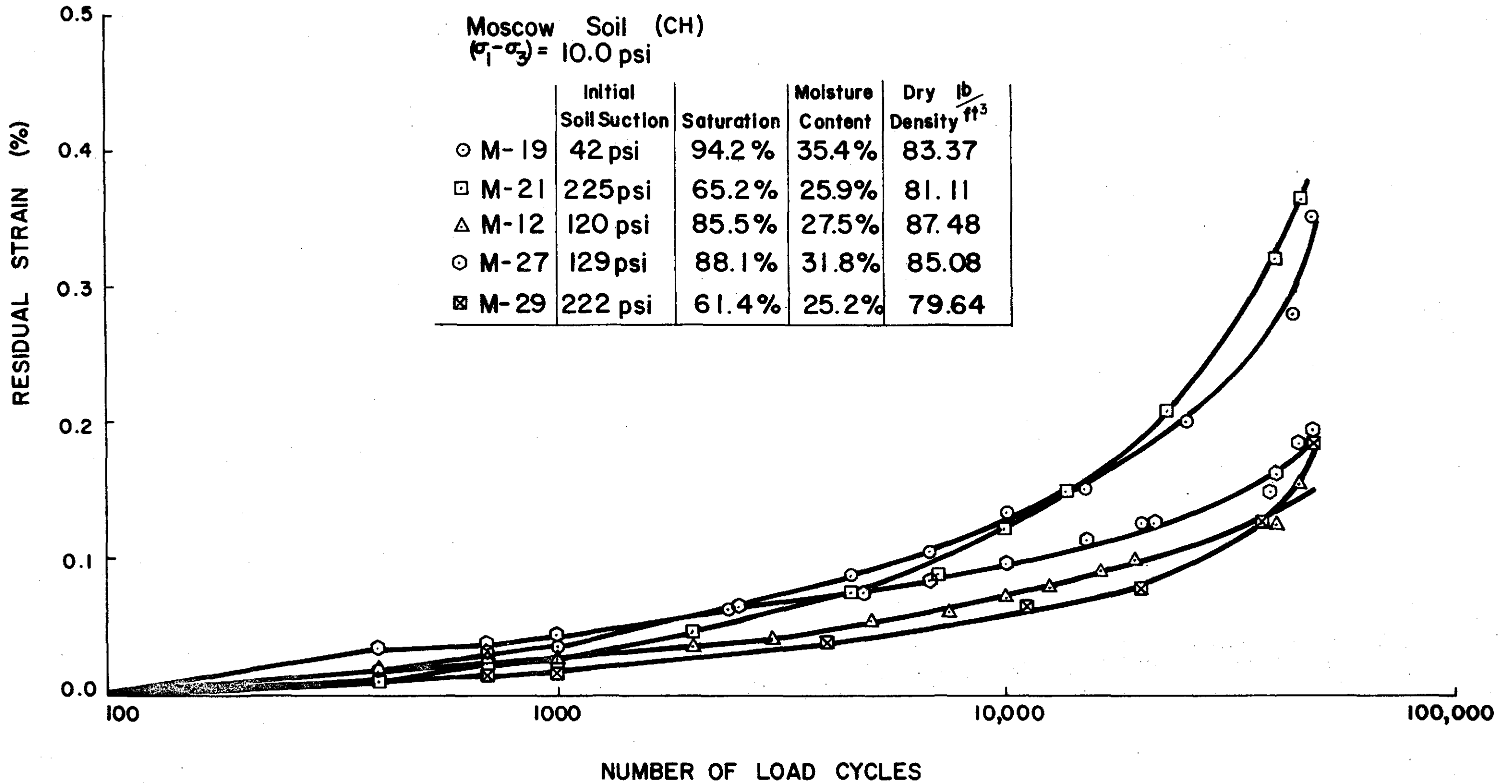

Figure A-4-12. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Moscow Soil (CH), 10.0 psi Deviator Stress

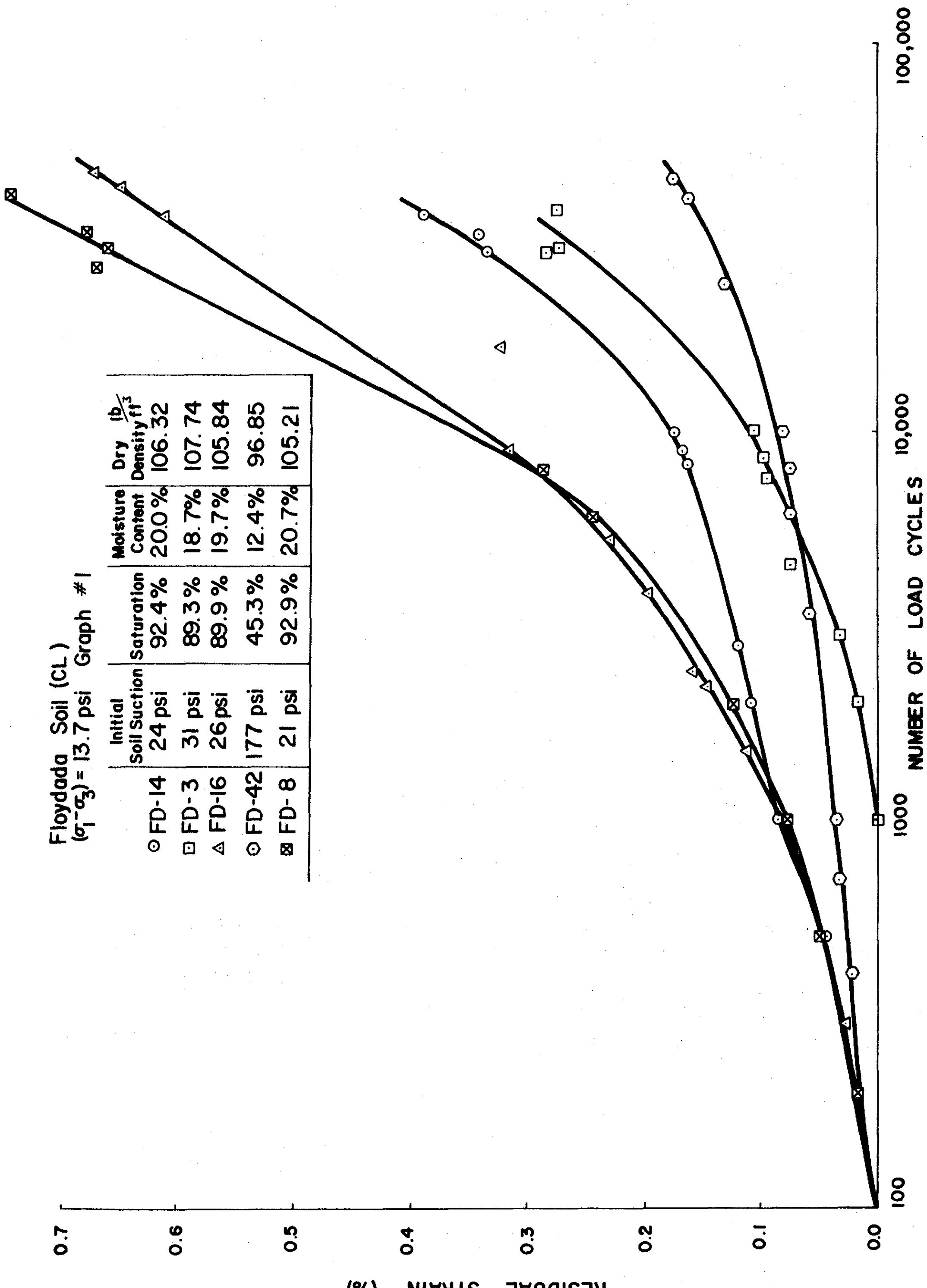

Figure A-4-13. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Floydada Soil (CL), 13.7 psi Deviator Stress, Graph #1

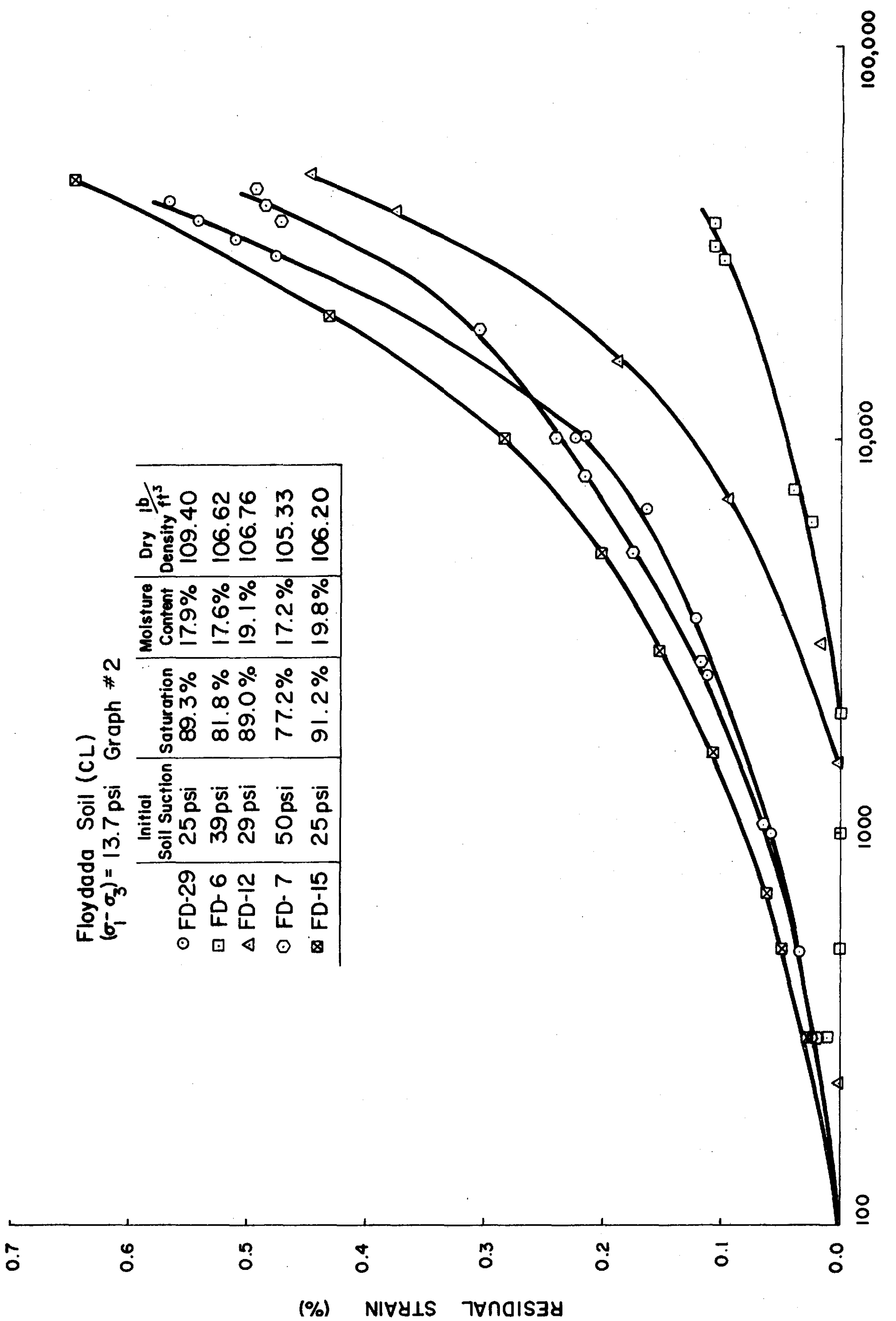

Figure A-4-14. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Floydada Soil (CL), 13.7 psi Deviator Stress, Graph #2

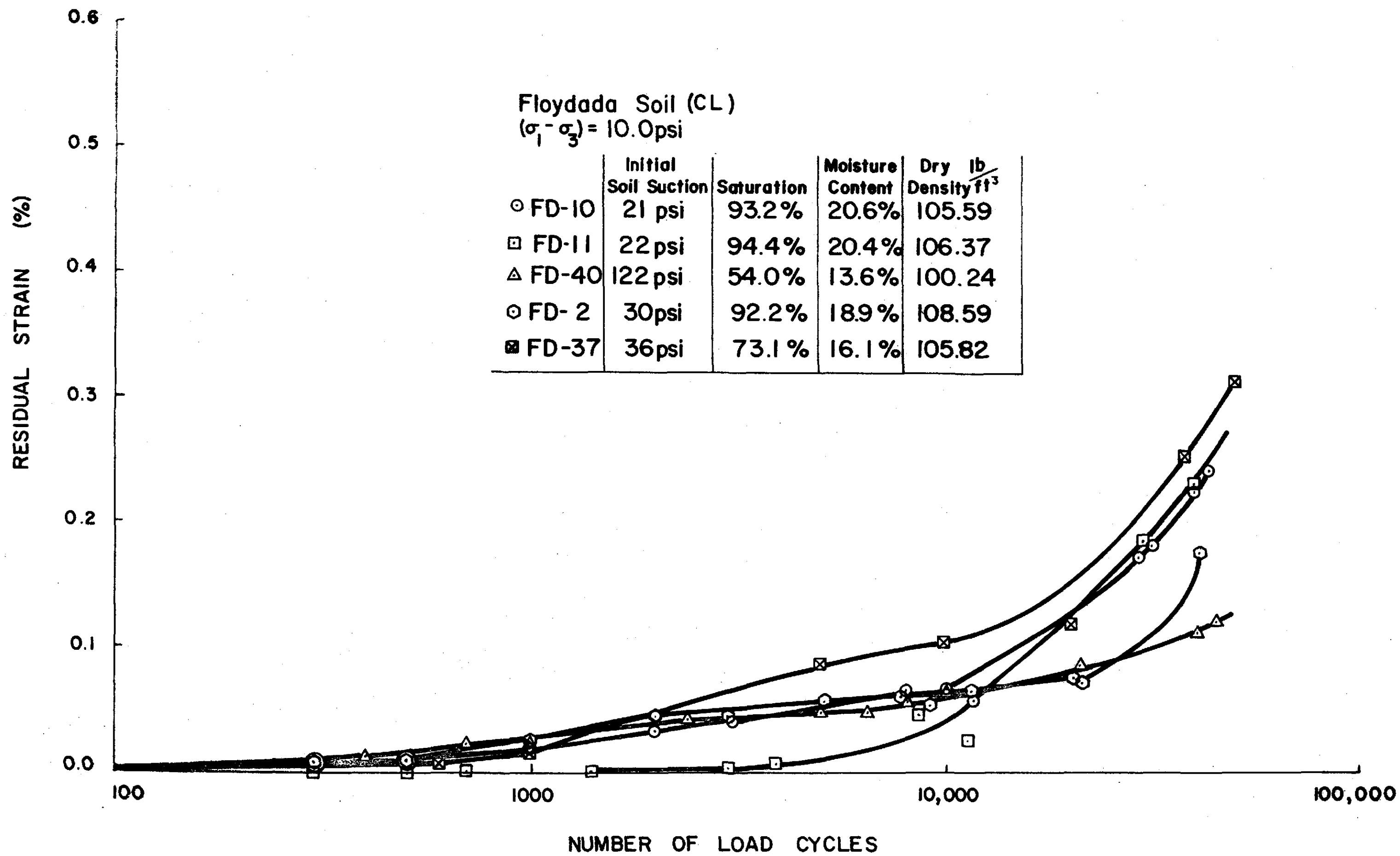

Figure A-4-15. Variation of the Reisdual Strain with the Number of Load Cycles, With Seating Correction, Floydada Soil (CL), 10.0 psi Deviator Stress

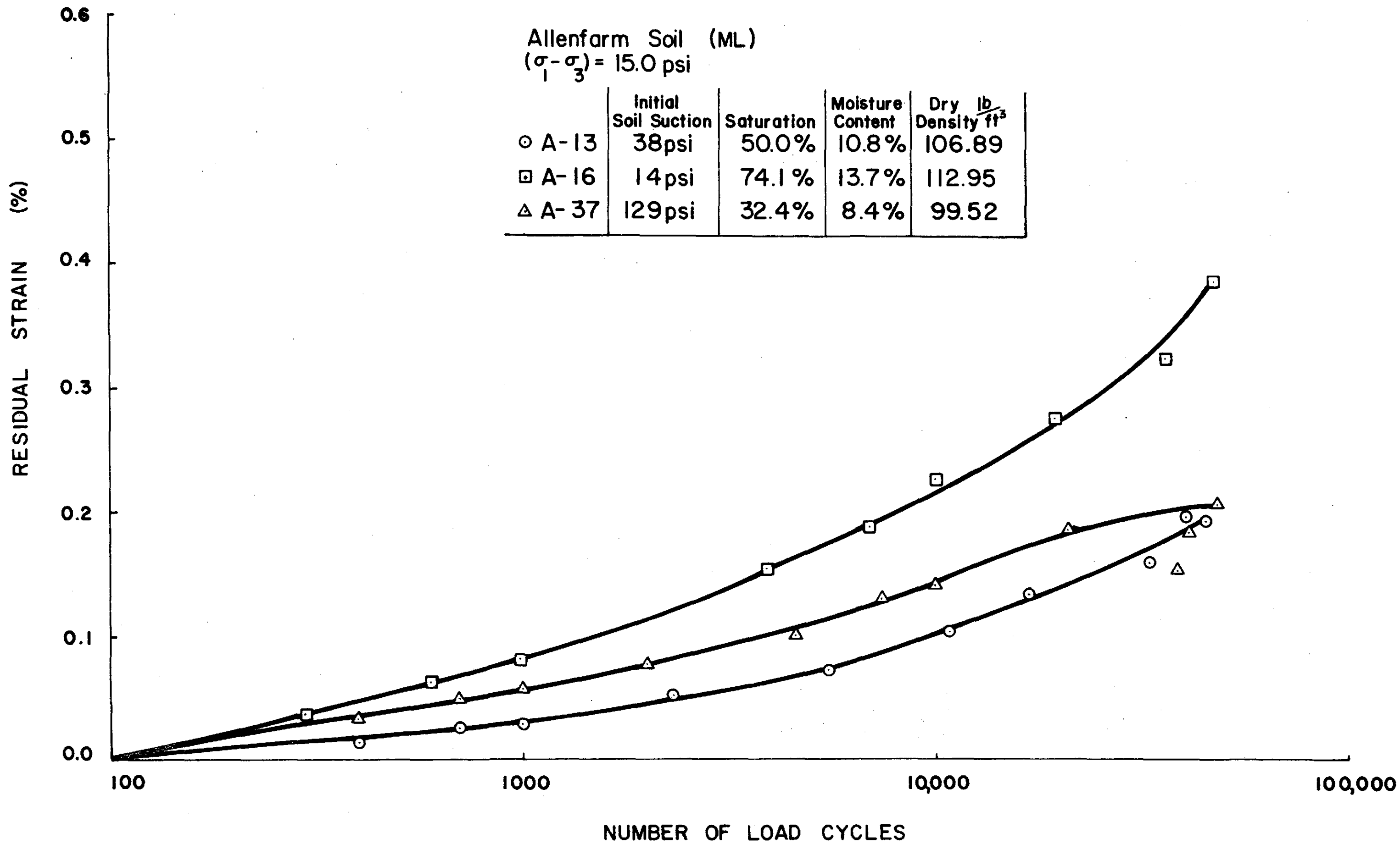

Figure A-4-16. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Allenfarm Soil (ML), 15.0 psi Deviator Stress

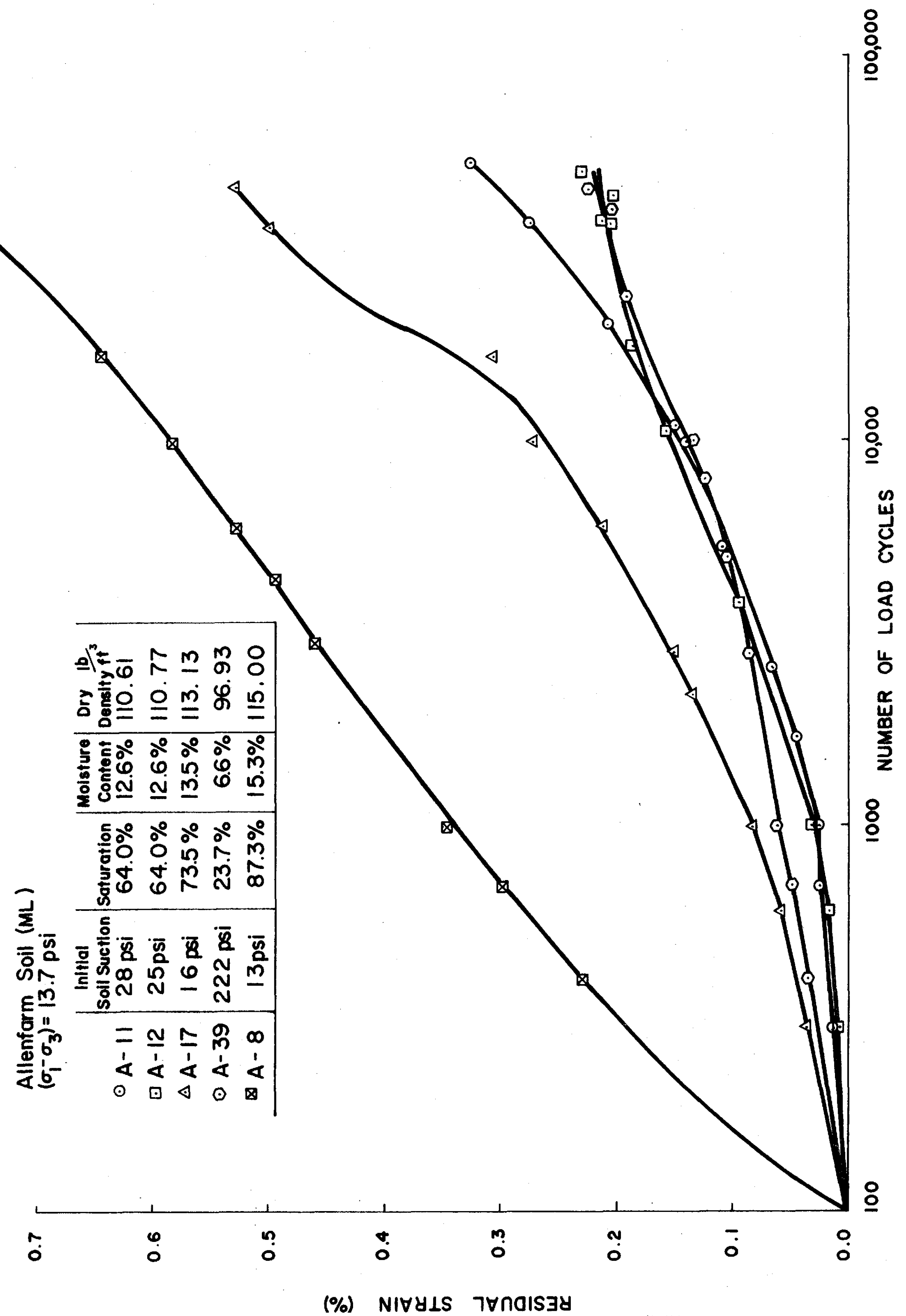

Figure A-4-17. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Allenfarm Soil (ML), 13.7 psi Deviator Stress

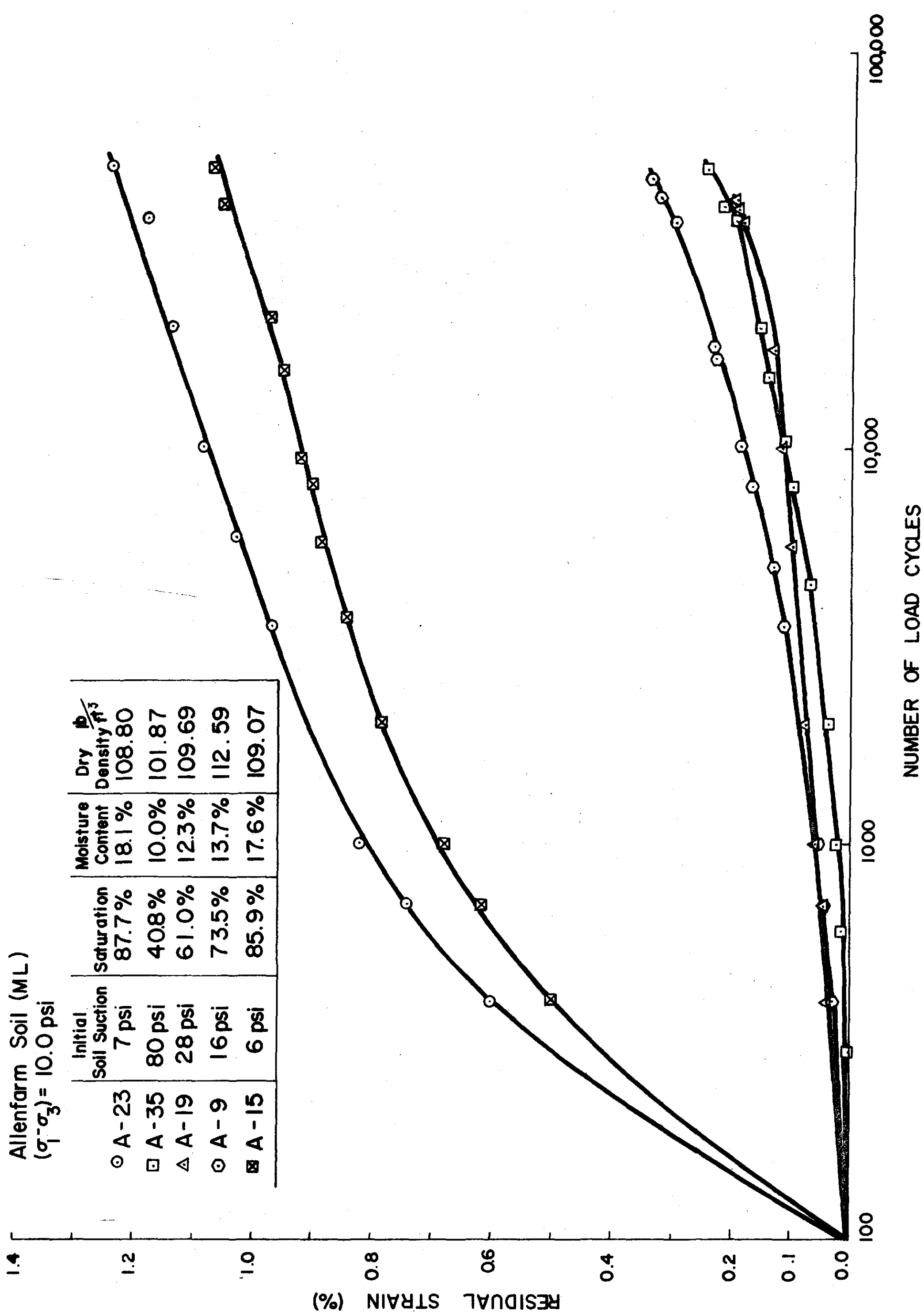

Figure A-4-18. Variation of the Residual Strain with the Number of Load Cycles, With Seating Correction, Allenfarm Soil (ML), 10.0 psi Deviator Stress

APPENDIX V

LISTING OF RESILIENT MODULUS AND RESIDUAL STRAIN TEMPERATURE CORRECTION FACTORS

	Temperature Ratio	Deviator Stress Ratio	Suction Ratio	Number of Load Cycle Ratio	f_{m_R}	f_{ε_p}
	0.472	1.00	1.191	1.00	0.755	0.679
Moscow	0.472	1.00	0.745	1.00	0.896	0.369
Soil (CH)	0.472	1.095	0.582	1.00	1.160	0.869
	0.472	0.730	1.582	1.00	0.847	0.417
standards	1.00	1.00	1.00	1.00	1.00	1.00
T=72°F	1.00	1.00	0.527	1.00	0.564	1.750
D=13.7 psi	1.00	1.00	0.736	1.00	0.963	2.143
h=110 psi	1.00	1.095	1.00	1.00	0.742	1.226
N=10,000 cycles	1.00	1.095	0.545	1.00	0.436	1.774
f_{m_R}=16300 psi	1.00	0.730	1.136	1.00	0.797	1.131
f_{ε_p}=0.084%	1.00	0.730	0.382	1.00	0.497	1.571
	1.389	1.00	0.718	1.00	0.399	3.071
	1.389	1.095	1.236	1.00	0.344	4.821
	1.389	0.730	0.973	1.00	0.478	5.774
	0.472	1.00	1.191	0.10/0.50*	0.706	0.559
	0.472	1.00	0.745	0.10/0.50	0.828	0.345
	0.472	1.095	0.582	0.10/0.50	1.123	0.798
	0.472	0.730	1.582	0.10/0.50	0.896	0.345
	1.00	1.00	1.00	0.10/0.50	0.834	0.857
	1.00	1.00	0.736	0.10/0.50	0.730	1.452
	1.00	1.00	0.527	0.10/0.50	0.503	1.417
	1.00	1.095	1.00	0.10/0.50	0.669	0.833
	1.00	1.095	0.545	0.10/0.50	0.411	1.476
	1.00	0.730	1.136	0.10/0.50	0.626	0.762
	1.00	0.730	0.382	0.10/0.50	0.454	1.083
	1.389	1.00	0.718	0.10/0.50	0.350	1.393
	1.389	1.095	1.236	0.10/0.50	0.325	3.464
	1.389	0.730	0.973	0.10/0.50	0.405	4.274
	0.472	1.00	1.191	4.00	0.804	1.107
	0.472	1.00	0.745	4.00	0.896	0.702
	0.472	1.095	0.582	4.00	1.239	1.274
	0.472	0.730	1.582	4.00	0.828	0.940
	1.00	1.00	1.00	4.00	1.123	4.345
	1.00	1.00	0.736	4.00	1.307	4.440
	1.00	1.00	0.527	4.00	0.613	3.071
	1.00	1.095	1.00	4.00	0.785	2.583
	1.00	1.095	0.545	4.00	0.472	2.750
	1.00	0.730	1.136	4.00	1.012	2.643
	1.00	0.730	0.382	4.00	0.509	3.179
	1.389	1.00	0.718	4.00	0.448	7.190
	1.389	1.095	1.236	4.00	0.350	12.024
	1.389	0.730	0.973	4.00	0.589	9.190
	0.472	1.00	1.280	1.00	1.140	0.108
Floydada	0.472	1.095	0.980	1.00	0.580	0.613
Soil (CL)	0.472	0.730	2.400	1.00	1.599	0.312
	1.00	1.00	1.00	1.00	1.00	0.312

*When a dual number appears in this column it means as follows: 0.10/0.50, the resilient modulus was based on 1000 cycles (0.10 of 10,000 cycles) and the residual strain was based on 5000 cycles (0.50 of 10,000 cycles)

	Temperature Ratio	Deviator Stress Ratio	Suction Ratio	Number of Load Cycle Ratio	f_{m_R}	f_{ε_p}
	1.00	1.00	3.540	1.00	1.191	0.337
Floydada	1.00	1.095	0.460	1.00	0.688	0.683
Soil (CL)	1.00	1.095	2.540	1.00	1.178	0.200
	1.00	0.730	0.720	1.00	1.325	0.433
standards	1.00	0.730	2.440	1.00	1.089	0.254
T=72°F	1.389	1.00	1.900	1.00	0.592	1.508
D=13.7 psi	1.389	1.095	3.700	1.00	0.707	0.708
h=50 psi	1.389	1.095	2.720	1.00	0.860	0.200
N=10,000 cycles	1.389	0.730	2.00	1.00	0.592	1.371
f_{m_R}=15700 psi	0.472	1.00	1.280	0.10/0.50	1.096	0.096
	0.472	1.095	0.980	0.10/0.50	0.580	0.533
f_{ε_p}=0.240%	0.472	0.730	2.400	0.10/0.50	1.567	0.200
	1.00	1.00	1.00	0.10/0.50	0.866	0.712
	1.00	1.00	3.540	0.10/0.50	1.076	0.292
	1.00	1.095	0.460	0.10/0.50	0.592	0.563
	1.00	1.095	2.540	0.10/0.50	1.121	0.137
	1.00	0.730	0.720	0.10/0.50	1.051	0.358
	1.00	0.730	2.440	0.10/0.50	0.962	0.204
	1.389	1.00	1.900	0.10/0.50	0.567	1.112
	1.389	1.095	3.700	0.10/0.50	0.605	0.579
	1.389	1.095	2.720	0.10/0.50	0.853	1.242
	1.389	0.730	2.00	0.10/0.50	0.522	0.879
	0.472	1.00	1.280	4.00	1.166	0.171
	0.472	1.095	0.980	4.00	0.592	0.750
	0.472	0.730	2.400	4.00	1.599	0.375
	1.00	1.00	1.00	4.00	1.159	2.042
	1.00	1.00	3.540	4.00	1.382	0.671
	1.00	1.095	0.460	4.00	0.790	1.217
	1.00	1.095	2.540	4.00	1.248	0.362
	1.00	0.730	0.720	4.00	1.624	1.096
	1.00	0.730	2.440	4.00	1.210	0.463
	1.389	1.00	1.900	4.00	0.643	2.767
	1.389	1.095	2.720	4.00	1.146	2.754
	1.389	1.095	3.700	4.00	0.694	2.087
	1.389	0.730	2.000	4.00	0.707	3.250
	0.472	1.00	1.286	1.00	2.023	0.507
Allenfarm	0.472	1.095	2.250	1.00	1.00	1.193
Soil (ML)	0.472	0.730	2.071	1.00	0.678	3.914
	1.00	1.00	1.00	1.00	1.00	1.00
standards	1.00	1.00	7.929	1.00	1.368	0.971
T=72°F	1.00	1.095	1.357	1.00	0.874	0.707
D=13.7 psi	1.00	1.095	4.607	1.00	1.632	1.007
h=28 psi	1.00	1.095	0.500	1.00	0.828	1.607
N=10,000 cycles	1.00	0.730	1.00	1.00	1.115	0.807
f_{m_R}= 8700 psi	1.00	0.730	2.857	1.00	1.138	0.850
	1.389	1.00	4.643	1.00	1.115	0.757
f_{ε_p}=0.140%	1.389	1.095	0.357	1.00	0.437	5.293
	1.389	0.730	0.964	1.00	1.012	2.164
	0.472	1.00	1.286	0.10/0.50	1.931	0.379
	0.472	1.095	2.250	0.10/0.50	1.046	0.879
	0.472	0.730	2.071	0.10/0.50	0.713	3.543

	Temperature Ratio	Deviator Stress Ratio	Suction Ratio	Number of Load Cycle Ratio	f_{m_R}	f_{ε_p}
	1.00	1.00	1.00	0.10/0.50	1.012	0.743
Allenfarm	1.00	1.00	7.929	0.10/0.50	1.276	0.743
Soil (ML)	1.00	1.095	1.357	0.10/0.50	0.782	0.507
	1.00	1.095	4.607	0.10/0.50	1.414	0.764
	1.00	1.095	0.500	0.10/0.50	0.828	1.186
	1.00	0.730	1.00	0.10/0.50	1.023	0.529
	1.00	0.730	2.857	0.10/0.50	1.092	0.686
	1.389	1.00	4.643	0.10/0.50	1.023	0.414
	1.389	1.095	0.357	0.10/0.50	0.402	4.243
	1.389	0.730	0.964	0.10/0.50	0.977	1.450
	0.472	1.00	1.286	4.00	2.023	0.800
	0.472	1.095	2.250	4.00	0.988	1.871
	0.472	0.730	2.071	4.00	0.655	3.964
	1.00	1.00	1.00	4.00	1.253	2.021
	1.00	1.00	7.929	4.00	1.563	1.457
	1.00	1.095	1.357	4.00	1.161	1.393
	1.00	1.095	4.607	4.00	1.862	1.286
	1.00	1.095	0.500	4.00	0.954	2.464
	1.00	0.730	1.00	4.00	1.471	1.593
	1.00	0.730	2.857	4.00	1.345	1.407
	1.389	1.00	4.643	4.00	1.299	3.900
	1.389	1.095	0.357	4.00	0.494	6.507
	1.389	0.730	0.964	4.00	1.253	3.729