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입상토질의 노상토 회복탄성계수의 계절적 변화

Seasonal Variation of Resilient Modulus of Granular Subgrade Soils

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요 지

본 연구의 목적은, 입상토질의 노상토에 대한 회복탄성계수의 계절적 변화를 측정하기 위한 실험적 방법을 제시함에 있다. 노상토의 현지 온도와 함수비를 측정키 위해 현장 두 곳에 노상토 온도, 함수비 측정기기를 매설했다. 이러한 계절적 요인을 고려한 회복탕성계수를 결정하기 위해 다회귀분석에 의한 방정식을 유도했다. 응력해석결과, 평균유효응력 깊이에서의 유효회복탄성계수를 사용하는 것이 전 노상토의 특성을 대표할 수 있음을 아울러 찾아내었다. 또한, 온도와 함수비 등 계절적 변화에 따른 회복탄성계수를 예측키 위한 이론적 모델을 본 연구를 통해 제시했다.

Abstract

A testing system has been developed to evaluate the seasonal variation of the resilient modulus of granular subgrade soils. Two sites were successfully instrumented with soil moisture-temperature cells to monitor over a period of one year, the field temperature and moisture content underneath the pavement. Multiple regression equations were developed to determine the resilient modulus under environmental conditions. It is noted that the use of the effective resilient modulus at the location of the Average Depth of Significant Stress (ADSS) provides a reasonable basis for determining subgrade properties. In addition, a theoretical model has been developed to predict the resilient modulus due to the change of temperature and moisture condition.

1. Introduction

The resilient modulus of subgrade soils hase been studied over the past two decades. However, no universally accepted laboratory technique has been developed at present (1992) for determining the resilient modulus of soils and its variation seasonally.

This study presents a modified procedure of the current AASHTO[1] and ASTM[2] methods and also addresses the effect of environmental conditions such as temperature and moisture content on the resilient modulus (Mr). Thus, the purpose of this study is to evaluate the seasonal variations of the resilient modulus of subgrade soils and to develop a theoretical model that accounts for temperature and moisture effects on the resilient modulus of granular materials.

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2. Field instrumentation

To incorporate the environmental conditions into the laboratory testing program, two field sites were selected considering two typical physiography and glacial geology in Rhode Island: upland till plains and outwash deposits for Rt. 146 and Rt. 2, respectively. Both sites were instrumented with Soiltest MC-310A soil moisture-temperature cells(3). The purposes of the installation of soil moisture-temperature cells are:

1. to measure the in-situ soil moisture content at different depths, which will be used for reconstituting the samples in the laboratory,
2. to measure the in-situ soil temperature at different depths, at which the resilient modulus test will be conducted in the laboratory, and
3. to measure the freezing and/or frost depth.

A pit was dug at the pavement shoulder deeper than the anticipated frost depth, 0.9 by 1.2 meter in plan. Three sets of soil cells were installed with different combinations of depth, because of random soil or moisture variations that occur even within a supposedly uniform area. The detailed description for these configurations at the Rt. 146 site is shown in Fig. 1 as an example.

Temperatures and moisture contents of the subgrade soil were measured twice a month with the Soiltest Meter, and the average values obtai-

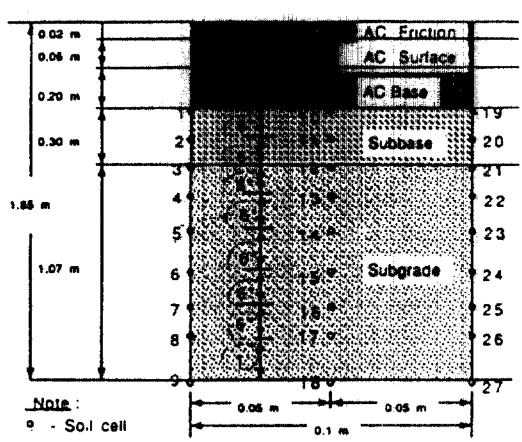

Fig. 1. Cross Section and Location of Soil Moisture-Temperature Cells at Rt. 146 Site

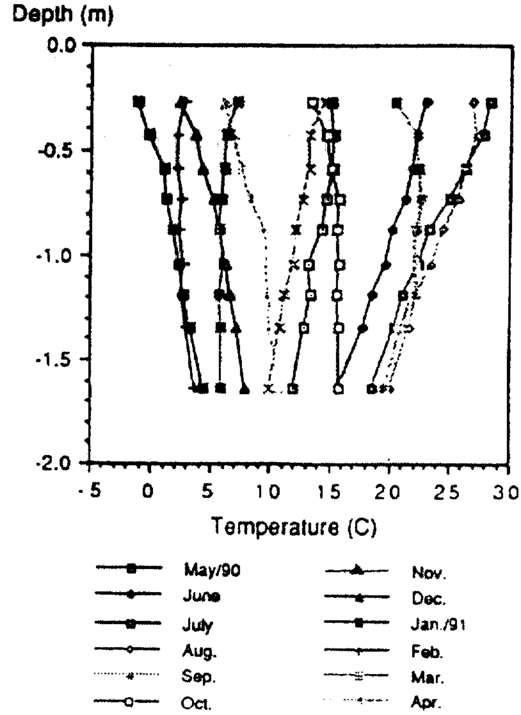

Fig. 2. Monthly Temperature Variations of Subgrade Soil with Depth at Rt. 146 Site

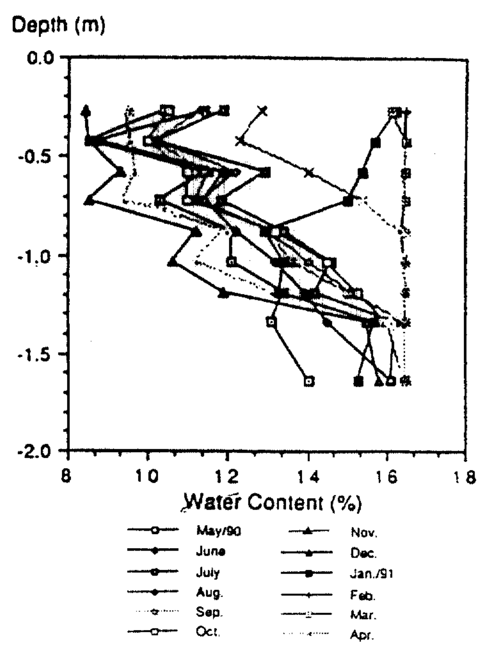

Fig. 3. Monthly Moisture Content Variations of Subgrade Soil with Depth at Rt. 146 Site

ned from three cells at each depth for the Rt. 146 site are shown in Fig. 2 and 3, respectively.

3. Establishment of Laboratory Testing System

3.1 Specimen Preparation Procedure

The AASHTO T1274-82 test method[1] requires that the selection of a compaction methods depends upon field conditions to be simulated by the laboratory specimen and divided by soil types: cohesive and granular. The AASHTO method specifies that granular materials are to be compacted by the use of a split mold surrounded by a membrane and a vibrator. Alternatively, the proposed ASTM method[2] applies the same procedure in the preparation of sample regardless of soil type, but varies by sample condition: undisturbed or disturbed sample.

A new method was developed through this study to prepare specimens for granular soils with the split mold and modified rammer specified in the AASHTO T180 method[1]. In establishing a new procedure, a maximum dry density at the Optimum Moisture Content (OMC) was used as a target value to be achieved. Modification of AASHTO T180 was required to adapt the density specimen size of 4-in. diameter with 5-in. height to the resilient modulus test specimen size of 4-in. diameter with 8-in. height. AASHTO T180 specifies 3 layers of soil for 5-in. sample height. Based on this 3:5 ratio, 5 layers were used to prepare an 8-in. height specimen. Several sample preparation trials with different compaction efforts at the OMC are needed to determine the appropriate number of blows that satisty the density requirements.

3.2 Subgrade Stress Analysis

Two types of soil stress occur in a subgrade of pavement structure: 1) static stress from the overburden pressure and 2) dynamic stress caused by moving wheel loads. The laboratory resilient modulus test reproduces these two stress conditions by: (1) applying an all-around confining pressure on all specimen surfaces to simulate the overburden pressure and (2) applying a dynamic deviator stress on the specimen ends to reproduce the moving wheel loads.

The Average Depth of Significant Stress (ADSS) concept proposed by Lottman[4] was utilized to determine the level of deviator stress and confining pressure which simulates the field conditions, and to determine the subgrade depth at which the moisture content and temperature would be read from the soil cell in order to establish the laboratory test procedure. The ADSS has been defined as the distance from the ground surface to one-third of the depth where the influence of the deviator stress at the subbase-subgrade interface becomes 0.1 of its original value.

The ADSS approach was undertaken using the multi-layer elastic computer program, ELSYM5. With known thickness, elastic modulus and Poisson's ratio of each pavement layer and wheel load on the pavement surface, the distribution of deviator stress at the subbase-subgrade interface varies within a small range from approximately 6.9 to 27.6 kPa. The static stress at ADSS was computed with known density and thickness of each layer. Therefore, the bulk stress at the location of the ADSS may be computed with the sum of static stress and the dynamic deviator stress.

3.3 Sample Conditioning Procedure

The AASHTO[1] and ASTM[2] procedures require that a specimen conditioning phase precede the data collection phase. Considerations were given that the principal stress ratio, σ_1/σ_3, should not exceed the stress ratio at failure, and that the stress sequence should reproduce the field conditions as close as possible. At failure, the principal stress ratio for a granular material is given by:

$$\sigma_1/\sigma_3=\tan^2(45+\phi/2) \quad (1)$$

in which, ϕ is the angle of internal friction of the soil. For a granular soil, a generally accepted range of ϕ value is 30 to 45 degrees. This range suggests that the corresponding principal stress ratios at failure range from 3 to 5.8.

A trial test was performed with a sample conditioning stress sequence provided by AASHTO and ASTM procedures[1,2]. As a result, the Rhode Island granular soils failed. It was observed that the application of a too high confining pressure with one set of stresses made a sample deform suddenly and become unstable. Based on these observations and soil stress analysis, the stress sequence of sample conditioning was reestablished as shown in Table 1.

3.4 Data Collection Procedure

The stress sequence for the data collection was also modified. Because the AASHTO stress sequence[1] is too time consuming and too wide in reflecting the field stress state, and the magnitude of the ASTM sequence[2] is too low to reproduce by most air-powered testing machines, the stress sequence for data collection was reestablished as shown in Table 2.

Table 1. The Proposed Sample Conditioning Stress Sequence

Confining Pressure (kPa)	Deviator Stress (kPa)	Bulk Stress (kPa)	Stress Ratio, σ_1/σ_3
27.6	27.6	110.3	2.0
	55.2	137.9	3.0
55.2	55.2	220.6	2.0
	82.7	248.2	2.5

Note: 250 repetitions at each deviator stress

Table 2. The Proposed Data Collection Stress Sequence

Confining Pressure (kPa)	Deviator Stress (kPa)	Bulk Stress (kPa)	Stess Ratio, σ_1/σ_3
55.2	82.7	248.2	2.5
	55.2	220.6	2.0
	27.6	193.1	1.5
	82.7	248.2	2.5
27.6	82.7	165.5	4.0
	55.2	137.9	3.0
	27.6	110.3	2.0
	82.7	165.5	4.0
13.8	55.2	96.5	5.0
	41.4	82.7	4.0
	27.6	69.0	3.0
	55.2	96.5	5.0
55.2	82.7	248.2	2.5
	55.2	220.6	2.0
	27.6	193.1	1.5
	82.7	248.2	2.5

Note: 200 repetitions at each deviator stress.

4. Laboratory Testing and Results

An experimental design was prepared to perform a series of resilient modulus tests based on the new testing procedure and system (Table 3). To evaluate the seasonal variation of moduli under field conditions, monitored ranges of temperatures, moisture contents, dry densities, and stress conditions were used. Considering the temperature variation observed by the soil cells throughout the year, it was necessary to use an environmental chamber for testing temperatures below freezing. The temperature range observed in the field through the soil cell was used, particularly for the freezing conditions. To see the effects of density on resilient modulus, two different compaction efforts were used at room temperature.

The results of the resilient modulus test are given as a function of bulk stress with a coefficient of determination, r^2. The summaries of testing results are presented in Table 4.

The 1986 AASHTO Guide for Design of Pavement Structures offered two different procedures for determining the seasonal variation of the modulus[5]. The first method performed in this study is to obtain a laboratory relationship between resilient modulus and moisture content. Then, with a value of the in-situ moisture content of the soil beneath the pavement, the resilient modulus for each of the seasons may be estimated. The second procedure is to back-calculate the resilient modulus for different seasons using deflections measured on in-service pavements utilizing the Falling Weight Deflectometer (FWD). In this study, the second procedure was used to verify the results of the laboratory study.

The computer program ELSYM5 was utilized for the back-calculation process. With known input data such as the modulus value, thickness and Poisson's ratio of each layer, the ELSYM5 program was run and a vertical deformation (deflection) was calculated. This calculated deflection value was compared with the deflection at the deflection sensor (geophone) located underneath the loading plate of FWD (Dynatest Model 8000). The comparison indicated that the FWD produces a relatively reliable and close deflection value that verifies the laboratory-determined modulus as correct.

5. Seasonal Variation of Resilient Modulus

The results of the resilient modulus test were plotted log-log scale as a 3 data group, based upon tests using same number of blows and tempera-

Table 3. Experimental Design for Laboratory Testing Program

Target Moisture Content %	Rt. 146 Soils			Rt. 2 Soils		
	Freezing Temperature	Room Temperature		Freezing Temperature	Room Temperature	
	25 blows	25 blows	35 blows	25 blows	25 blows	35 blows
OMC−4.0 (3.8/2.9)	6MR1	6MR4	6MR7	2MR1	2MR4	2MR7
OMC (7.8/6.9)	6MR2	6MR5	6MR8	2MR2	2MR5	2MR8
OMC+2.0 (9.8/8.9)	6MR3	6MR6	6MR9	2MR3	2MR6	2MR9

Note: The values in parenthesis indicate target moisture contents for Rt. 146 and Rt. 2 specimens, respectively. The symbols at each cell indicate the testing identification number for that particular test.

Table 4. The Summary of Resilient Modulus Test Results

Testing Identification No.	m/c %	Temp., ℃	γ_d, Mg/m^3	Regression Equation, M_r/θ in ksi/Psi	r^2
6MR1	4.3	−0.8	2.011	$M_r=8560\theta^{0.37}$	0.90
6MR2	8.0	0.0	2.021	$M_r=5368\theta^{0.54}$	0.77
6MR3	9.1	−0.8	1.981	$M_r=2972\theta^{0.52}$	0.88
6MR4	3.8	23.5	1.973	$M_r=5283\theta^{0.30}$	0.91
6MR5	7.8	20.2	2.010	$M_r=2028\theta^{0.66}$	0.96
6MR6	9.8	24.2	1.968	$M_r=909\theta^{0.87}$	0.89
6MR7	3.8	22.2	2.011	$M_r=4045\theta^{0.45}$	0.94
6MR8	7.8	20.3	2.042	$M_r=2447\theta^{0.63}$	0.91
6MR9	9.7	23.8	1.989	$M_r=1702\theta^{0.74}$	0.93
2MR1	3.3	0.0	1.976	$M_r=9832\theta^{0.24}$	0.71
2MR2	6.7	0.0	2.026	$M_r=4742\theta^{0.50}$	0.83
2MR3	8.9	−1.1	1.968	$M_r=4418\theta^{0.46}$	0.87
2MR4	4.6	22.0	1.960	$M_r=10211\theta^{0.10}$	0.75
2MR5	7.7	17.1	2.000	$M_r=6612\theta^{0.16}$	0.82
2MR6	8.9	23.1	1.947	$M_r=2539\theta^{0.46}$	0.81
2MR7	3.0	20.4	1.973	$M_r=10119\theta^{0.10}$	0.73
2MR8	6.9	21.3	2.030	$M_r=9149\theta^{0.10}$	0.84
2MR9	8.9	12.2	1.960	$M_r=3192\theta^{0.40}$	0.79

Note: OMC=7.8 and 6.9% for Rt. 146 and Rt. 2 site, respectively.
Max. Dry Density=2.107 and 2.134 Mg/m^3 for Rt. 146 and Rt. 2 site, respectively.
See Table 3 for Testing Indentification No.

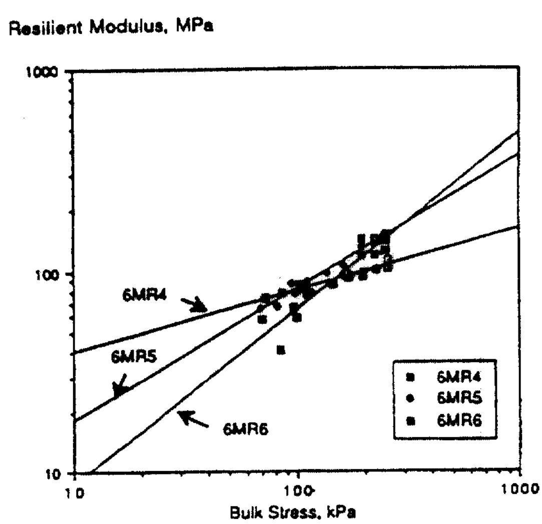

Fig. 4. Results of Resilient Modulus Test for Soils from Rt. 146 Site

ture (at/near freezing and room temperature). Fig. 4 shows an example of three data groups for the Rt. 146 soils. These results indicate that the resilient modulus value decreases as the moisture content increases up to a certain bulk stress; thereafter, it varies regardless of the moisture content. These results show the necessity to carefully select the bulk stress so that field conditions are represented as closely as possible to obtain the representative resilient modulus.

In order to predict the resilient modulus under various environmental conditions, a multiple regression analysis was performed with the laboratory data. Regression equations with four variables were developed as follows:

$$\log M_r=2.16+0.533(\log \theta)-0.01(M/C)-0.00838(T)+1.62(\gamma_d) \quad (2)$$

where, M_r = resilient modulus, MPA,
θ = bulk stress, kPa,
m/c = moisture content, %
T = temperature, degree in celsius, and
γ_d = dry density, Mg/cubic m.

Eq. 2 was used directly to predict the resilient modulus in this study. The bulk stress computed at the ADSS, and the moisture content and temperature at the ADSS, obtained monthly from the soil cells, were used in calculating the monthly resilient modulus using the developed regression equation.

6. Effective Resilient Modulus

In order to identify seasonal moduli, an effective resilient modulus equivalent to the combined effect of all the seasonal moduli values has been used. The basic steps used to determine the effective resilient modulus are described in AASHTO [5].

Based on the monthly resilient modulus at the ADSS, the effective resilient modulus was calculated. These effective resilient moduli reflect the overall capacity of subgrade soils to support the pavement during the year considering the seasonal variation. In an attempt to see if there is any variation of effective resilient moduli with depth, the same calculations were performed at the locations of all the soil cells. The results indicate that the effective resilient moduli do not change much with depths. Therefore, it can be concluded that the use of the effective resilient modulus at the location of the ADSS provides a reasonable basis for the determination of effective subgrade resilient modulus value that considers the seasonal variation in pavement design.

7. Theoretical Modelling

A theoretical model was also developed in this study to predict the resilient modulus at different temperature and moisture condition by estimating the change of resilient modulus due to the change of temperature and soil suction. A micromechanical approach was used for modelling granular soil behavior at different temperatures and moisture conditions. The models developed here view the granular soil as an assemblage of soil particles in contact, subjected to temperature and moisture changes, as proposed by Chandra et al.[6].

In the temperature submodel, the soil particles are considered to be confined in all directions. Because of the confinement of the particles, temperature changes will cause a variation of contact pressures between particles. The change of contact pressure which is the change of confining pressure, $\Delta\theta$, will affect the stiffness of the soil. The moisture submodel treats the soil particles as a two-phase system: a solid phase and a air-water phase surrounding it.

When the two-phase system is subjected to moisture or suction changes, the solid phase remains unchanged, but the variation of the air-water phase may result in changes of the confining pressure, $\Delta\theta$. Again, the change in the principal stress is related to the stiffness of the soil. The change of resilient modulus of granular soils with respect to the change of bulk stress is obtained by taking the derivative as shown in Eq. 3, because the resilient modulus for the granular soil is given as a function of bulk stress.

$$\Delta M_r = K_1 K_2 \theta^{K_2-1} \Delta\theta \tag{3}$$

The above equation can be rewritten to include the change of the bulk stress due to the temperature and the suction change as follows:

$$\Delta M_r = K_1 K_2 \theta^{K_2-1} (\Delta\theta_T + \Delta\theta_S) \tag{4}$$

where subscripts T and S denote temperature and suction, respectively.

7.1 Temperature Submodel

For the temperature submodel, the face-centered cubic (fcc) and simple cubic (sc) packing configurations, which represent the densest and loosest arrangement of equal spheres are considered.

According to Hertzian contact theory, a linear dependence between the volumetric strain and the two-thirds power of the external pressure on a unit element is derived. Assuming X represents the volumetric fraction of fcc grains, the bulk stress change due to the temperature variation, $\Delta\theta_T$, for an assembly of randomly packed spherical particles is derived as follows:

$$\Delta\theta_T=\left(\frac{X}{\sqrt{2}\omega}+\frac{(1-X)}{4\omega}\right)\left(\frac{1}{3}\alpha_v\Delta T\right)^{3/2} \quad (5)$$

where, $\omega=3/4\cdot(1-\nu^2)/E$, a property of the material,
α_v = cubical thermal coefficient,
ν = Poisson's ratio of the material, and
E = Young's modulus of elasticity of the material.

7.2 Moisture Submodel

The moisture submodel utilizes the thermodynamic laws representing the load-deformation behavior of a partly saturated soil. Details of the first and second law of thermodynamics can be found in Sposito[7], Fran[8], and Huang[9].

Now, consider a closed system constrained to constant temperature and volume. For a change of state for this system, it is derived from the first law of thermodynamics that

$$\bar{d}Q=dU \quad (6)$$

where, $\bar{d}Q$ = differentially small amount of heat change, and
dU = changes in internal energy.

Also, it is derived from the second law of thermodynamics that

$$dS\geq\frac{\bar{d}Q}{T} \quad (7)$$

where, dS = entropy change, and
T = constant temperature.

Combining these two equations yields:

$$d(U-TS)\leq O \quad (8)$$

The expression in parentheses is called the Helmholtz free energy, F. Therefore, Eq. 8 becomes

$$dF\leq O \quad (9)$$

Eq. 9 gives the direction of change for a closed system constrained to constant temperature and volume. It implies that a change of state of such a system is only possible if its Helmholtz function decreases. Thus, at equilibrium, the Helmholtz function of such a system must have attained the minimum value. All neighboring equilibrium states of a system of constant temperature are, therefore, given by the mechanical form:

$$dF=-\bar{P}dV \quad (10)$$

where, $\bar{P}$ = mean principal stress, and
dV = total volume change.

7.3 Moisture Effects on Principal Stress

The concept of the above Helmholtz free energy can be applicable for two-phase system which consists of solid and air-water phase, assuming that this system is a closed system.

According to Eq. 10, the mean principal stress acting on a two-phase system is related to the Helmholtz free energy per unit initial volume of the two phases and strain tensor. If the total volume for two-phase system is V and occupied volumes by solid and water are V_s and V_w, respectively, the relation becomes

$$\bar{P}=-\left(\frac{V_s}{V}\frac{\partial\bar{F}_s}{\partial\bar{\varepsilon}}+\frac{V_w}{V}\frac{\partial\bar{F}_w}{\partial\bar{\varepsilon}}\right) \quad (11)$$

where, $\bar{F}_s$, $\bar{F}_w$ = Helmholtz free energy of the solid and water phase, respectively, and
$\bar{\varepsilon}=dV/V$ = volumetric strain.

A change in suction will alter the Helmholtz free energy of the water phase only. Thus, the first term in Eq. 11 will be equal to zero. The change in the mean principal stress, ΔP, is obtained by taking the derivative of Eq. 11 with respect to the volumetric strain, and yields

$$\Delta P=-\Delta(\text{suction})\frac{V_w}{V} \quad (12)$$

where V_w and V are volume of water and total volume, respectively.

7.4 Development of Computer Program For Theoretical Modelling

Based on the micromechanical approach and the theory of thermodynamics law described above, a computer program was developed. This theoretical model is capable of predicting the change of the resilient modulus of granular material due to the variation of temperature and moisture suction.

The input values required for running the program are:

1. type of material, such as limestone, granite, etc.

2. coefficient K_1 and K_2 from the resilient modulus equation,

3. dry density of specimen,

4. temperature and suction value at which the resilient modulus was obtained, and

5. temperature and suction value at which the resilient modulus is predicted.

The theoretical modelling was constructed to see the change of the resilient modulus due to the change of the soil suction based upon thermodynamics. For this purpose, the soil-moisture-characteristics curve was used which shows the relationship between the moisture content and soil suction. Croney et al.[10] have described the methods used to determine the soil-moisture-characteristics curve. Generally, these methods consist of the tensiometer method, the direct suction method, the pressure-plate method, and the centrifuge method. In this study, a typical curve for granular soil, which was developed by Sauer and Monismith[11] based on the pressure-plate method, was used. This curve is shown in Fig. 5.

The prediction of the resilient modulus by the theoretical modelling starts with May/90 data. For this purpose, Eq. 2 is rewritten with given data of moisture content, temperature, and dry density at May/90 as follows:

$$M_r = 3162\theta^{0.54} \tag{13}$$

where, Mr in kSi and θ in PSi.
The corresponding soil suction to a given moisture content at each month, which is obtained from Fig. 5, and a temperature are input into the developed computer program. Thus, the resilient modulus at each month is predicted based upon the theoretical modelling. The results are shown

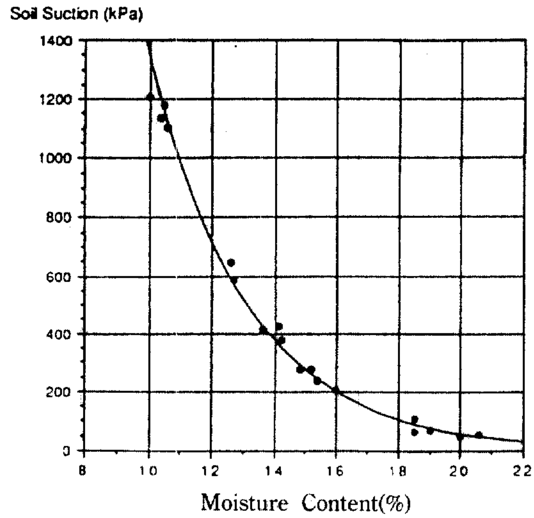

Fig. 5. Typical Soil-Moisture-Characteristics Curve for Granular Soil (after Sauer and Monismith[11])

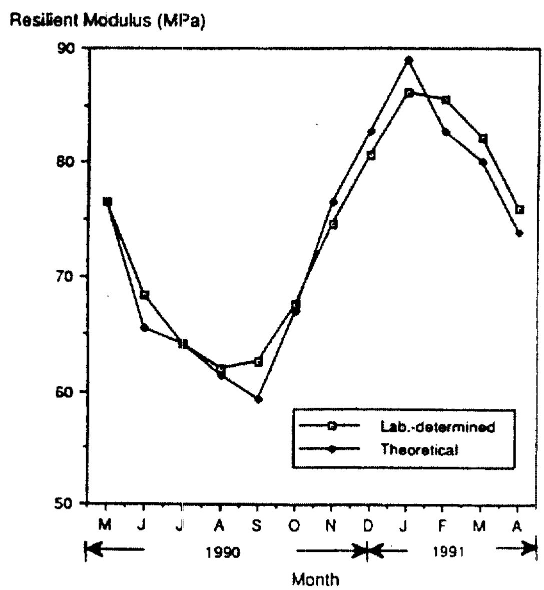

Fig. 6. Comparison Between Lab-Determined and Theoretical Values

in Fig. 6.

The verification of the developed theoretical modelling is done by comparing the laboratory-determined value with the predicted value obtained by the theoretical model. The monthly resilient moduli with temperatures and moisture contents obtained from the soil cells were used for the verification purpose. Fig. 6 indicates that a good agreement between the laboratory-determined value and the predicted value by theoretical modelling does exist.

8. Conclusions and Recommendations

Based on the results of this study, the following conclusions and recommendations are drawn:

1) Soil moisture-temperature cells have been successfully used to monitor the field temperature and moisture content of subgrade soils for laboratory testing.

2) The current AASHTO and ASTM resilient modulus testing methods should be modified to better simulate the actual field stress conditions using soil stress analysis.

3) It is observed that the use of the effective resilient modulus at the location of the ADSS provides a reasonable basis for determining the subgrade property for pavement design.

4) A theoretical model developed based on the micromechanical approach and thermodynamics law for granular materials predicts the resilient moduli very closely to the measured value.

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