SUBGRADE SOILS: AN IMPORTANT FACTOR IN CONCRETE PAVEMENT DESIGN

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INTRODUCTION

Concrete pavements are constructed over a subbase layer(s) or in some instances directly on the subgrade. In either case, the subgrade significantly influences the ultimate pavement performance.

Normally, subgrade effects are considered based on an evaluation of subgrade property - concrete stress relations. However, subgrade structural response effects are more pronounced based on pavement deflection considerations.

The subgrade has a tremendous impact on pavement construction operations and efficiency. Unstable subgrades present problems relative to placing and compacting subbase materials and providing adequate support for subsequent paving operations. Such construction operations as placing reinforcing steel, dowels, and jointing devices are sensitive to placement details. Without an adequate "working platform", such critical pavement construction details may not be accomplished within acceptable tolerances. Frequently, such construction deficiencies are undetected because they are "hidden" in the finished pavement!

It is the contention of the authors that more detailed consideration should be directed to evaluating subgrade soils in rigid pavement analysis, design, and construction. Fluctuating subgrade support (as a function of time and space) has a substantial influence on the behavior and performance on concrete pavements.

SOIL PROPERTIES AND CLIMATIC EFFECTS

Water content and temperature are the major climatic factors that influence the strength and deformation properties of soils. Assuming that the paving concrete possesses adequate freeze-thaw durability, the effects of moisture and temperature on the engineering properties of the concrete should not be substantial. Such factors as pavement concrete warping, contraction, and expansion are obviously factors of major importance in concrete pavement response and performance, but they are not considered in this presentation.

Moisture-Stability Effects

Moisture content has a pronounced effect on the strength and deformation (static and resilient) properties of soils. Extensive studies by Croney, Coleman and Black (1) in England have emphasized the development of relations between soil suction, which is a function of water content, and stability, Figures 1 and 2.

Sauer and Monismith (2) have studied the repeated load behavior of a glacial till at different suctions (moisture contents). Shackel (3) found that suctions exhibited by a compacted soil were functions not only of moisture content and dry density at compaction but also of the stress history experienced by the soil. He found that resilient axial strains decreased linearly with increase in suctions.

Moisture content effects on the permanent deformation behavior of Fayette B, a loess-derived AASHTO Class A-7-6 soil, are illustrated in Figure 3. The data in Figure 3 are for 5000 stress applications.

Resilient Behavior of Fine-Grained Soils

The resilient response of fine-grained soils is stress dependent. A commonly used measure of resilient response is the "resilient modulus" as defined below:

$$E_R = \frac{\sigma_D}{\varepsilon_R} \qquad (1)$$

E_R = resilient modulus

σ_D = repeated deviator stress

ε_R = recoverable axial strain

Robnett and Thompson (4) have demonstrated that for practical pavement design and analysis purposes repeated unconfined ($\sigma_3 = 0$) compression testing is satisfactory for resilient testing of cohesive soils.

Two basic stress dependent behavior models have been utilized. The arithmetic model is demonstrated in Figures 4 and 5 and the semi-log model is shown in Figure 6.

Recent extensive resilient testing studies at the University of Illinois (5) have been primarily analyzed based on the arithmetic model. E_{Ri}, see Figure 4, is a good indicator of a soil's resilient behavior. The slope values, K_1 and K_2, display less variability and influence pavement structural response to a smaller degree than does E_{Ri}.

For well designed rigid pavements, subgrade stresses are quite small. However, it is important to recognize that:

1) Basically all of the deformation in a rigid pavement occurs in the subgrade.
2) The accumulation of small amounts of differential permanent deformation in the subgrade may contribute to "non-uniform" support conditions.
3) Subgrade support is not constant, but will vary depending on stress state. For example, the E_R value beneath the loaded area will be smaller than at remote points since the stress is reduced at points further away from the loaded area.

There are many factors that influence the resilient response of fine-grained soils. A general summary of the major factors, based on the Illinois study (5) of 50 typical fine-grained soils, is presented below:

Soil Properties - For a given compaction condition (for example 95% AASHTO T99 density and optimum or optimum + water content), E_{Ri} is significantly correlated with liquid limit, plasticity index, group index, silt content, clay content, specific gravity, and organic carbon content. Those properties that tend to contribute to low resilient moduli (low E_{Ri}) are low plasticity (LL, PI), low group index, high silt content, low clay content, low specific gravity, and high organic carbon contents.

Soil Classification Effects - Analysis of variance results indicated that the resilient behavior (E_{Ri}, K_1 response parameters) of the various groups in the classification systems (Unified, AASHTO, USDA) are not in general significantly different. Thus, classifying the soil in the AASHTO, Unified, or USDA system is not sufficient for the purpose of placing fine-grained soils into distinctive resilient behavior groups.

Moisture-Density Effects - Degree of saturation is a factor that reflects the combined effect of density and moisture content. E_{Ri} is strongly correlated with degree of saturation. The regression equations shown in Figure 7 indicate that E_{Ri} can be estimated based on degree of saturation. The E_{Ri}-degree of saturation regression equations differ for 95% AASHTO T-99 and 100% AASHTO T-99 compaction. One hundred percent compaction provides higher E_{Ri} for a given degree of saturation. The difference in E_{Ri} values for 100% and 95% AASHTO T-99 compaction is reduced at increased degrees of saturation.

The combined effects of compaction moisture content and density are easily discerned using the E_{Ri}-degree of saturation relations. For soils substantially wet of optimum, high degrees of saturation and low E_{Ri} values are characteristic, regardless of level of compaction.

Additional E_{Ri}-degree of saturation regression equations of the form $E_{Ri} = a + b\ S_R$ were developed (E_{Ri} = resilient modulus, a = intercept, S_R = degree of saturation, %) for various soil classification groups. The regression coefficient, b, is indicative of moisture sensitivity. It was noted that for the B and C horizons those classification groups with higher clay contents and increased plasticity tend to be less sensitive to changes in degree of saturation. For example, the CH group in the United system and the silty clay loam, clay and silty clay groups in the USDA system have regression coefficients substantially less than the other groups.

Freeze-Thaw Effects - Recent studies by Bergan and Fredlund (6), Culley (7), Chamberlain (8), Bergan and Monismith (9), Bergan and Culley (10), and Robnett and Thompson (11), have shown that the resilient behavior of fine-grained cohesive soils is also greatly affected by cyclic freeze-thaw action. The studies revealed that substantial increases in resilient deformation were caused by the imposition of a small number of freeze-thaw cycles even though no gross moisture changes were allowed (closed system freeze-thaw).

Typical data illustrating the freeze-thaw effect for Tama B [LL = 46, PI = 25, 32% < 2u clay, AASHTO Class A-7-6(27)] are shown in Figure 8. It is significant to note that one freeze-thaw cycle is sufficient to drastically reduce the resilient modulus of the soil.

Summary - It is apparent that many factors influence the resilient behavior of fine-grained soils. Careful engineering consideration must be given to determining what resilient properties (subgrade support values) should be utilized in the analysis and design of concrete pavements.

Temperature-Soil Property Effects

The number of published reports pertaining to temperature effects on pavement systems has grown to vast proportions. In a recent review of literature, Johnson (12) has referenced more than 800 publications which deal either entirely or partly with problems of soil freezing and frost damage. Lovell and Herrin (13) summarized much of the earlier knowledge on soil freezing and related frost problems. Researchers such as Dempsey (14), Christinson (15), and Berg (16) have referenced many of the more recent publication concerned with temperature effects on pavement systems.

A recent International Conference Proceedings (17) was devoted solely to the topic, "Effects of Temperature and Heat on Engineering Behavior of Soils." Lower strengths are generally associated with higher temperatures (17). Sherif and Burrous (18) have cited several references that substantiate this concept and their experimental data also support the concept.

Murayama (19) has demonstrated the effect of temperature on the elastic properties of a clay soil. He found that the elastic moduli measured within the limit of critical strain decreased with an increase in temperature. Data presented by Mitchell (20) indicated a moderate effect of temperature on stress-strain properties of remolded San Francisco mud.

Studies conducted by the Corps of Engineers (21) indicated that the dynamic modulus of materials ranging from clay to gravel display moderate to substantial increases when frozen. Dynamic modulus values ranging from 1 million to 3 million psi were common for the frozen materials.

Temperature and frost action effects on pavements and subgrades have been documented by Dempsey (22), Thompson (23), and Thompson and Dempsey (24). These factors have substantial influence on subgrade strength properties because of their influence on water content changes.

CLIMATIC EFFECTS ON PAVEMENT SYSTEMS

Climatic factors having the most influence on the behavior and performance of rigid pavement systems are temperature and moisture. Periodic and cyclic variations in temperature and moisture can have substantial influence on the behavior and performance of the structural section and the underlying subgrade to a considerable depth below the pavement surface. Dempsey (22) has cited numerous examples of how temperature and moisture affect the behavior and performance of pavement systems.

Extensive plate loading field test studies for several states in freezing zones have shown that spring bearing values are substantially less than fall values. The load carrying capacity (30 in. plate, 0.1 in. deformation) of concrete runways studied by Linnel and Haley (25) were reduced, during the spring frost melting period, to approximately 70 percent of the normal load carrying capacity.

Darter and Barenberg demonstrated in their "Zero Maintenance" study (26) that the "climatic regional factor" (RF) for performance based thickness design of plain jointed concrete pavements varied from 0.43 for dry/non-freeze areas to 0.93 for wet/freeze areas. Note that the major climatic factors considered were moisture and temperature effects.

Ring (27) has indicated that spring subgrade bearing strengths in the northern states range from 30 percent to 100 percent of the fall values, Figure 9. The influence of degree of saturation on the elastic modulus of subgrade reaction for selected AASHO Road Test subgrade locations (28) is shown in Figure 10. Note the similarity between Figure 10 and Figure 7 which illustrates the effect of degree of saturation on resilient behavior.

Jessberger and Carbee (29) found that for many silt and sand soils CBR was reduced by an average of 64 percent after freeze-thaw cycling. For several of the silt soils the CBR reduction was greater than 90 percent after freeze-thaw cycling.

On the Catskill-Cairo experimental rigid pavement test in New York (30), the plate bearing test comprised the major effort in field strength testing. For all subgrade tests the variation (σ = 1024 pci) in plate bearing modulus was greater than the average ($\overline{X}$ = 845 pci) value. The subgrade encountered included rock, earth, and skimming cuts; earth and skimming fills; and transitions. The high degree of variability in the plate bearing values was attributed to non-uniformity and discontinuities in the subgrade and to variations in the ground water level and soil moisture content. Based on the study it was felt that the wide variations and lack of correlation demonstrated by the data placed doubt on the value of the plate bearing test for evaluating subgrades.

Cumberledge, Cominsky, and Bhajandas (31) related pavement surface deflection measured with the Road Rater to the moisture content in the base and subgrade and to precipitation in Pennsylvania. They found that the deflection generally increased as the moisture content increased, except during the winter months when the deflection was constant due to the frozen condition of the pavement base and subgrade.

Pumping, a major problem related to rigid pavement performance, is associated with excessive moisture contents in the support materials beneath the slab. All failures in the rigid pavement sections at the AASHO Road Test were preceded by pumping of material from beneath the concrete slab (32). Both Yoder (33) and Cedergren (34) noted damage to airport runways and taxiways caused by pumping. These observations were especially prevalent where pavement overload and channelized traffic had occurred.

Most studies of moisture conditions in pavement systems indicate that moisture content varies with seasons, climatic conditions, geographic location, and type of pavement system. Low and Lovell (35) concluded from their study of current literature that the moisture contents show continuous, if small, variation with the seasons. Based on a long term study of moisture conditions beneath rigid pavements in Missouri, Guinnee and Thomas (36) demonstrated that moisture variations in the top levels of the subbase and subgrade were greater than those noted at deeper levels. Chu and Humphries (37) found that moisture contents in pavement systems in South Carolina varied with season, soil type, and location in the pavement system, and that the subgrade moisture content was influenced by the depth of the ground water table.

Marks and Haliburton (38), based on a short term study of typical Oklahoma highways, concluded that most moisture variations occur beneath highway pavements on an annual cycle with maximum moisture contents occurring during the winter months. Hicks (39) found that for 20 stations in North Carolina the moisture contents for the bases and subgrades were highest during later winter or early spring.

Frost action effects accentuate pavement system moisture content increases. Road Research Laboratory studies (40) indicate a significant increase (1 to 3 percent) in granular base moisture content due to frost action. Stevens, Maner, and Shelburne (41) observed that spring pavement breakup in Virginia could be related to the amount of fall precipitation and the length of the freezing period.

Observations by Turner and Jumikis (42) showed that moisture content beneath a pavement was affected by the ground water table. They found that more water from melting snow precipitation percolated into the ground than if the precipitation was in the form of rain.

CURRENT PROCEDURES FOR EVALUATING SUBGRADE SUPPORT

Several procedures have been utilized for evaluating subgrade support for rigid pavement design and analysis purposes. Typical procedures are discussed below:

Modulus of Subgrade Reaction

The most widely used procedure is to conduct a plate test and then calculate a "modulus of subgrade reaction." ASTM D1195 (AASHTO T221) and D1196 (AASHTO T222) provide details for repetitive and non-repetitive plate load tests, respectively. Details concerning the conduct of plate loading tests for Department of Defense Agencies and the Federal Aviation Agency are given in Reference 43.

A 30-inch diameter plate is used in all of the test procedures. The modulus of subgrade reaction, k, can be calculated from the plate loading test results. The Portland Cement Association (PCA) (44) defines k as the ratio of the plate load (in psi) to the displacement of the bearing plate (in inches). PCA suggests calculating k for a plate displacement of 0.05 inches. The Corps of Engineers procedure (43) utilizes the displacement for a 10 psi plate pressure. The concept of an "elastic k-value" (k_E = unit load divided by the elastic deformation during repeated plate loading) was utilized at the AASHO Road Test (28) in addition to the "gross k-value" (k_G = unit load divided by the maximum gross deflection.). The Road Test data indicated that $k_E = 1.77\ k_G$.

A major consideration in conducting a plate bearing test is the state of the soil at the time of test. Moisture content and density variations in the soil will have a significant effect on the k value determined as illustrated by Figure 10. Corps of Engineers procedure (43) suggests that, "For a better evaluation, a correction for subgrade saturation should be considered." The correction technique suggested is based on a consolidation type test in which undisturbed subgrade samples are evaluated at the "in-situ water content" and the "saturated" condition. The field k value is adjusted in proportion to the ratio of the consolidation deformations (at 10 psi) for the "in-situ" and the "saturated" specimens as shown below:

$$k = \frac{d}{d_s} \times k_u \qquad (2)$$

where

k = subgrade modulus corrected for saturation and bending of the plate,
k_u = subgrade modulus, uncorrected for saturation, but corrected for bending of the plate when necessary,
d_s = deformation of a standard specimen under a unit load of 10 psi in inches, and
d = deformation of a specimen at field conditions under a unit load of 10 psi in inches.

Note: The value of $\frac{d}{d_s}$ is limited to less than one.

Questionnaire data summarized in NCHRP Report 128 (45) indicate that of the 55 highway agencies surveyed, the plate bearing test was not used by any group for establishing "subgrade support." However, NCHRP 128 does indicate that two states "measure the subgrade k-value directly in the field."

Other Strength Based Procedures

The NCHRP 128 survey (45) indicated that nineteen agencies used CBR, 10 used R-value, and 5 used triaxial procedures for evaluating subgrade support.

Some agencies utilize CBR tests (ASTM D1883, AASHTO T193) for evaluating subgrade support for rigid pavement analysis and design. For example, the British (46) classify subgrades into three groups (weak, normal, and very stable) based on CBR value and the depth to water table. The classification scheme is shown in Table 1.

The AASHO Interim Guide (47) indicates, "the k value may be estimated on the basis of previous experience by correlation with other tests." No particular reference is made regarding a preferred correlation(s).

The Illinois Department of Transportation procedure for selecting subgrade support (48) indicates, "The soil support CBR value selected for use by the designer should represent a minimum value for the soil to be used." It is recommended that a soil survey be made and laboratory tests be conducted with the "soils to be used in construction." To establish a k value for the IDOT pavement design scheme (AASHO Road Test based procedure), the k value is correlated with CBR as shown in Table 2.

The R-value test (ASTM D2844, AASHTO T190) is widely used in the western United States. California has pioneered in developing the R-value procedure. Six states (45) use the R-value - k correlation shown in Figure 11.

Correlation With Non-Strength Parameters

Many correlations have been developed for estimating soil support values based on soil classification data. The NCHRP 128 survey (45) indicated that 9 state highway departments used group index (AASHTO Soil Classification) and 12 used other non-strength test procedures. PCA (44) has summarized some of the classification correlations as shown in Figure 12.

Correlations used by the Illinois Department of Transportation (48) are shown in Table 2. A CBR-k relation, Table 2, is used to convert from CBR to k.

General relations between Unified Soil classification and k have been established by the Corps of Engineers (43). The relations are summarized in Table 3.

Summary

There are many procedures utilized to determine the k value for use in rigid pavement analysis and design. Plate bearing tests, correlations between k and other strength parameters, and correlations with non-strength parameters are available.

In general, it appears that little specific guidance is provided in most design procedures concerning the technique to be used for properly assessing anticipated subgrade support conditions. It seems that the evaluation of subgrade support is not considered to be an item of major significance, although "uniformity of support" is frequently indicated to be a major consideration.

RIGID PAVEMENT RESPONSE AND PERFORMANCE

Rigid pavement design procedures generally incorporate design criteria related to concrete flexural stresses and concrete fatigue. Westergaard and, to a limited extent, layered elastic system structural analyses, are normally utilized to predict the concrete stresses. In most instances, Westergaard analyses are based on the assumption of a "dense liquid subgrade" (Westergaard modulus of subgrade reaction, k). It is also possible to utilize an elastic solid subgrade assumption. According to Packard (44) the modulus of subgrade reaction is used most frequently. Packard further states:

> "The dense-liquid subgrade assumption results in computed stresses that are somewhat higher than measured stresses. These differences are not great in most cases. The computed stress is on the conservative side and is suggested for design purposes. When the elastic-solid assumption is used, theoretical stresses closer to measured values are obtained, provided the proper value for the subgrade modulus is used. However, there are practical difficulties in determining the elastic constants from soil test data or plate-load tests."

Relative to actually conducting plate bearing tests for evaluating k, Yoder and Witczak (49) state, "This test is very time consuming and except for special cases, is rarely performed for design of highway pavements."

Modulus of Subgrade Reaction Effects

Figure 13 illustrates the effect of k on concrete flexural stresses and deflections (concrete thickness of 8 inches, concrete modulus = 3.5×10^6 psi, Westergaard interior loading condition). Note that although the effect of k on stresses is minor there is a very pronounced effect of k on pavement deflections. Increasing k from 50 psi/in to 5000 psi/in decreases the concrete flexural stress from 202 psi to 158 psi but the deflection decreases from 0.0119 inch to .0036 inch. It is apparent that pavement deflection is quite sensitive to subgrade support.

Deflection Considerations

Several studies have demonstrated the relation between rigid pavement deflection and performance. Brief summaries are presented below:

AASHO Road Test - Two deflection-performance equations were developed from the AASHO Road Test data (28). Equations 3 and 4 were established for static edge and corner deflections as shown below:

$$\overline{\log w_{2.5}} = 0.74 - 3.15 \log d_e \qquad (3)$$

$$\log w_{2.5} = 0.95 - 3.29 \log d_c$$

$w_{2.5}$ = number of wheel load applications until the pavement reaches a present serviceability index of 2.5
d_e = static edge deflection (inches) corrected to a constant temperature condition
d_c = static corner deflection (inches) corrected to a constant temperature condition

Indiana CRCP Study - Faiz and Yoder (50) have reported the findings of a study of continuously reinforced concrete pavements in Indiana. The study results indicated a "Significant difference in pavement deflection between good and failed locations within a test section". Average pavement deflection in the "good" locations was about 58% of the average deflection at "failed" locations. It is particularly interesting to note that the study data did not indicate any "significant differences in subgrade CBR" between the "good" and "failed" locations.

WES Studies for Wide-Body Aircraft - Hutchinson (51) has summarized the results of several Waterway Experiment Station studies. Highlights (relative to deflection) are listed below:

1) The results of the MWHGL test track series prompted the following statement:

> "Thus, while the practice of increasing the number of wheels and wheel spacing achieves lower concrete stresses and thinner pavements, it draws attention to either the increased need for stronger and higher quality foundations or the use of a limiting deflection criteria for pavement thickness determination."

2. The structural layer test track performance data indicated the improved performances of keyed longitudinal construction joints when deflections were reduced. "Excessive deflection and the working of joints under the rolling loads" apparently were responsible for longitudinal joint spalling observed in 15-inch concrete pavements constructed over polystyrene or lightweight concrete insulating layers.
3. Hutchinson concluded by stating, "More attention to limiting deflections of the pavement system is essential to improve performance in intensely trafficked areas."

Design Guide Information

Several design guides recognize the significance of deflection relative to joint behavior and performance. The Federal Aviation Administration (52) recommends special longitudinal construction joints (doweled or thickened edge) for low-strength foundations (k less than 200 psi/in). PCA recommendations (44) for heavy-duty airport pavements also indicate the possible need for special longitudinal jointing techniques if the k value is less than 400 psi/in. In fact, PCA suggests (53) that for highway pavements, "the main function of stabilized subbases with respect to joint design is to reduce potential joint deflection."

CLIMATIC PREDICTION FOR PAVEMENT ANALYSIS AND DESIGN

The general response of a rigid pavement to given traffic loading is controlled by the thickness of the various structural layers, the significant engineering properties of the paving materials, and the subgrade soil. It is apparent that if the engineering properties of the soils and materials are affected by temperature or moisture, pavement response and thus performance will likewise be influenced. Predicting temperature and moisture content in the pavement system as a function of time and space is thus needed in an adequate rigid pavement analysis and design process.

Temperature Prediction

Procedures for predicting temperature distributions in pavement systems have been described by Dempsey (22). A heat-transfer model developed by Dempsey (14) and Dempsey and Thompson (54) found widespread use in predicting temperatures and frost line locations in rigid pavement systems. Procedures for quantitatively describing frost action in pavement systems have been described by Thompson and Dempsey (55).

Moisture Prediction

The Organization for Economic Cooperation and Development (OECD) (56) has indicated that the general methods for predicting moisture movement and moisture equilibria in pavement systems can be placed into two categories as follows:

1. Empirical methods based on experience and field studies.
2. Theoretical methods based on the equations governing moisture conditions in porous materials.

Empirical Methods - The Thornthwaite moisture index, which relates subgrade moisture conditions to climatic indices, has been a popular means of empirically estimating moisture conditions in pavement subgrade soils (57). The Thornthwaite moisture index is positive for subgrades with high moisture content and negative for subgrades with low moisture contents.

OECD (56) has summarized numerous relationships between water content and soil characteristics such as plastic limit, liquid limit, and particle size.

Theoretical Methods - In studies of moisture movement and moisture equilibria, it is evident that experience and empirical relationships will often be inaccurate and impractical because of the rapidly changing climatic conditions which generally occur and influence pavement systems. It becomes apparent that formal mathematical procedures based on thermodynamic principles which incorporate the necessary daily environmental boundary conditions of a given geographical area are needed.

A rational method based on the thermodynamic theory of equilibrium distribution of water in a porous body has been developed by researchers of the British Road Research Laboratory (58). The procedure for using the rational method has been described in a report prepared by the OECD (56). The method is based on three principles as follows:

1. The trend in pore water pressure, under certain conditions at a given level of the subgrade, is towards an equilibrium value depending solely on the height above the ground water level.
2. The existence of a relation between the pore water pressure in the soil at a given level and the suction of the soil.
3. The existence of a relation between the suction and the water content of the soil.

The conditions for equilibrium to be reached depend upon the following:

1. The temperature of the subgrade is constant, uniform, and above freezing.
2. The subgrade cannot receive moisture by infiltration through the highway pavement or by migration from adjacent soil masses with a higher pore water pressure, nor can it give up moisture by evaporation or migration to adjacent soil masses having a lower pore water pressure.

In the rational method the pressure of the pore water at any given level must tend towards an equilibrium which cancels out the algebraic sum of the various water potentials. The British Road Research Laboratory (58) expressed the equilibrium condition as follows:

$$u = -Z \tag{5}$$

In Equation 5 u is the relative pore water pressure which is negative above the water table and Z is the height above the ground-water table. Graphically when the same scale is used for pressure u and height Z, the function u = f(Z) is a straight line with slope of 45^{o} regardless of the nature and dry density of the various soil layers making up the mass in question. In principle, estimating the equilibrium pressure profile of a highway subgrade is dependent upon estimating the position of the ground water level after building the highway.

By definition soil moisture tension or suctio· is the value of the pore water pressure of an undisturbed sample which, because of its removal, has been relieved of all external stress. The suction of the soil after removal can be represented by the following equation:

$$s = u - \alpha P \tag{6}$$

In Equation 6 the suction, s, and the pore water pressure, u, are negative. However, s is more negative than u because prior to removal the soil sample was subjected to a vertical pressure, P, caused by the overburden weight of the soil, pavement, and load. When the sample is taken, the stress release causes a volume increase and a corresponding decrease in the pore water pressure. This fact is usually accounted for by the compressibility factor, α, in the expression.

According to the OECD (56), the value of α for a cohesive soil can be obtained from the following approximate formula:

$$\alpha = 0.03\ PI \tag{7}$$

In Equation 7 PI is the plasticity index.

The application of the rational method developed by the British Road Research Laboratory (58) and as described by the OECD (56) for predicting the equilibrium water content in subgrade soil is shown in Figure 14.

The procedure for developing Figure 14 is as follows:

1. Calculate the values of the overburden pressure, P, and the product of αP at the desired depths.

2. For the desired depths determine the equilibrium pore water pressure by Equation 5 and the equilibrium suction by Equation 6.
3. The equilibrium water contents corresponding to the equilibrium suctions determined in 2 above are obtained from the soil water characteristic curve $w_{eq} = f(s)$.
4. The equilibrium water contents for various points in the profile are determined graphically from the $w_{eq} = f(Z)$ relationship.

OECD (56) has indicated that the rational method is a valuable tool for predicting water content of soils even though it has limitations. The fact that it is necessary to determine the applicability of the method by examining the ground water level, permeability of the pavement structure, and climatic factors provide much useful information. However the procedure does provide a means for determining the equilibrium moisture profile in subgrade soil and gives the pavement designer some guidance for choosing strength values which will correlate with subgrade moisture conditions.

Recently Dempsey and Elzeftawy (59) have developed a moisture model for characterizing the transient moisture conditions in subgrade soil for a wide range of boundary conditions. The model is capable of generating data for both one-dimensional and two-dimensional pavement systems for isothermal and non-isothermal conditions. Figure 15 shows a comparison between predicted and measured isothermal moisture contents for a laboratory compacted Illinoian till soil (AASHTO Classification A-4) for a water table condition. It is evident that the moisture model accurately predicts water content in compacted soil. The initial water content of 0.21 cm^3/cm^3 (gravimetric water content = 12.0%) is the optimum water content for the soil. The compacted dry density of the soil was 107.3pcf which was about 88% of AASHTO T-99 dry density.

From Figure 15 is is important to note that the water content with depth in the Illinoian till changed substantially with time from the initial compaction water content. The moisture profile with depth for 60 days is estimated to be close to equilibrium with the water table. The changing moisture conditions with time shown in Figure 14 also occur in the field. Although field compaction may be at optimum moisture content as related to a specified dry density it should be emphasized that after construction the subgrade moisture contents can change substantially depending on the water table depth and climatic conditions. Figure 16 shows these moisture content changes may be even greater if there is a thermal gradient. Figure 16 was developed for the Illinoian till with the same properties specified in Figure 15. The temperature in the soil increased from the top towards the water table at a rate of 0.9 F/in. In Figure 16 it is again noted that the water content with both depth and time have changed considerably from the compacted water content of 0.21 cm^3/cm^3.

Through the use of the procedure developed by the Road Research Laboratory (58) and the model developed by Dempsey and Elzeftawy (59) it is possible to estimate the subgrade water content which would ultimately occur after construction is completed and the pavement system has reached some degree of equilibrium with the climatic conditions and water table position. A certain degree of transient subgrade water content conditions can be expected as climate changes and water table depth fluctuates.

It is because of this variation in subgrade moisture content that strength evaluation for rigid pavement design should be carefully studied. The water content which has substantial influence on strength may be greater or lesser than optimum water content once climate and water table influences have been established. O'Reilly, Russam, and Williams (60) indicated that at maximum dry density the wettest condition under the pavement surface will be wet of optimum if the water table depth is less than 3 feet for sands and about 20 feet for heavy clays. Although surface permeability and climate would have some influence; it would seem, based on this work, that considerable water table depth would be necessary if the optimum subgrade water content is to be maintained.

Russam (61) has shown that effective pavement drainage systems can be used to increase the strength of subgrade soils. In his procedure, the soil CBR is corrected for soil moisture suction as shown in Figure 17. As noted earlier in this report, the soil suction is directly related to the strength of fine-grained soils and is affected by the depth of water table and the overburden pressure. Based on this relationship,

Russam (61) found that the structural pavement thickness could be reduced as the water table is lowered since soil suction and strength will increase.

APPLICATION OF CONCEPTS TO RIGID PAVEMENT DESIGN

Subgrade strength and its variability in relation to intrinsic and extrinsic conditions must be a primary consideration in rigid pavement design and analysis. Parameters which influence subgrade strength, and therefore the performance and serviceability of rigid pavement systems, must be both understood and included in design and analysis procedures.

Temperature and moisture are two important parameters influencing pavement subgrade support. Temperature models have been developed to the extent that accurate predictions of temperature with respect to time and position in the pavement system can be accomplished. Some models also have the advantage of predicting pavement and soil temperatures and their variability based on many years of local climatic data. Quantitative data (number of freeze-thaw cycles, temperature profiles, depths of frost penetration, etc.) obtained from temperature models can be used to refine subgrade strength evaluation procedures.

Similarly, with the advent of moisture prediction models and programs, it is possible to more accurately quantify the moisture regime in subgrade soils with reference to soil type, ground water position, soil hydraulic properties, and climate. The influence of moisture content on the strength and stiffness properties of fine-grained soils is becoming better defined and some usable functional relations have been developed.

Assuming temperature and moisture content predictions can be made as a function of space and time, it should then be possible through the application of appropriate temperature-engineering property and moisture-engineering property relationships to establish subgrade soil support levels and variations. Through the utilization of an adequate structural response model, the effects of varying subgrade support levels can be more accurately assessed. Such capabilities should provide significant improvements in rigid pavement design, analysis, and performance prediction capabilities.

Initial attempts to incorporate seasonal variation of subgrade support into the rigid pavement design process have been made in the "Zero Maintenance" pavement study conducted at the University of Illinois (26). Experience with the suggested procedure should permit further refinements and improvements to be made.

SUMMARY AND CONCLUSIONS

The importance of subgrade support evaluation in the design, analysis, and construction of concrete pavement has been demonstrated. Subgrade soil strength and stiffness properties significantly influence the structural response (concrete flexural stresses, surface deflection) and the performance of concrete pavement systems.

Moisture and temperature are the major climatic parameters that influence soil strength and stiffness. The effects of moisture and temperature factors on fine-grained soil behavior are documented. The necessity of considering variable subgrade support (as a function of time and space) is emphasized.

Techniques for predicting temperature and moisture conditions in pavement systems are considered. Present technology is capable of providing quantitative information for "quasi-rational" selection of subgrade support values.

Application of improved subgrade support evaluation concepts to the rigid pavement design problem is considered. More emphasis must be placed on subgrade support evaluation if the impact of climatic factors (moisture and temperature in particular) and their variability are to be adequately assessed.

REFERENCES

1. Croney, D., Coleman, J. D., and Black, W. P. M., "Movement and Distribution of Water in Soil in Relation to Highway Design and Performance," Special Report 40, Highway Research Board, Washington, D. C., 1958.

2. Sauer, E. K. and Monismith, C. L., "Influence of Soil Suction on Behavior of a Glacial Till Subjected to Repeated Loading," Highway Research Record 215, Highway Research Board, Washington, D. C., 1968.

3. Shackel, B., "Changes in Soil Suction in a Sand-Clay Subjected to Repeated Triaxial Loading," Highway Research Record 429, Highway Research Board, Washington, D. C., 1973.

4. Robnett, Q. L. and Thompson, M. R., "Interim Report - Resilient Properties of Subgrade Soils - Phase 1 - Development of Testing Procedure," Civil Engineering Studies, Transportation Engineering Series No. 5, Illinois Cooperative Highway Research Program, Series No. 139, University of Illinois at Urbana-Champaign, May, 1973.

5. Thompson, M. R. and Robnett. Q. L., "Final Report - Resilient Properteis of Subgrade Soils," Civil Engineering Studies, Transportation Engineering Series No. 14, Illinois Cooperative Highway and Transportation Series No. 160, University of Illinois at Urbana-Champaign, June, 1976.

6. Bergan, A. T. and Fredlund, D. G., "Characterization of Freeze-Thaw Effects on Subgrade Soils," Symposium on Frost Action on Roads, Report Volume II, Organization for Economic Cooperation and Development, Oslo, Norway, 1973.

7. Culley, R. W., "Effect of Freeze-Thaw Cycling on Stress-Strain Characteristics and Volume Change of a Till Subjected to Repetitive Loading," Technical Report 13, Saskatchewan Department of Highways, Regina, Saskatchewan, Canada, September, 1970.

8. Chamberlain, E. J., "A Model for Predicting the Influence of Closed System Freeze-Thaw on the Strength of Thawed Clays," Symposium on Frost Action on Roads, Report Volume III, Organization for Economic Cooperation and Development, Oslo, Norway, 1973.

9. Bergan, A. T. and Monismith, C. L., "Characterization of Subgrade Soils in Cold Regions for Pavement Design Purposes," Highway Research Record 431, Highway Research Board, 1973.

10. Bergan, A. T. and Culley, R. W., "Some Fatigue Considerations in the Design of Asphalt Concrete Pavements," Symposium on Frost Action on Roads, Report Volume II, Organization for Economic Cooperation and Development, Oslo, Norway, 1973.

11. Robnett, Q. L. and Thompson, M. R., "Effect of Lime Treatment on the Resilient Behavior of Fine-Grained Soils," Record No. 560, Transportation Research Board, 1976.

12. Johnson, A. W., "Frost Action in Roads and Airfields," Special Report No. 1, Highway Research Board, Washington, D. C., 1952.

13. Lovell, C. W., Jr. and Herrin, M., "Review of Certain Properties and Problems of Frozen Ground, Including Permafrost," SIPRE Report 9, Purdue University Engineering Experiment Station, Snow, Ice, and Permafrost Research Establishment, Corps of Engineers, U. S. Army, Wilmette, Illinois, 1953.

14. Dempsey, B. J., "A Heat-Transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered Pavement Systems," Ph.D. Thesis, University of Illinois, Department of Civil Engineering, Urbana, Illinois, 1969.

15. Christison, J. T., "The Response of Asphaltic Concrete Pavements to Low Temperatures," Ph.D. Thesis, University of Alberta, Department of Civil Engineering, Edmonton, Alberta, 1972.

16. Berg, R. L., "Thermoinsulating Media Within Embankments on Perennially Frozen Soil," Ph.D. Thesis, University of Alaska, Department of Engineering, College, Alaska, 1973.

17. "Effects of Temperature and Heat on Engineering Behavior of Soils," Special Report 103, Highway Research Board, Washington, D. C., 1969.

18. Sherif, M. A. and Burrous, C. M., "Temperature Effects on the Unconfined Shear Strength of Saturated Cohesive Soil," Special Report 103, Highway Research Board, Highway Research Board, Washington, D. C., 1969.

19. Murayama, S., "Effect of Temperature on Elasticity of Clays," Special Report 103, Highway Research Board, Washington, D. C., 1969.

20. Mitchell, J. R., "Shear Resistance of Soils as a Rate Process," Journal, Soil Mechanics and Foundations Division, Vol. 90, SM 1, ASCE, January, 1964.

21. "Investigation of Description, Classification, and Strength Properties of Frozen Soils," SIPRE Report 8, The Frost Effects Laboratory, Corps of Engineers, U. S. Army, Boston, Mass., 1952.

22. Dempsey, B. J., "State-of-the-Art: Climatic Effects on Airport Pavement Systems," FAA RD-75-196, Federal Aviation Administration, Washington, D. C., 1975.

23. Thompson, M. R., "Environmental Factors and Pavement System, State of the Art," Proceedings, Allerton Park Conference on Systems Approach to Airfield Pavements, Technical Report P-5, Construction Engineering Research Laboratory, Champaign, Illinois, June, 1973.

24. Thompson, M. R. and Dempsey, B. J., "Rational Approach to Freeze-Thaw Durability Evaluation of Stabilized Materials," Accepted for Publication, Transportation Research Board, Washington, D. C., 1976.

25. Linnel, R. A. and Haley, J. F., "Investigation of the Effect of Frost Action on Pavement Supporting Capacity," Special Report 2, Highway Research Board, Washington, D. C., 1952.

26. Darter, M. I. and Barenberg, E. J., "Design Manual for Zero-Maintenance Plain Jointed Concrete Pavements," Final Report, Department of Civil Engineering, University of Illinois @ Urbana-Champaign, July, 1976.

27. Ring, G. W., "Seasonal Strength of Pavements," Public Roads, September, 1974.

28. "The AASHO Road Test, Pavement Research," Special Report No. 61E, Highway Research Board, 1962.

29. Jessberger, A. C. and Carbee, D. L., "Influence of Frost Action on the Bearing Capacity of Soils," Highway Research Record 304, Highway Research Board, Washington, D. C., 1970.

30. Bryden, J. E. and Phillips, R. G., "The Catskill - Cairo Experimental Rigid Pavement: Construction and Materials Testing," Research Report 2, New York State Department of Transportation, Albany, New York, 1971.

31. Cumberledge, G., Cominsky, R. J., and Bhajandas, A. C., "Moisture Variation Beneath Highway Pavements and the Associated Change in Subgrade Support," Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, 1973.

32. "The AASHO Road Test, Report 7," Special Report 61G, Highway Research Board, Washington, D. C., 1962.

33. Yoder, E. J., "Pumping of Highway and Airfield Pavements," Joint Highway Research Project, Purdue University, Lafayette, Indiana, 1946.

34. Cedergren, H. R., "Methodology and Effectiveness of Drainage Systems for Airport Pavements," Technical Report C-13, Department of the Army Construction Engineering Research Laboratory, Champaign, Illinois, 1974.

35. Low, P. F. and Lovell, C. W., Jr., "The Factor of Moisture in Frost Action," Bulletin 225, Highway Research Board, Washington, D. C., 1959.

36. Guinnee, J. W. and Thomas, C. E., "Subgrade Moisture Conditions Under an Experimental Pavement," Bulletin 111, Highway Research Board, Washington, D. C., 1955.

37. Chu, T. Y. and Humphries, W. R., "Investigation of Subgrade Moisture Conditions in Connection with the Design of Flexible Pavement Structures, Research Project No. 523, University of South Carolina, Columbia, South Carolina, 1971.

38. Marks, B. D. and Haliburton, T. A., "Subgrade Moisture Variations Studied with Nuclear Depth Gauges," Highway Research Record 226, Highway Research Board, Washington, D. C., 1969.

39. Hicks, L. D., "Observations of Moisture Contents and Densities of Soil Type Bases and Their Subgrades," Proceedings, Vol. 28, Highway Research Board, Washington, D. C., 1948.

40. Jacobs, J. C. and West, G., "Investigations into the Effect of Freezing on a Typical Road Structure," Report No. 54, Road Research Laboratory, Crowthorne, Berkshire, England, 1966.

41. Stevens, T. C., Maner, A. W., and Shelburne, T. E., "Pavement Performance Correlated with Soil Areas," Proceedings, Vol. 29, Highway Research Board, Washington, D. C., 1949.

42. Turner, K. A., Jr. and Jumikis, A. R., "Subsurface Temperatures and Moisture Contents in Six New Jersey Soils, 1954-1955," Bulletin 135, Highway Research Board, Washington, D. C., 1944.

43. "Materials Testing", Army, TM 5-530; Navy, NAVFAC MO-330; Air Force Manual No. 89-3; 1971.

44. Packard, R. G., "Design of Concrete Airport Pavements," Engineering Bulletin, Portland Cement Association, 1973.

45. Van Til, C. J., et al., "Evaluation of AASHO Interim Guides for Design of Pavement Structures," Report 128, National Cooperative Highway Research Program, Highway Research Board, 1972.

46. "A Guide to the Structural Design of Pavements for New Roads," Road Note 29, Third Edition, Road Research Laboratory, England, 1971.

47. "AASHO Interim Guide for Design of Pavement Structures," American Association of State Highway Officials, 1972.

48. "Design Manual", Illinois Department of Transportation, Division of Highways, Springfield, Illinois.

49. Yoder, E. J. and Witczak, M. W., "Principles of Pavement Design," John Wiley & Sons, Inc., 1975.

50. Faiz, A. and Yoder, E. J., "Evaluation of Parameters Significantly Influencing the Performance of Continuously Reinforced Concrete Pavements," Roadways and Airport Pavements, Publication No. SP-51, American Concrete Institute, 1975.

51. Hutchinson, R. L., "Performance of Concrete Pavements Subjected to Wid-Body Jet Aircraft Loading," Roadways and Airport Pavements, Publication No. SP-51, American Concrete Institute, 1975.

52. "Airport Pavement Design and Evaluation", Advisory Circular No. 150/5320-6B, Federal Aviation Administration, May 28, 1974.

53. "Joint Design for Concrete Highway and Street Pavements," Concrete Information Series, Portland Cement Association, 1975.

54. Dempsey, B. J. and Thompson, M. R., "A Heat-Transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered Pavement Systems," Highway Research Record 342, Highway Research Board, Washington, D. C., 1970.

55. Thompson, M. R. and Dempsey, B. J., "Quantitative Characterization of Cyclic Freezing and Thawing in Stabilized Pavement Materials," Highway Research Record 304, Highway Research Board, Washington, D. C., 1970.

56. "Water in Roads: Prediction of Moisture Content of Road Subgrades," Organization for Economic Cooperation and Development," Paris, France, 1973.

57. Thornthwaite, C. W., "An Approach Toward a Rational Classification of Climate," The Geological Review, Vol. 38, No. 1, 1948.

58. "Estimation of Subgrade Moisture Content," Leaflet L. F. 98, Road Research Laboratory, England, 1967.

59. Dempsey, B. J. and Elzeftawy, A., "A Mathematical Model for Predicting Moisture Movement in Pavement Systems," Accepted for Publication, Transportation Research Board, Washington, D. C., 1976.

60. O'Reilly, M. P., Russam, K, and Williams, F. H. P., "Pavement Design in the Tropics," Road Research Technical Paper No. 80, Road Research Laboratory, England, 1968.

61. Russam, K., "Sub-Soil Drainage and the Structural Design of Roads," RRL Report LR 110, Road Research Laboratory, England, 1967.

Table 1

British Classification of Subgrades for Concrete Pavement Design (Reference 46)

Subgrade Class	Definition
Weak	All subgrades of CBR value 2 percent or less as defined below
Normal	Subgrades other than those defined by other categories
Very Stable	All subgrades of CBR value 15 percent or more as defined below. This category includes undisturbed foundation of old roads

Estimated Laboratory CBR Values for British Soils Compacted at the Natural Moisture Content

Type of Soil	Plasticity Index (%)	CBR (per cent) Depth of water-table below subgrade surface: More than 24 inches	24 inches or less
Heavy clay	70	2	1
	60	2	1.5
	50	2.5	2
	40	3	2
Silty clay	30	5	3
Sandy clay	20	6	4
	10	7	5
Silt	---	2	1
Sand (poorly graded)	non-plastic	20	10
Sand (well graded)	non-plastic	40	15
Well-graded sandy gravel	non-plastic	60	20

Table 2

Illinois Department of Transportation CBR - AASHTO Classification and CBR-k Relations

AASHTO Class	CBR
A-1	20
A-2-4; A-2-5	15
A-2-6; A-2-7	12
A-3	10
A-4; A-5; A-6	3
A-7-5; A-7-6	2

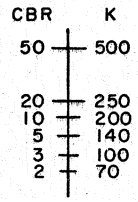


Table 3

Unified Soil Classification - Modulus of Subgrade Reaction Relations (Corps of Engineers, Reference 43).

Unified Soil Classification	Modulus of Subgrade Reaction, psi/in
GW; GP; GM (LL<28, PI<6)	300 or more
GM (LL>28); GC; SW; SP; SM; SC	200-300
ML; CL; OL; MH	100-200
CH; OH	50-100

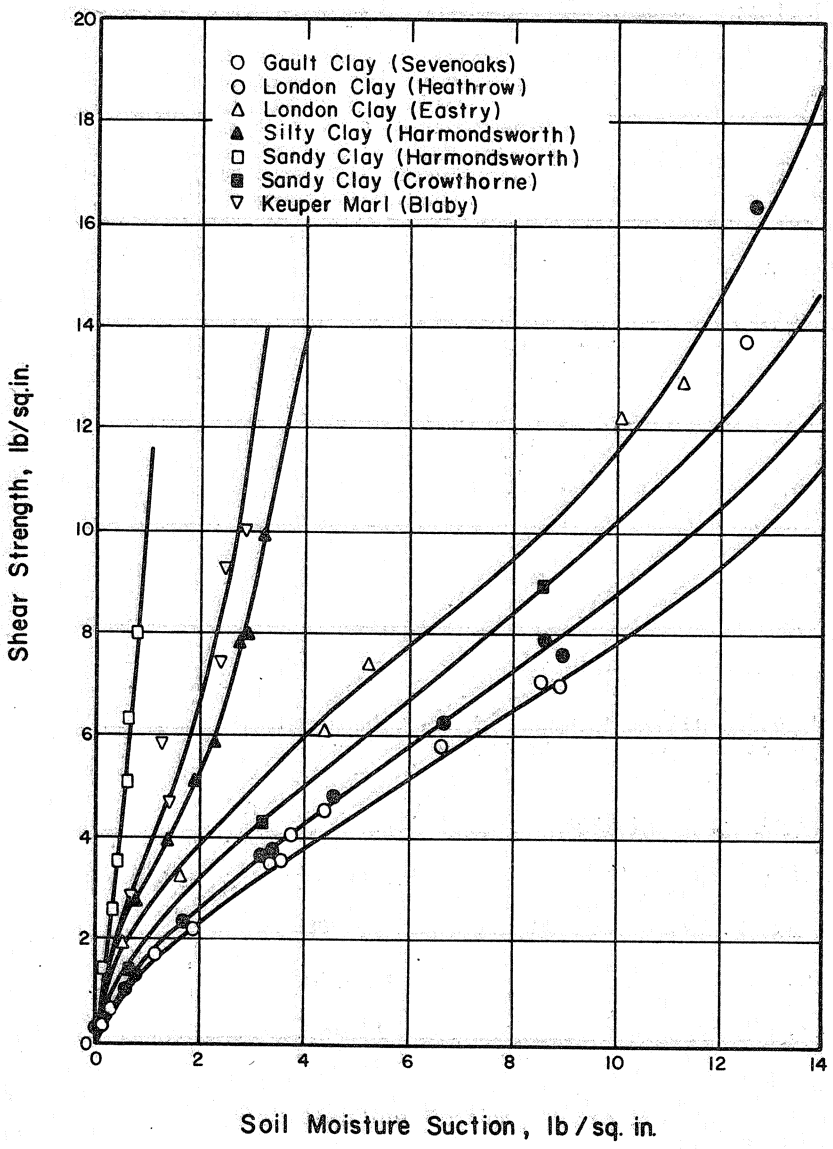


Figure 1. Influence of Soil Suction on Shear Strength (Reference 1).

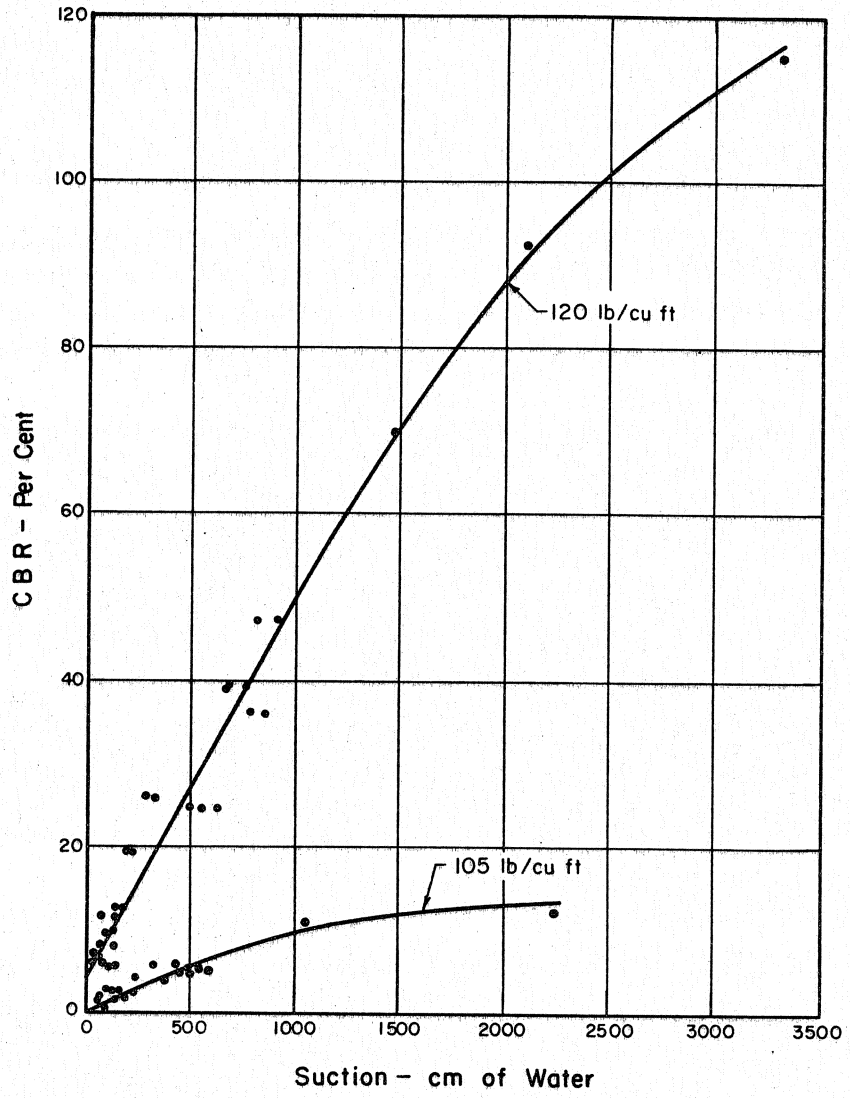


Figure 2. Effect of Suction on the CBR of a Silty Sand (Reference 1).

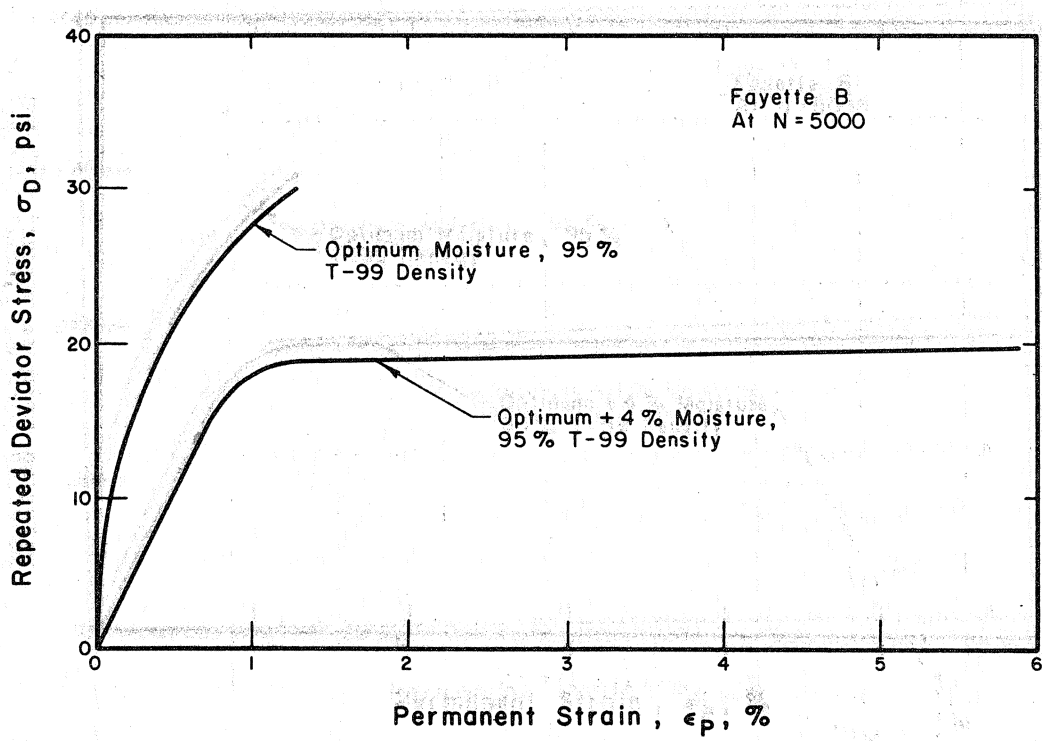


Figure 3. Influence of Moisture Content on the Permanent Strain Response of a Loess-Derived Soil. [AASHTO A-7-6 (23)].

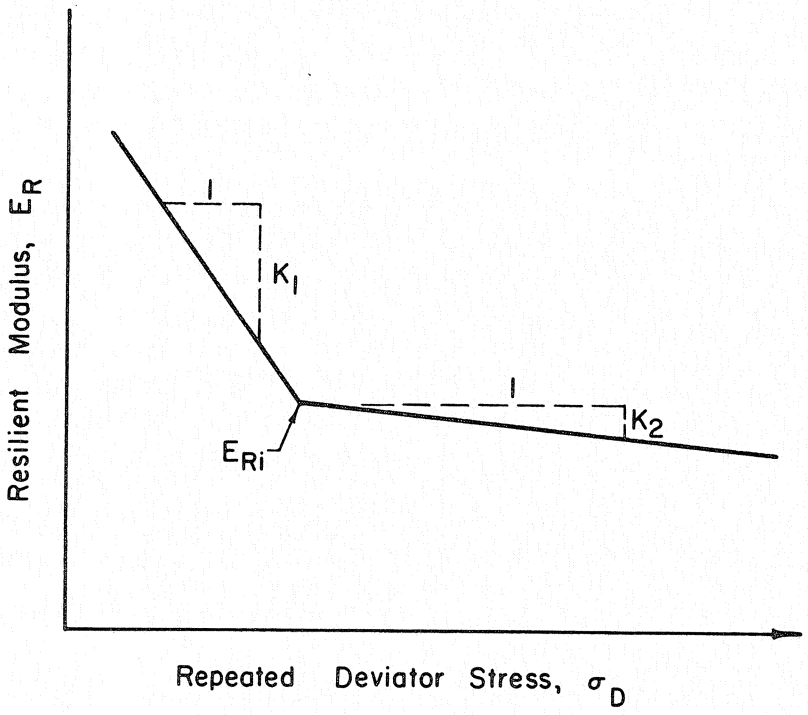


Figure 4. Arithmetic Model for Stress Dependent Resilient Behavior of Fine-Grained Soils.

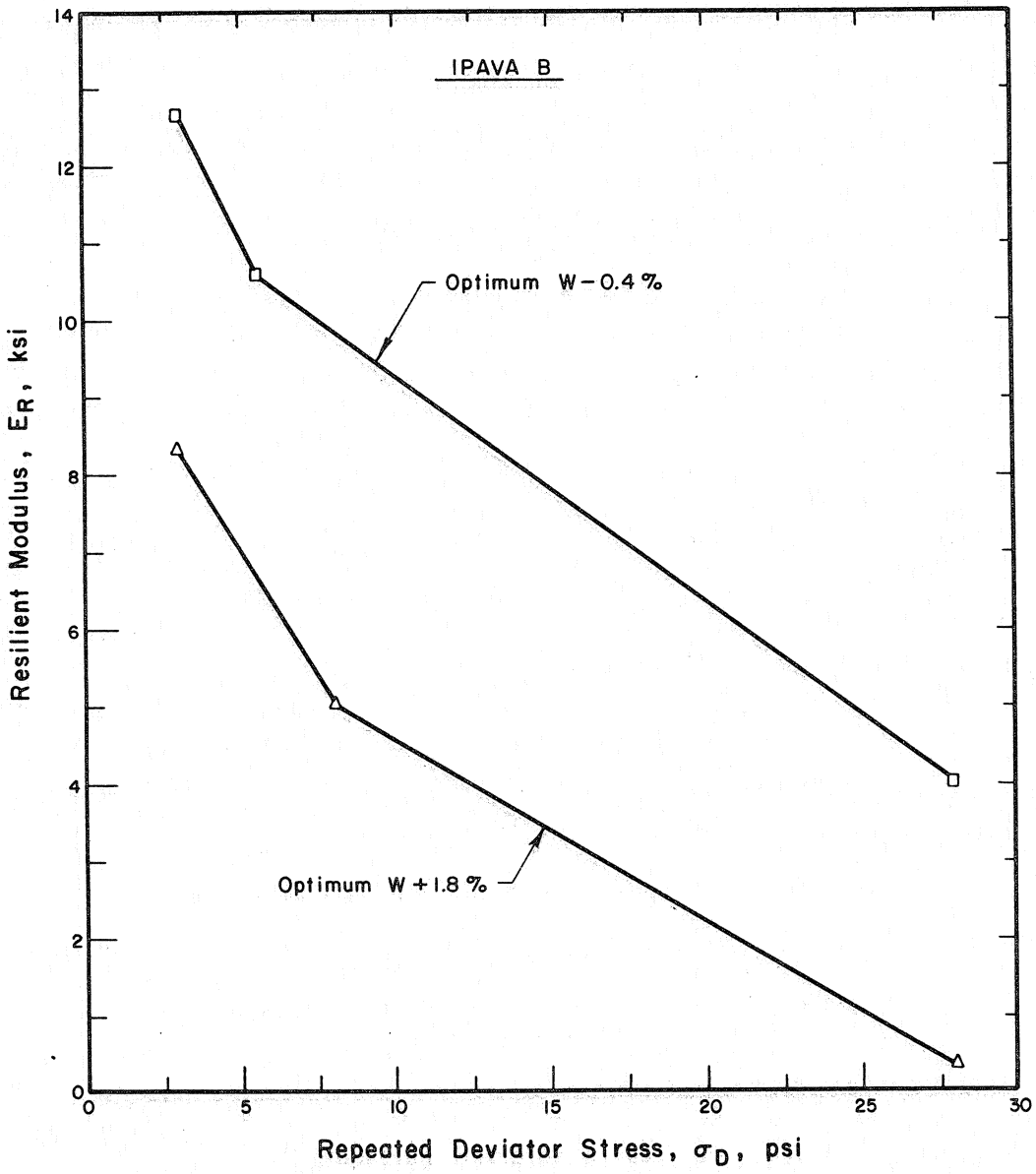


Figure 5. Typical Stress Dependent Resilient Behavior of a Fine-Grained Soil [AASHTO A-7-6(36)].

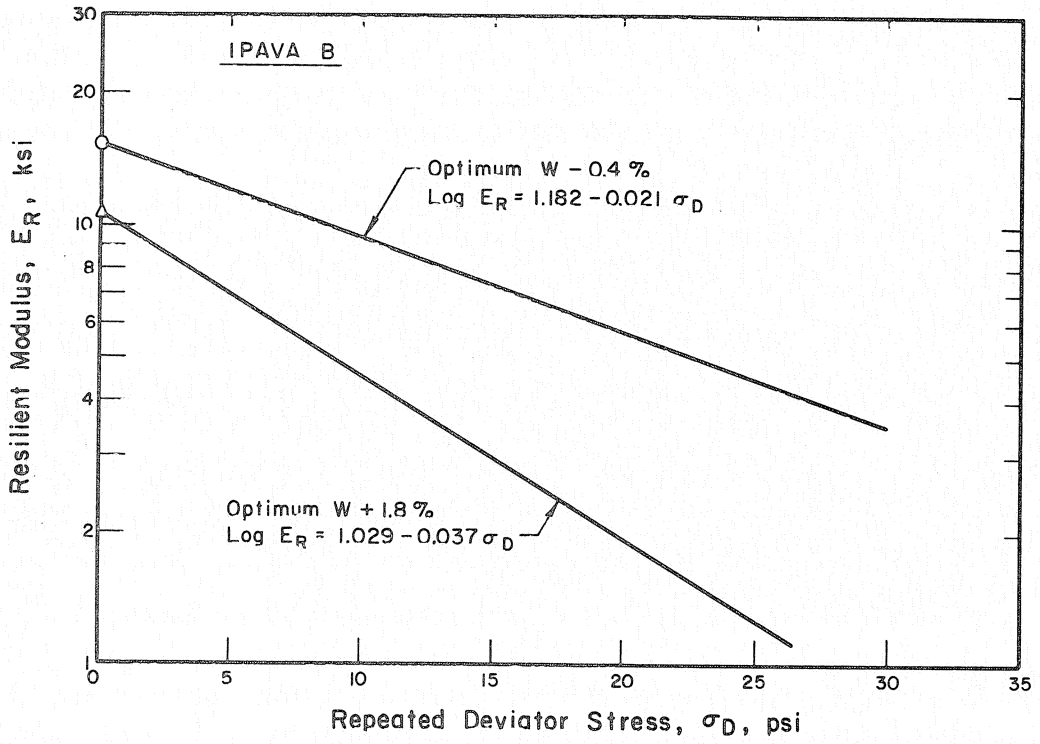


Figure 6. Semi-Log Model for Stress Dependent Resilient Behavior of a Fine-Grained Soil [AASHTO A-7-6(36)].

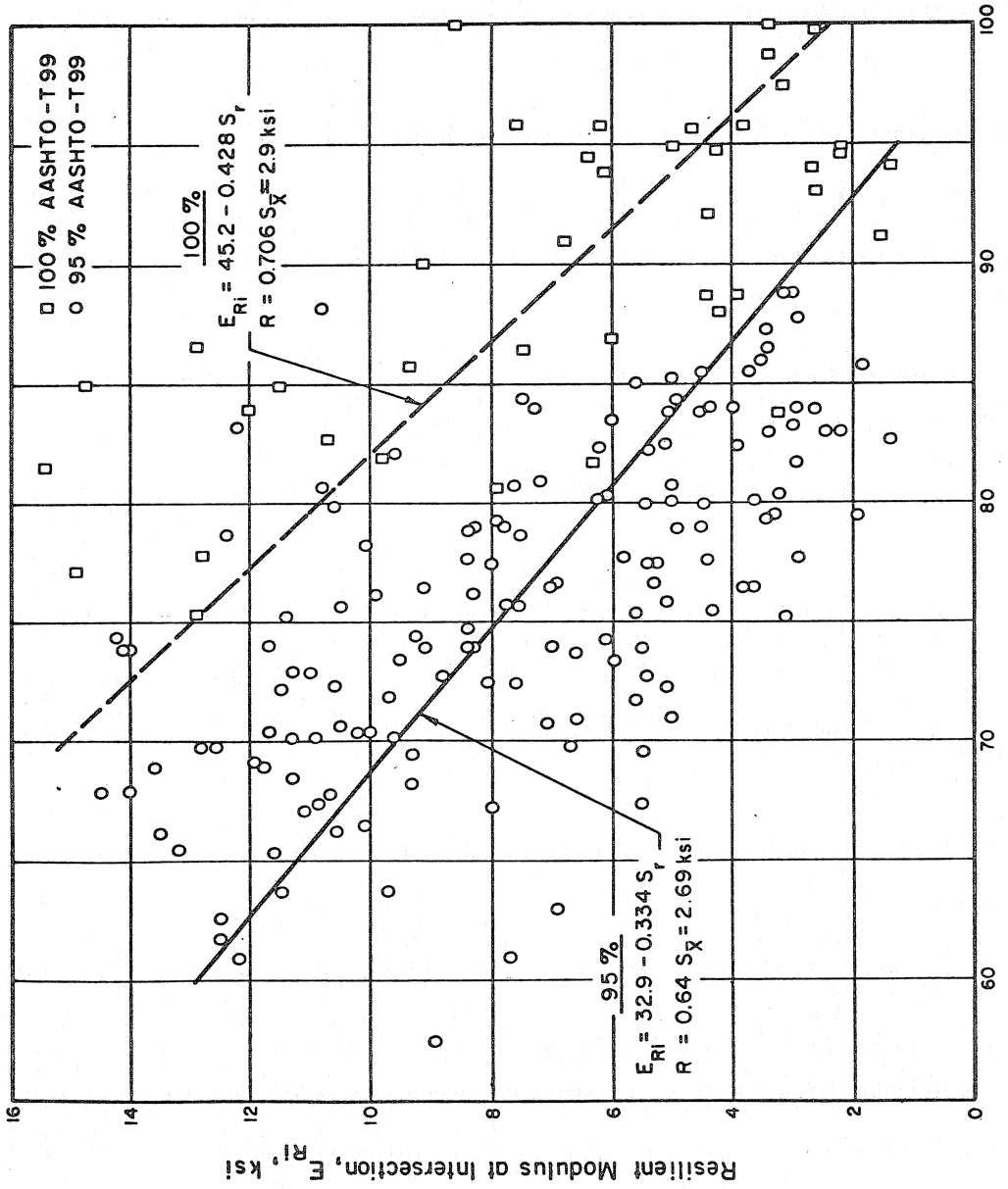


Figure 7. Resilient Modulus - % Saturation Relations for Fine-Grained Soils (Reference 5).

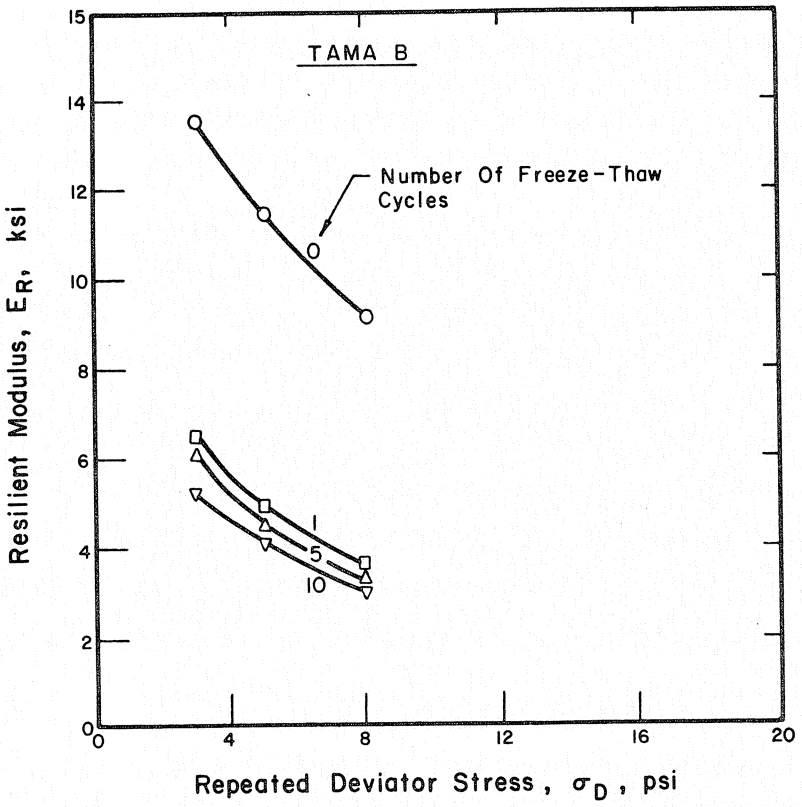


Figure 8. Influence of Cyclic Freeze-Thaw on the Resilient Behavior of a Fine-Grained Soil [AASHTO A-7-6(27)] (Reference 11).

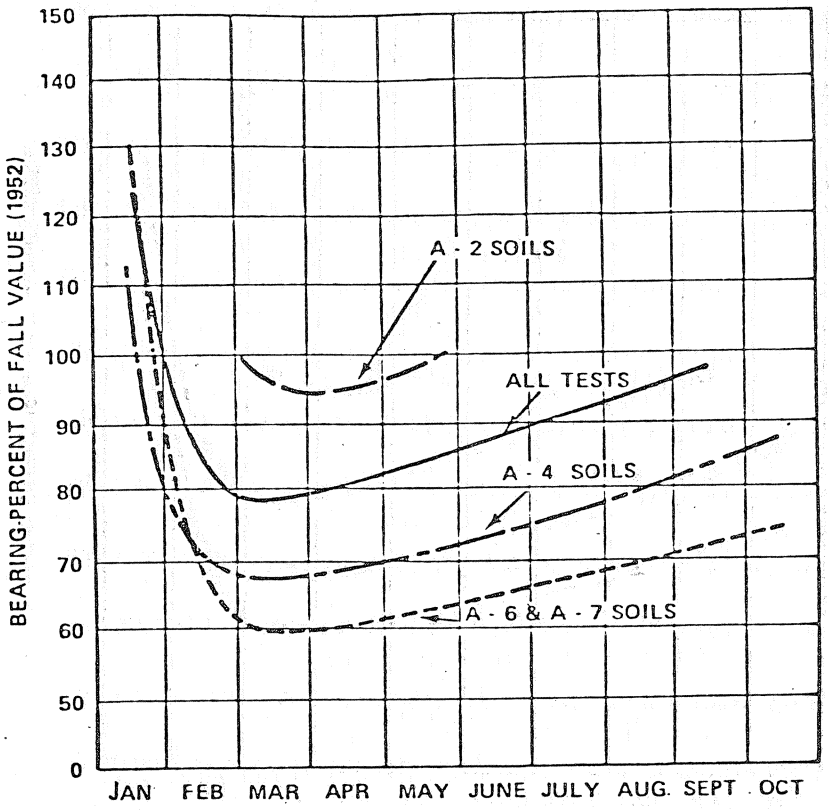


Figure 9. Seasonal Changes in Bearing Capacity (Reference 27).

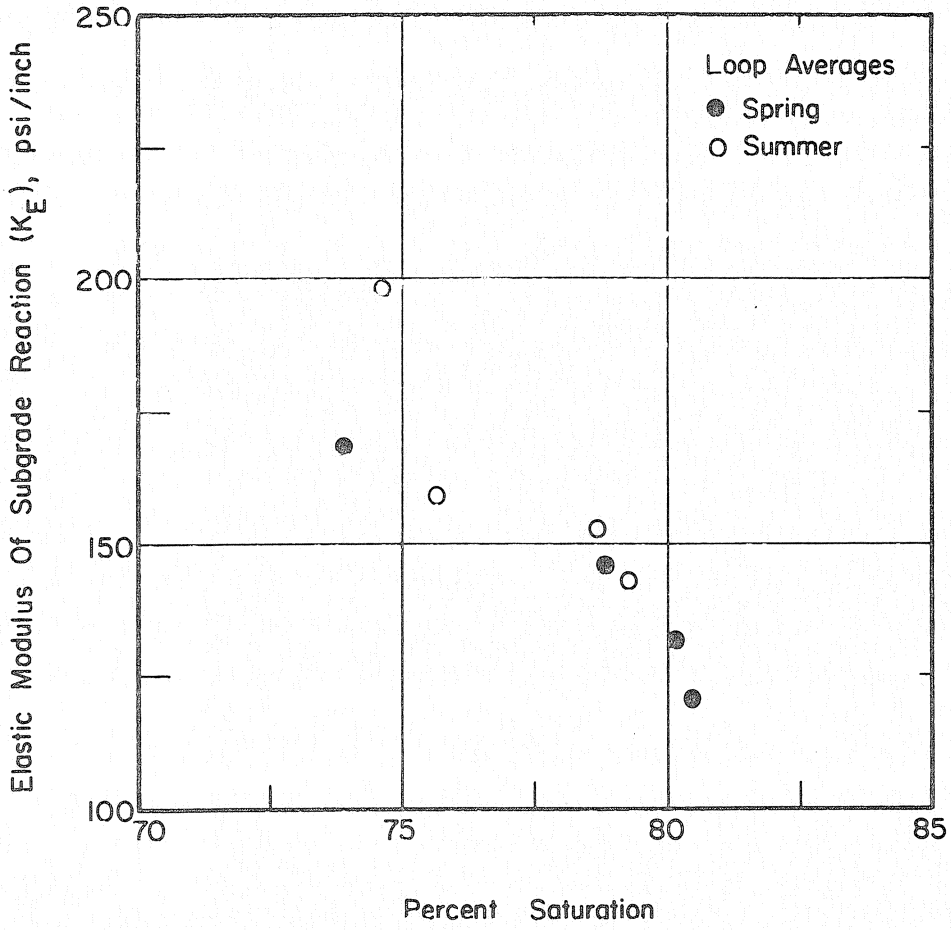


Figure 10. Effect of Percent Saturation on Elastic Modulus of Subgrade Reaction (Reference 32).

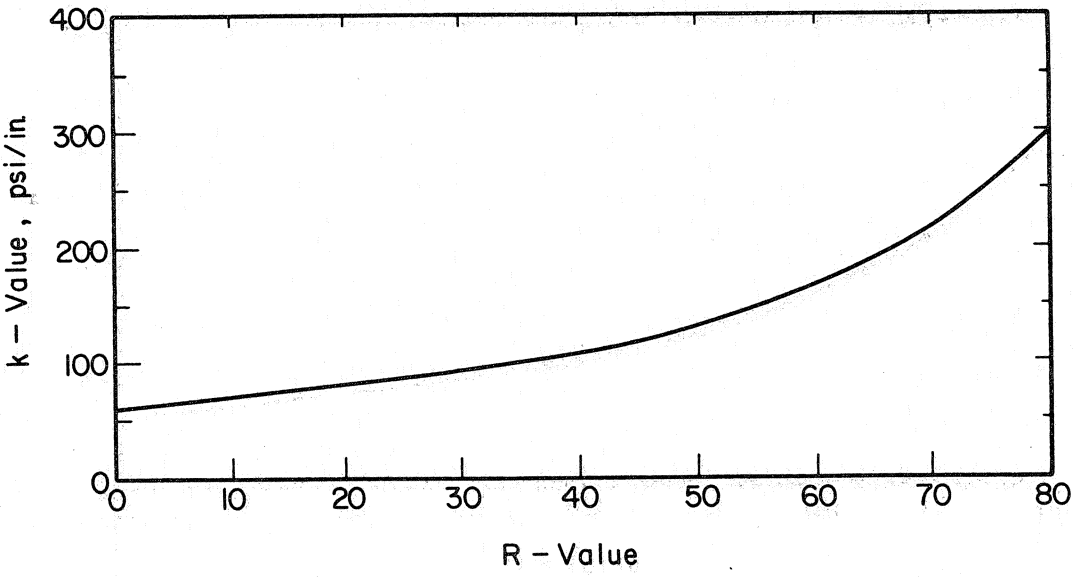


Figure 11. R-k Correlation (Reference 45).

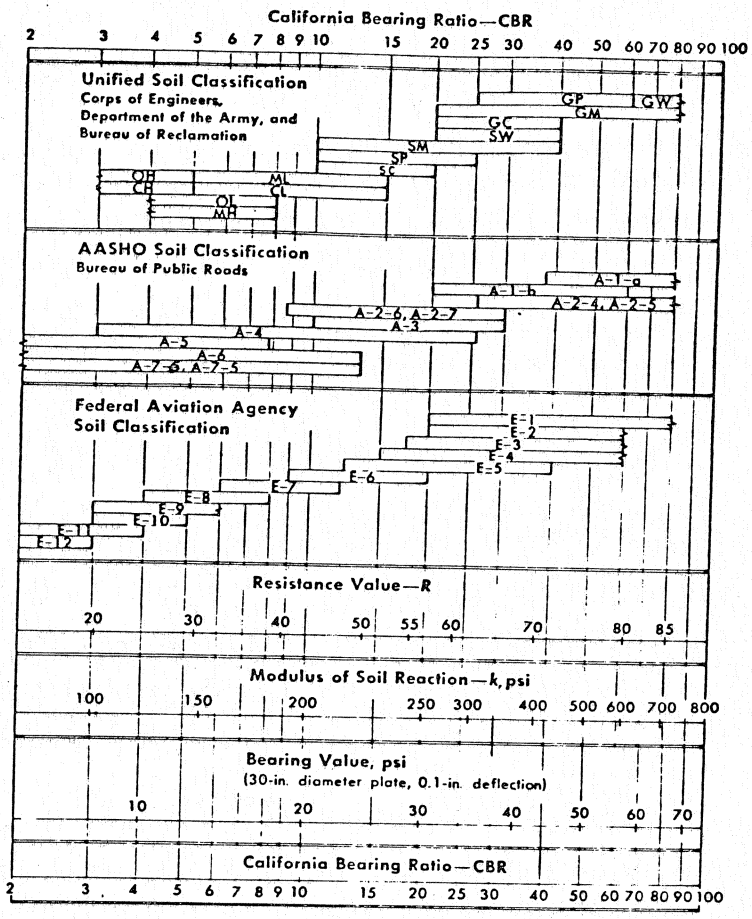


Figure 12. Soil Classification - Soil Strength Correlations (as summarized by the Portland Cement Association, (Reference 44).

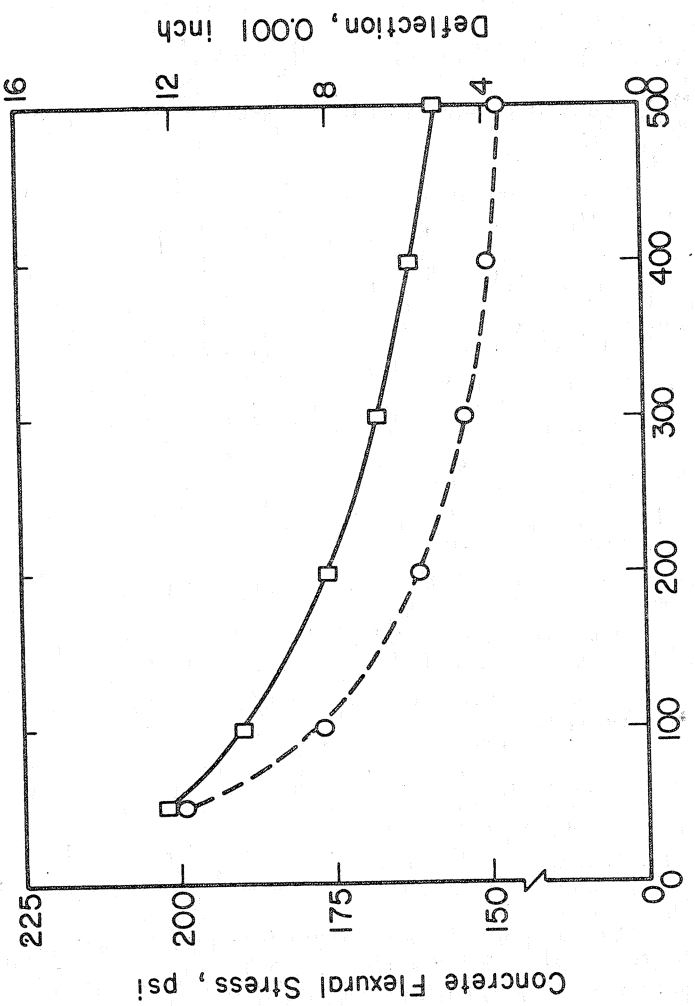


Figure 13. Effect of Modulus of Subgrade Reaction on Concrete Stresses and Pavement Deflections (Interior Loading, Westergaard Theory).

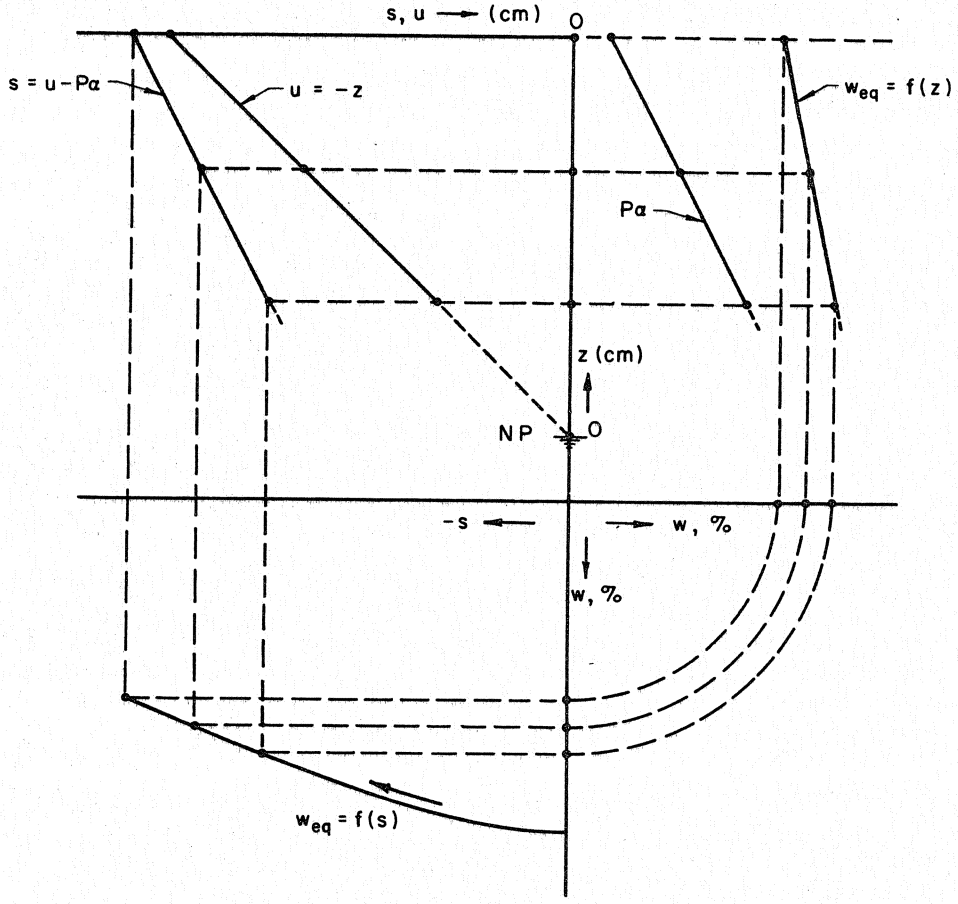


Figure 14. British Road Research Laboratory Method for Determining Equilibrium Moisture Content in Subgrade Soil (Reference 56).

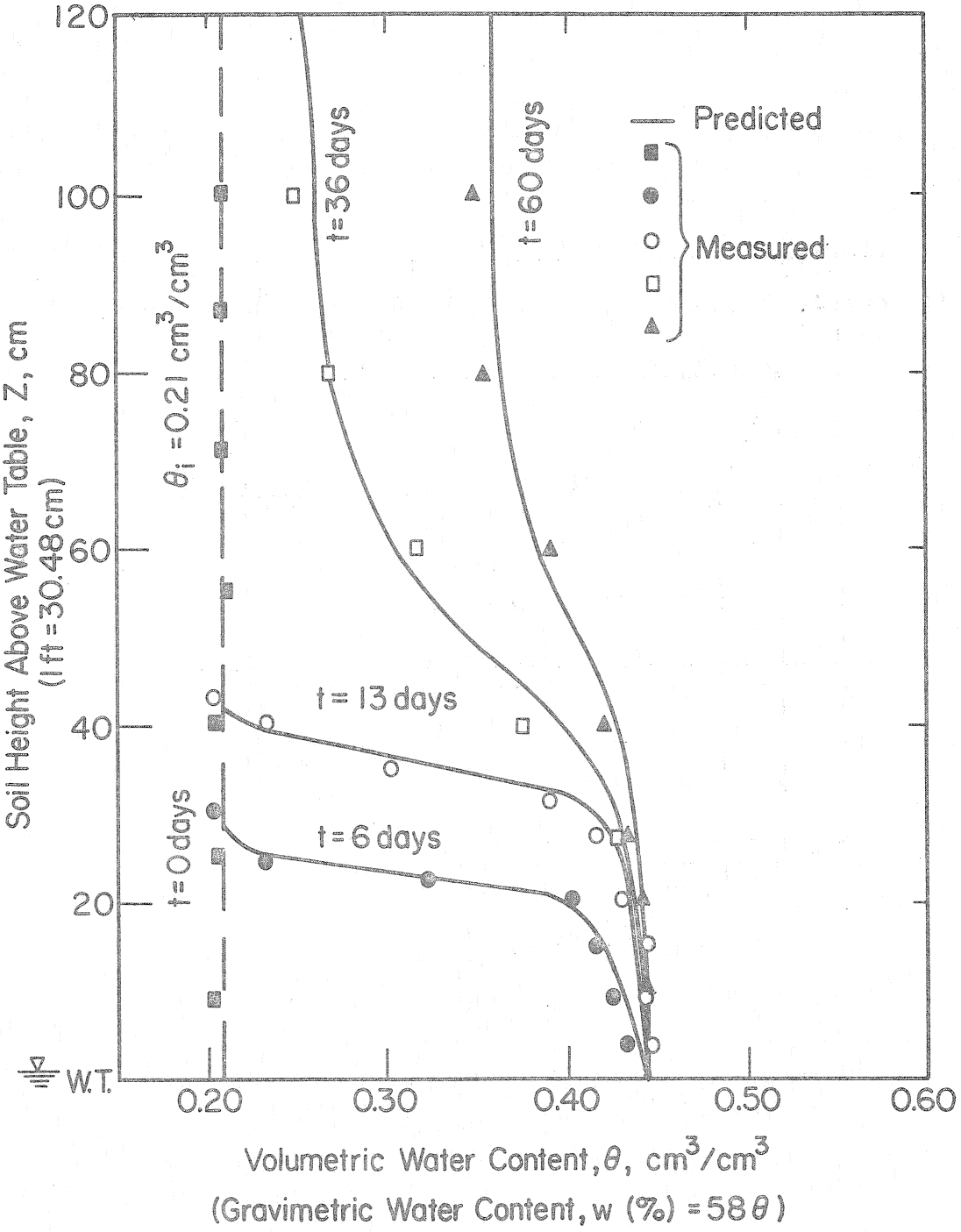


Figure 15. Comparison between Predicted and Measured Moisture Contents for Illinoian Till above a Water Table (Reference 59).

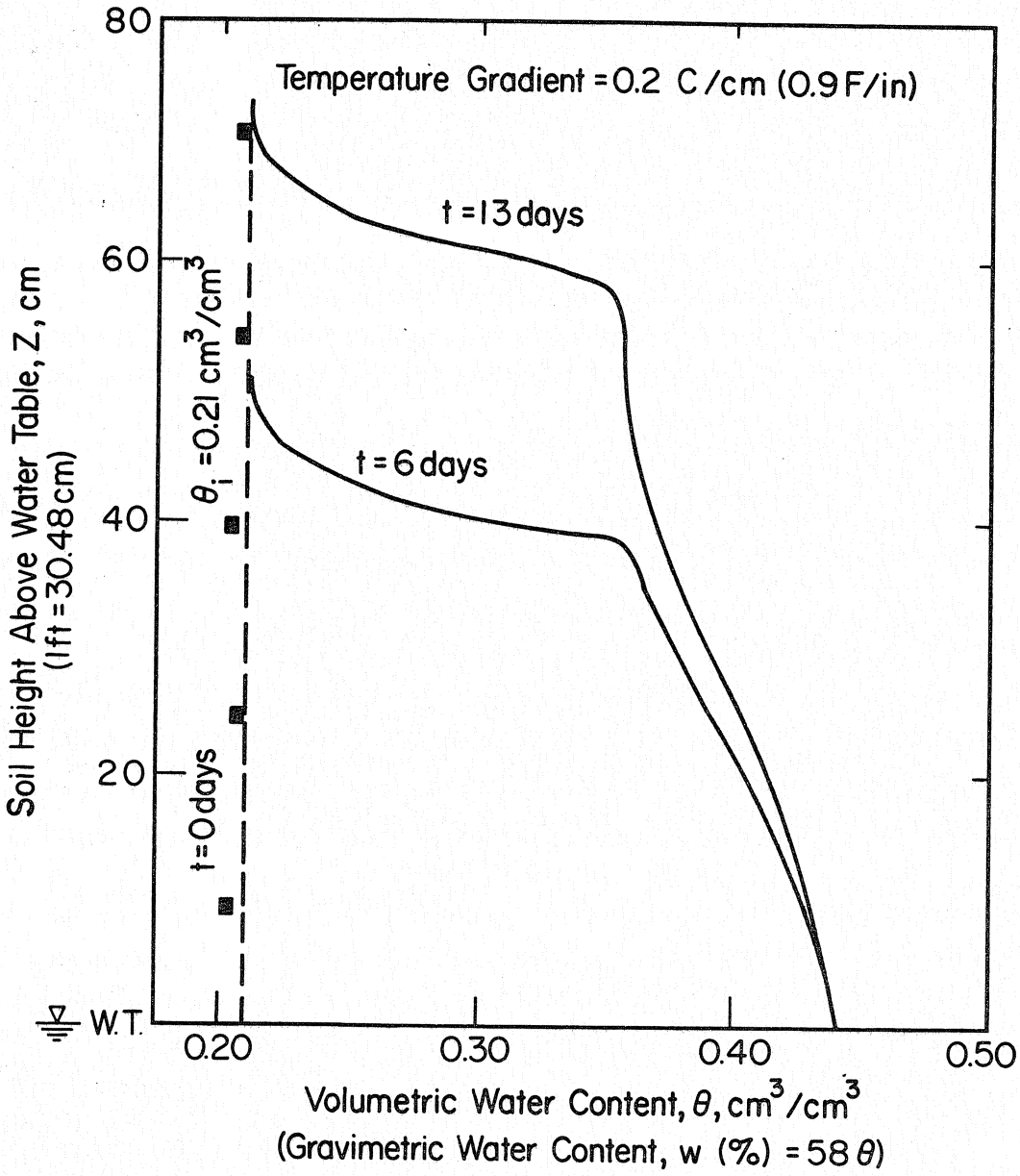


Figure 16. Predicted Nonisothermal Moisture Movement for Illinoian Till above Water Table.

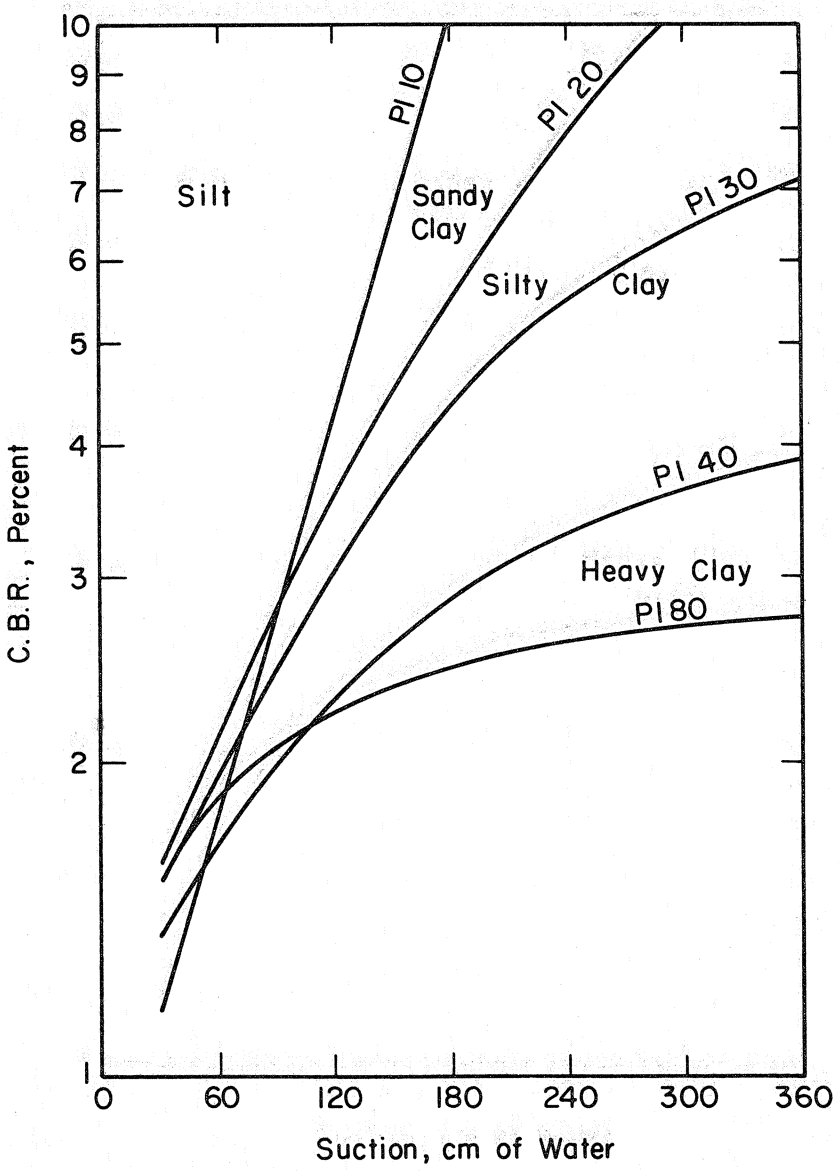


Figure 17. Relations Between CBR Value and Suction for Soils of Various Plasticities (Reference 61).