RAPID METHOD OF SUBGRADE COMPACTION AND PERFORMANCE EVALUATION

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The dynamic modulus and its variations with time are predicted from dynamic deflections by using elastic layered theory. Field moisture and density variations are measured by using deep probe nuclear equipment. Undisturbed field samples were obtained just after construction and a year or two later. Laboratory testing showed agreement with field measurements, and it is concluded that the subgrade gains moisture after construction and suffers loss of density and modulus. Simulation of seasonal variations (saturation and freeze-thaw in an open system) was conducted in the laboratory, and the trends agreed closely with those obtained from the field.

•IN the rational design of pavement structures, subgrade soil is considered as an important component of the system, and its performance or serviceability under repeated loading and weathering needs to be evaluated on a sound theoretical basis. For a rational design system, the performance characteristics of compacted subgrade soils should be known in terms of parameters that realistically describe the dynamic state of stresses, environmental variations, and related material properties throughout the life of pavement. These performance parameters include moisture-density relation, dynamic modulus or modulus of resilience, permanent deformation characteristics, and resistance to environmental factors. Of equal importance is the methodology of performance prediction and determination of the engineering properties associated with pavement serviceability. The development of a rapid means of field soil compaction quality control to ensure that desired engineering properties are achieved is also important.

The results of laboratory and field study of soil compaction and the relative significance of various performance parameters have been presented in detail (1, 2, 3). Similarly, the effects of moisture content, severe environmental factors, state of stress, and compaction process on the moduli response of subgrade soil have been studied. Part of the research results concerned with field and laboratory characterization of subgrade soils will be presented later. In this paper, however, the use of a nondestructive method of subgrade soil evaluation and the correlation of results with laboratory measured properties are discussed. An attempt is made to demonstrate the applicability of Dynaflect deflection measurements to performance evaluation of compacted subgrade soils.

SCOPE OF FIELD INVESTIGATION

This study is concerned with the development of a new or modified methodology that permits a rapid evaluation of soil compaction process and determination of pertinent design variables. To achieve this objective, five sites representing different geographical and climatic conditions were selected in Ohio. The subgrade compaction process and the construction activities were monitored, and raw and undisturbed materials were collected for laboratory soil characterization. The nature of the terrain and the road profile were also carefully reviewed to provide additional design inputs.

A number of observation stations were chosen in each project site so that information could be obtained with respect to variations of moisture and density with depth.

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The moisture density readings were obtained just after construction and for a period of about 2 years. Each project site had about twelve 5-ft nuclear probe access tubes located just off the edge of the shoulder. Special care was given to the installation and maintenance procedures. Soil properties (i.e., moisture and density) were measured indirectly by radiation backscatter phenomena in both the moisture and density probes. Calibration curves were obtained from the manufacturer and from soil type calibration procedures developed by Moore and Haliburton (5). The density readings obtained were by volume and for wet density and were converted to weight and dry density basis.

Typical moisture versus depth curves for one station are shown in Figure 1. In addition to the moisture and density setup, thermocouples were also installed at various depths to record pavement temperatures.

The field observation also included the measurements of dynamic deflections for each station at chosen test sites. The Dynaflect equipment used in the field measurements consists of a dynamic force generator, a sensor assembly, and a calibration unit (geophone). The purpose of the system is to permit rapid and precise measurement of roadway dynamic deflections while the trailer is halted briefly at successive test locations. These deflections are sensed by a series of geophones located on a line perpendicular to the wheel axis (Fig. 2).

These dynamic deflection measurements were carried out as soon as the subgrade was compacted and proof-rolled prior to resurfacing. In such cases where completed subgrade remained unprotected (i.e., without surfacing for a period of time), periodic deflection measurements were conducted to detect changes in the subgrade support condition.

In each project site, by using the results of deflection measurements, a preliminary evaluation of subgrade support condition was made, and the subgrade support was then categorized into regions of expected, poor, fair, and satisfactory performance. Undisturbed soil samples were then obtained from each of these regions to be used for laboratory evaluation of soil performance parameters.

ANALYSIS

The following analysis procedures were pursued so that an interrelation between field and laboratory measured soil characteristics and a methodology for field soil compaction evaluation could be developed: (a) determination of in situ soil support condition, (b) validation of in situ measured properties, and (c) validation of laboratory-simulated field conditions.

Determination of In Situ Soil Support Parameters

Dynaflect-deflection measurements can be used to determine the subgrade soil support condition. The maximum deflection and the shape of the deflection profile are indicative of the relative stiffness of the subgrade soil. Figure 3 shows typical deflection profiles representing soils with poor and excellent support conditions. When the results of the deflection measurements are used, the dynamic modulus of subgrade soil can be calculated by means of computer programs developed for this purpose.

This method of analysis uses the multilayer elastic theory, which has been extensively used for determination of stresses and displacement in pavement layered systems. According to this method, the moduli of the pavement layers and in some cases the layer thickness are calculated by using measured surface deflections. A number of other investigators (4) have already presented similar analysis techniques and programs for pavement moduli determination, which require that the thickness of the pavement structure be known and a Poisson's ratio of 0.5 be assumed.

However, the method of analysis and the computer program developed in this paper deal with the pavement structure system more realistically and provide more flexibility in the selection of design variables. Specifically, this method can estimate the thickness of the compacted subgrade and deals with materials with Poisson's ratios different from the ideal 0.5. It also has a considerably reduced execution time. In this analysis, the layers are assumed to be homogeneous and isotropic elastic mate-

Figure 1. Pavement moisture content and depth.

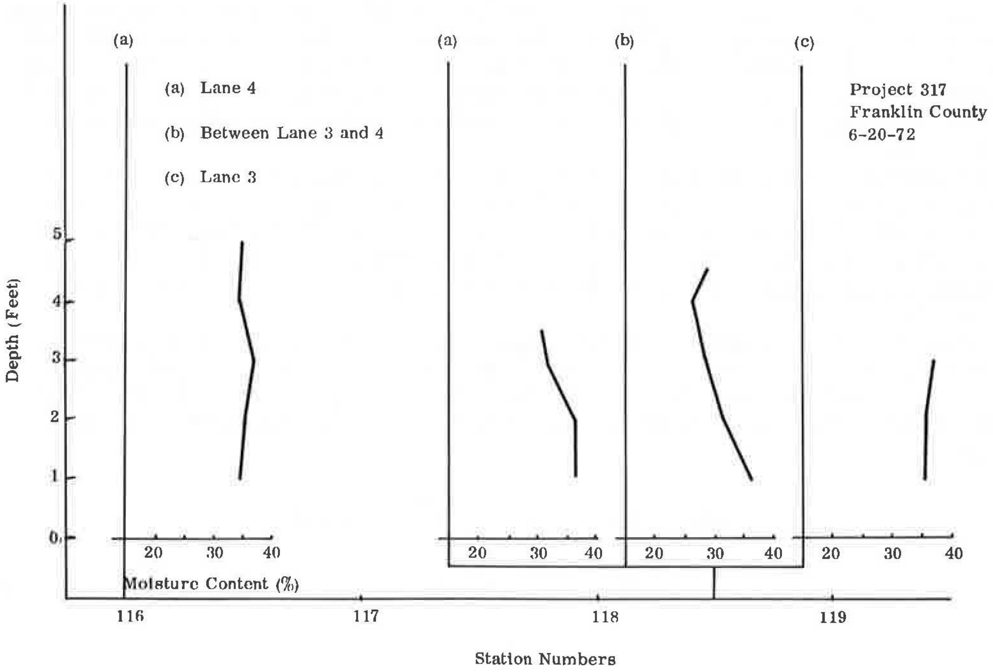
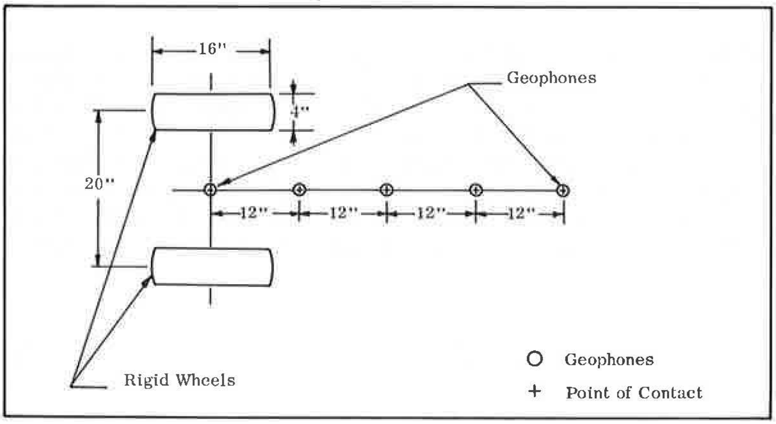


Figure 2. Sensor array.



rials and infinite in extent. The bottom layer is assumed to be infinite in depth. The interfaces between layers are considered rough so that the assumption of continuity of stresses and displacements is fulfilled. The pavement surface is also assumed to be stress-free except for the vertical Dynaflect load distributed over a circular area of known radius. The method of solution is the stress function approach, which leads to and can be evaluated by a relation between deflection, stress, material, and geometrical variables.

The calculation of moduli from surface deflections is considerably more complicated than the determination of deflection from known material and geometric conditions. The complication is caused by the nonlinear inhomogeneous functional relation existing between modulus and deflection. A number of methods exist for the solution of such nonlinear functions, among which is Newton-Raphson's method, which offers more promise.

An inspection of the deflection integral equation, as shown in Eq. 1, indicates that the ratio of deflection w_i/w_j is independent of moduli and only depends on Poission's ratios, layer thickness, and the modulus ratio, $L_1 = (1 + \nu_1)/(1 + \nu_2) \cdot E_2/E_1$. This representation reduces the number of variables by one and considerably simplified calculations.

$$w_2\,(r) = \frac{1 + \nu_1}{E_1}\, a \int_0^\infty \frac{1}{m}\, J_0\,(mr)\, J_1\,(ma)$$

$$f(m,\; h_1\, \nu_1,\; \nu_2\, L_1)\; dm \qquad (1)$$

where

a = load radius,
h_1 = layer thickness,
ν_1 and ν_2 = Poisson's ratios, and
J_0 and J_1 = Bessel's functions.

Application of the moduli calculation program to subgrade soils, however, requires assumptions differing from those used in the analysis of pavement layered systems. As was pointed out earlier for design purposes, the subgrade soil is often considered as a homogeneous, isotropic elastic layer of infinite depth. In such cases, the analysis of a pavement system requires only independent determination of the modulus and Poisson's ratio. A subgrade soil represented by a one-layer system exhibits a unique deflection profile that is characterized by a spreadability ratio of 49.9 percent. The spreadability is defined as the average deflection expressed as a percentage of maximum deflection and is given by

$$\text{SP percent} = 20 \sum_{i=1}^{5} w_i/w_1 \qquad (2)$$

where

w_1 = maximum deflection and
w_i = deflection of sensors 1 to 5.

The spreadability ratio is a complex function of moduli ratio E_1/E_2, pavement thickness, and Poisson's ratio. The higher spreadability ratios are indicative of greater system rigidity and ability to distribute load.

The experimental data indicate that, in subgrade soil compaction evaluation, the assumption of a one-layer system is not always justified, that is, in most instances, the

Figure 3. Dynaflect-deflection profile.

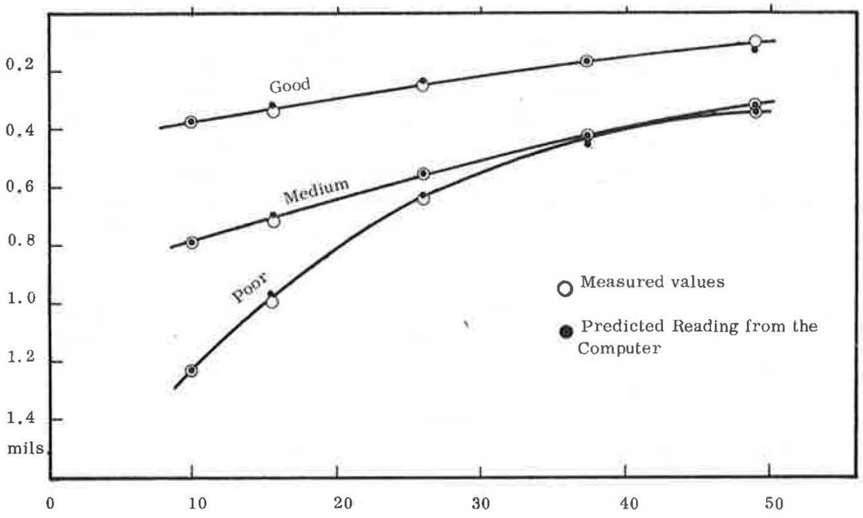


Table 1. Comparison of laboratory and field determined parameters (Pike County SR-124).

Measurements	Date	Location Depth (in.)	Water Content, W/C (percent)	Density, γ_d (pcf)	Modulus, E* (10^3 psi)
Undisturbed field samples	8/15/72		14.6		19.0
		15.0 to 20.0	14.5		16.2
		8.0 to 15.0	16.1		14.0
	4/24/73	6.0 to 12.0	16.7	114.7	7.0
		5.0 to 10.0	18.7	109.8	6.2
		20.0 to 26.0	23.9	102.2	3.3
		2.0 to 8.0	19.2	110.2	5.0
		12.0 to 16.0	18.9	109.8	7.2
Field (nuclear and Dynaflect)	11/11/72	2 ft avg.	23.0	114.5	15.0
	3/21/73	2 ft avg.	22.0	105.0	

Note: 1 in. = 0.0254 m; 1 pcf = 16.018 46 kg/m^3; 1 psi = 6.894 757 kPa.

Table 2. Comparison of laboratory and field determined parameters (Franklin County I-70).

Measurements	Date	Location Depth (in.)	Water Content, W/C (percent)	Density, γ_d (pcf)	Modulus, E* (10^3 psi)
Undisturbed field samples,	7/2/72		8.6	129.9	16.7
Station 223+15			8.9	122.0	25.1
			6.4	123.8	17.7
	4/16/73	8.0 to 15.0	8.1	137.0	10.0
		18.0 to 25.0	7.7	137.6	22.6
		4.0 to 11.0	11.2	123.8	6.8
		11.0 to 22.0	6.1	139.3	18.2
		4.0 to 10.0	9.0	130.7	9.5
		14.0 to 19.0	8.2	131.0	27.6
Field (nuclear and Dynaflect),	7/20/72		9.3	124.4	
Station 212+11	4/16/73	8.0 to 12.5	14.7	120.6	5.1
		19.0 to 24.0	15.5	138.1	9.4
		8.0 to 15.0	12.7	125.4	7.9
		6.0 to 12.0	15.2	113.6	8.9
		12.0 to 18.0	15.3	116.3	7.2

measured deflection data exhibit characteristics of multilayer structure. Whenever soil is compacted on the dry side of optimum moisture content, the top few inches of soil exhibit greater stiffness and better load distribution capacity than the remaining soil media. This results in a greater apparent slab action by the subgrade soil and a higher spreadability value. In such cases, the analysis of deflection data results in two modulus values E_1 and E_2, where E_1 might be many times greater than E_2. Under such conditions, often the strength and quality of the upper few inches of subgrade conceal the real weaknesses of the underlying layers. Surface observations of moisture and density measurements cannot reflect weaknesses of the soil support characteristics. Variations of subgrade modulus in depth can be determined by using undisturbed soil specimens.

Similarly, the analysis of deflection data can yield information pertaining to the relative support characteristics of various subgrade strata. Generally, a relatively high maximum deflection is indicative of a low E_2 modulus, whereas the spreadability or surface curvature index (sci), which is the difference between the deflection of the first two sensors, is indicative of the moduli ratio E_1/E_2.

Contrary to the previous case, during the subgrade compaction process in some instances, the upper part of the compacted soil might attain support characteristics smaller than lower strata. In such cases, the subgrade is represented by a layer system of $E_1 < E_2$ where the thickness of the uppermost layer might vary from a few inches to a few feet.

The analysis program developed for use in this study is also applicable, as was indicated previously, to subgrades consisting of two strata differing in moduli and with an unknown layer thickness. By using deflection data, the program attempts to find the unknown parameters h_1, E_1, and E_2 satisfying the mathematical requirements of the theory. Depending on the h_1, E_1/E_2 ratio, the solution might not be always unique but at most two solutions exist. The program attempts to find all the possible solutions. Determination of variables is achieved by comparing the experimental and calculated deflection data. This fit can be carried out using either maximum deflection and deflection of sensor 2, deflection of sensors 1 and 3, or sensor 1 and spreadability. Figure 3 shows the comparison of the calculated and experimental data.

These analyses can also be carried out with a least squares fit to the deflection data. However, this is rather expensive, and the analysis time is many times greater than with other procedures.

The modulus values calculated using deflection data are given in Tables 1, 2, and 3. Figures 4, 5, 6 and 7 show typical variations of maximum deflection and sci along two typical roadways. Figures 4 and 5 show the maximum deflection and sci of a section of roadway showing localized problems. As is indicated, the overall subgrade deflection is rather low except for the stations between 1568 and 1573, where erratic subgrade response is noted. Figure 6 shows the maximum deflection of another section of the same project and extreme variability throughout the entire length of the section is indicated. Figure 7, on the contrary, represents the deflection response of a subgrade exhibiting good support characteristics as well as excellent material uniformity.

The correlation of measured deflection and in situ field condition has frequently shown that field problem areas can be easily detected with these measured parameters. And extreme variability in the deflection measurements is more often observed in the cut to fill transition sections than in the fill sections.

Validation of Field Measurements

To check the validity of in situ dynamic modulus measurements required that undisturbed subgrade samples be obtained soon after construction and after 1 or more years of service. The in situ measurements of moisture and density and the analysis of undisturbed samples indicated seasonal changes in the physical and engineering properties of subgrade soil. As given in Tables 1, 2, and 3, most subgrades gained moisture after construction and suffered loss of density and modulus. Undisturbed soil samples were obtained at a few stations for each site. The results of analysis,

Table 3. Comparison of laboratory and field determined parameters (Gallia County SR-554).

Measurements	Date	Location Depth (in.)	Water Content, W/C (percent)	Density, γ_d (pcf)	Modulus, E* (10^3 psi)
Undisturbed field samples	10/31/72	1.5 to 5.0	12.0	120.4	10.5
		10.5 to 15.0	9.1	130.4	10.1
		1.5 to 6.0	12.7	91.3	10.1
		6.0 to 10.0	14.3	121.3	9.7
		15.0 to 21.0	10.7	126.5	10.1
		2.0 to 8.0	7.6	127.7	
	4/26/73	10.0 to 12.0	14.6	116.3	2.4
		13.0 to 18.0	15.7	112.8	3.6
		18.0 to 22.0	16.6	110.1	5.1
		7.0 to 12.0	16.7	114.8	2.9
		14.0 to 19.0	18.3	108.1	3.8
		20.0 to 25.0	19.7	112.2	5.3
		6.0 to 12.0	18.1	113.7	2.6
		22.0 to 27.0	13.6	123.6	7.9
Field (nuclear and Dynaflect)	10/31/72	2 ft avg.	15.5	113.5	
	4/26/73	2 ft avg.	17.7	Not available	

Figure 4. Maximum deflection and sci of a test section of roadway showing localized problems (less erratic subgrade response).

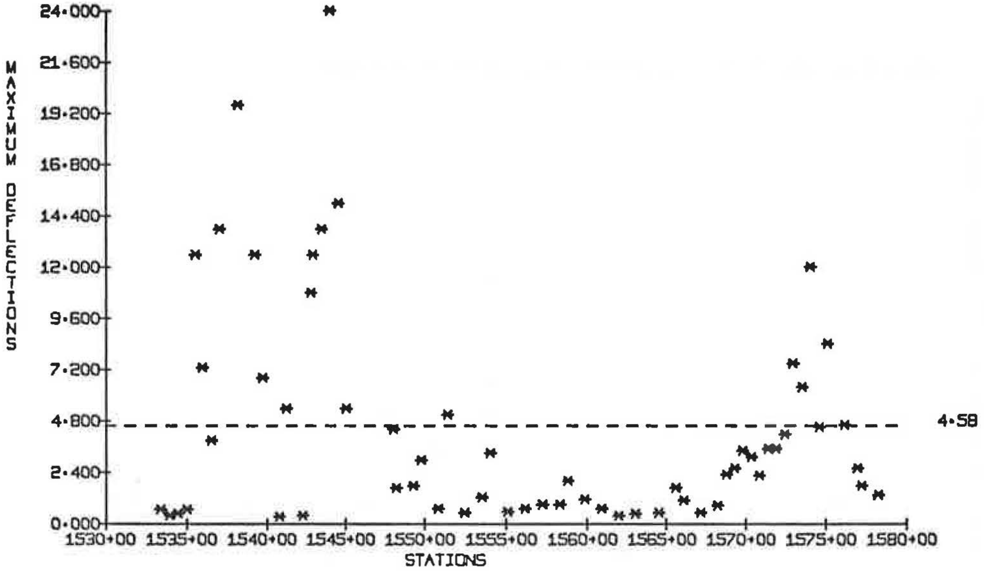


Figure 5. Maximum deflection and sci of a test section of roadway showing localized problems (more erratic subgrade response).

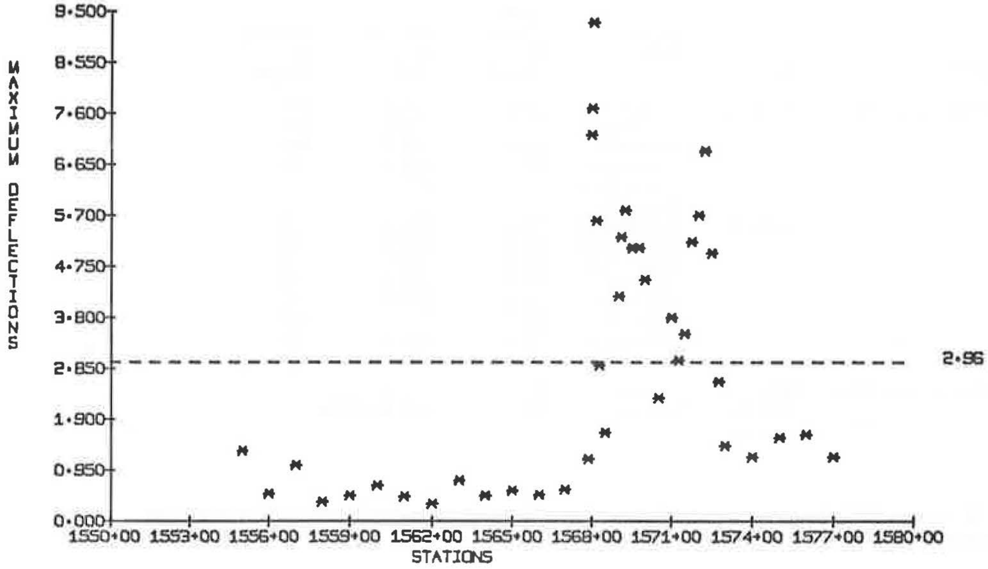


Figure 6. Maximum deflection and sci with extreme variability in subgrade response.

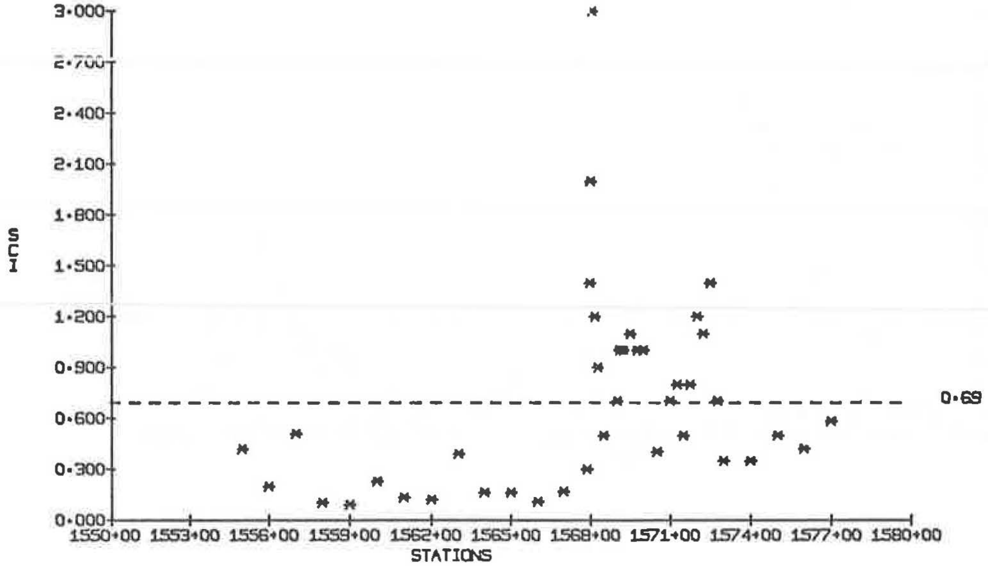


Figure 7. Maximum deflection and sci with good support characteristics and material uniformity.

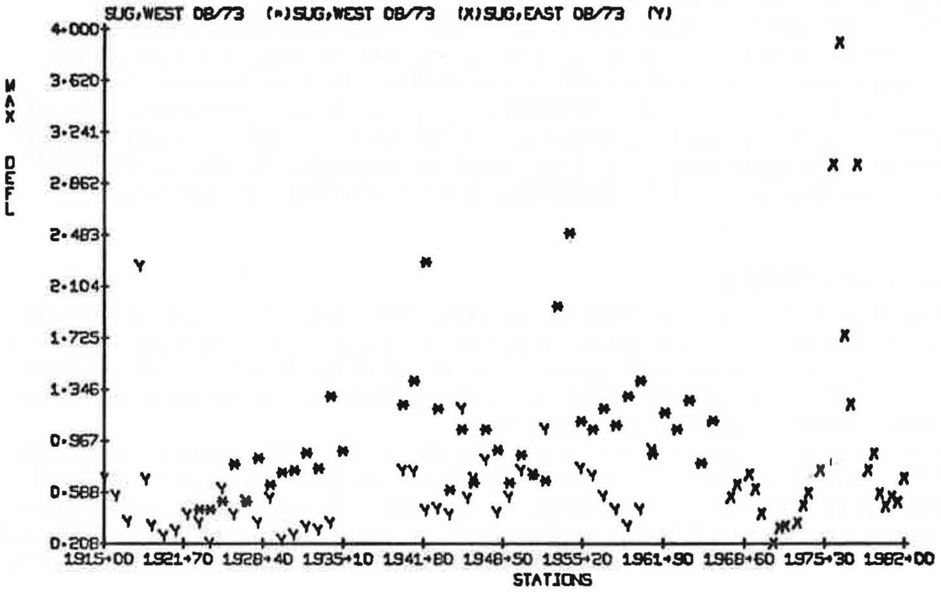
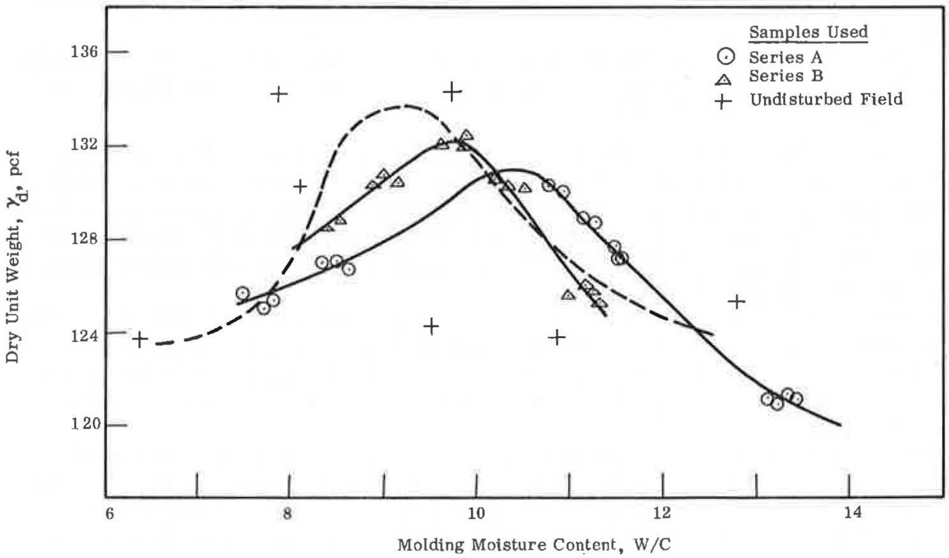


Figure 8. Relation between dry unit weight and molding moisture content.



wherever possible, are tabulated to show variations of soil characteristics with depth. There appears to be a good correlation between these observations.

Similarly, in verifying the validity of field in situ modulus measurements, undisturbed soil samples were subjected to dynamic loads, and the modulus of resilience and the dynamic modulus were calculated with procedures discussed in previous reports (2). The values of the dynamic modulus calculated with field deflection data and data of undisturbed field samples are compared in Tables 1, 2, and 3. There appears to be an excellent correlation between these measured parameters. For undisturbed field samples, the dynamic modulus was calculated for samples obtained at various depths.

Simulation of Field Conditions

In this phase, research was carried out to evaluate the effect of simulated environmental field conditions on the engineering characteristics of compacted soils. Laboratory experiments were carried out to evaluate the effect of increases of moisture content, due to saturation and freeze-thaw cycles after saturation, on the strength and deformation characteristics of compacted soils (6).

Laboratory compacted specimens were prepared by using drop hammer compaction covering a wide range of molding moisture contents. Soil specimens were saturated by simulating the boundary condition existing in the pavement subgrade. Soil samples were also subjected to several freeze-thaw cycles by using the open system that allowed additional moisture to enter the system and be drawn toward the ice lens as a result of freezing.

The properties considered were (a) parameters associated with physical properties—dry density and moisture content, (b) primary response parameters describing nonfailure behavior—complex modulus E* and resilient modulus M_R, and (c) ultimate response parameters describing failure conditions—shear strength and permanent deformation at failure.

The combined effects of compactive effort, moisture content at compaction, and its increase due to saturation and freeze-thaw cycles after saturation on the physical and mechanical properties are analyzed as follows:

1. The results showed that the percentage of dry unit weight loss suffered during capillary wetting and several freeze-thaw cycles was small, indicating that the soaking procedure was such that the increase in saturation occurred with no appreciable change in volume. On the other hand, the moisture content after saturation increased after several freeze-thaw cycles. This increase in moisture content significantly influenced the parameters investigated (Fig. 8).
2. There was a decrease in the value of unconfined compressive strength and an increase of the permanent deformation at failure due to saturation and freeze-thaw of the specimens. The loss in strength was greatest in those specimens with the lowest initial moisture content because of their greater absorption capacity and structural effect (Figs. 9 and 10).
3. The resilient modulus, M_R, was determined by using a constant stress level and samples with different molding moisture contents. With an increase of moisture content to full saturation, the soil loses an appreciable amount of its strength and approaches a minimum value of the resilient modulus. Again it was shown that the decrease in resilient modulus is greatest for those specimens with the lowest initial moisture content (Fig. 11).

For the design of a pavement structure, the variation of modulus of elasticity or the modulus of resilience with the environment and load is the critical factor because this parameter controls serviceability and deformation characteristics of the different components of the pavement structure. Therefore the input data gathered through environmental simulation are valuable for pavement performance analysis.

Figure 9. Relation between unconfined compressive strength and molding moisture content.

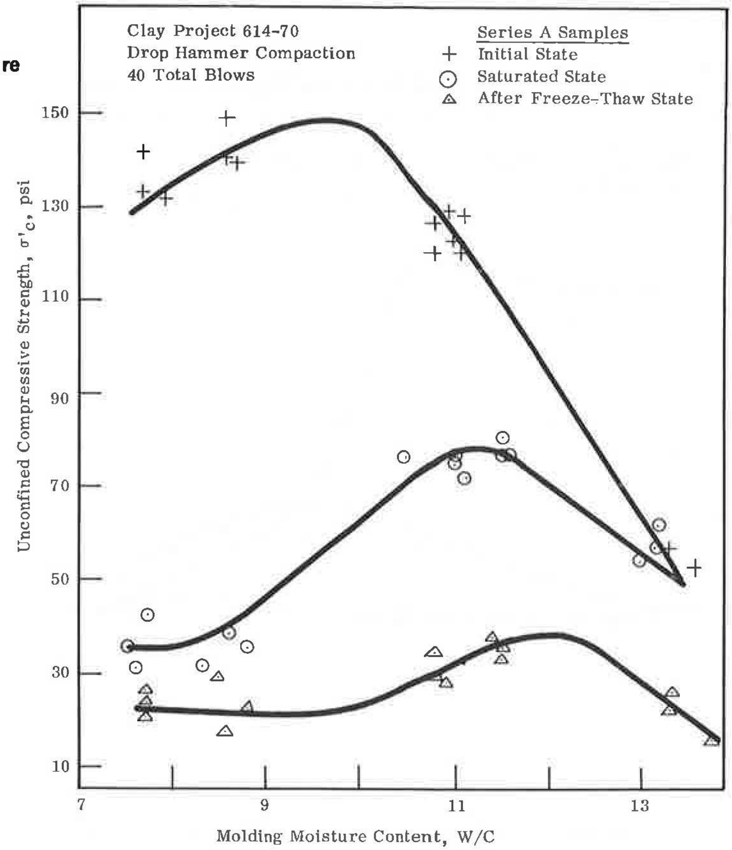


Figure 10. Relation between permanent deformation at failure and molding moisture content.

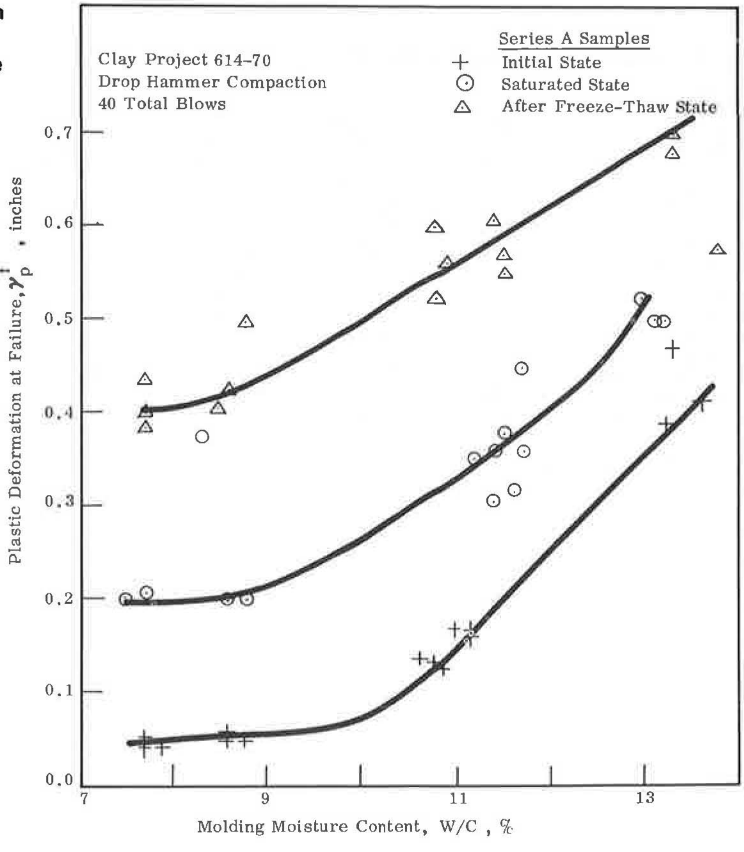


Figure 11. Relation between resilient modulus and molding moisture content.

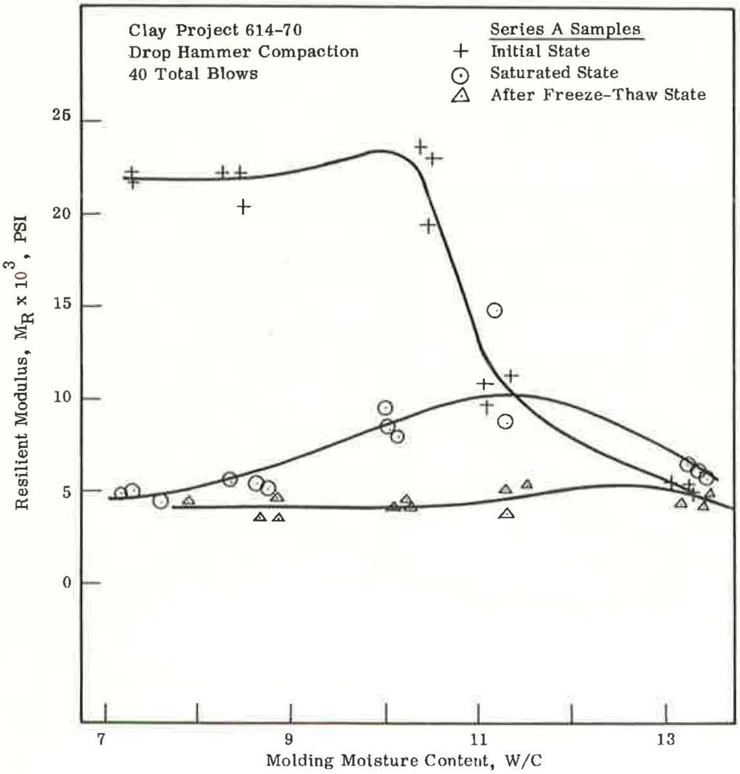


Table 4. Field samples (Franklin County SR-317).

Station	Location Depth (in.)	Water Content, W/C (percent)	Density, γ_d (pcf)	Unconfined Compressive Strength, σ_o'	Dynamic Modulus, $M_R \times 10^3$ psi		Subgrade Thickness (in.)
					Laboratory	Dynaflect	
116+00	12 to 18	17.2		132.3	16.0	4.1	0 to 8.71
116+00	18 to 24	16.3		142.0	23.0	24.3	8.71 on
118+50	16 to 22	13.0		123.0	18.4	3.3	0 to 11.34
118+50	20 to 24	14.8		129.9	18.0	20.3	11.34 on
118+50	26 to 32	12.2		121.8	11.10		
121+00	9 to 15	13.2		130.7	18.9	27.4	0 on
126+00	7 to 13	10.6		61.7	11.3	27.6	0 on
129+00	10 to 16	13.6		122.6	15.7	5.0	0 to 10.4
129+00	24 to 30	12.8		125.8	15.9	19.1	10.4 on
130+00	6 to 12	15.4	110.07	77.9	23.5	5.7	0 to 14.33
130+00	12 to 18	16.0	110.43	64.9	24.2	21.1	14.33 on
138+00	8 to 14	12.8	114.22	108.4	31.4	—[a]	—[a]
150+00	6 to 12	10.1		114.4	19.0	4.4	0 to 10.3
150+00	18 to 24	11.7		123.4	20.1	21.8	10.3 on

[a] Data cannot be calculated.

CONCLUSIONS

The applicability of Dynaflect deflection measurements for use in in situ subgrade soil characterization and modulus evaluation and the use of maximum deflection and the shape of deflection profile, as presented by the spreadability concept, are discussed. Present data indicate that the Dynaflect can provide an accurate representation of quality of compaction, detect changes in pavement support as they occur, and point out areas of future problems.

A comparison of the results of undisturbed field samples with those obtained from laboratory testing indicates a very close agreement between various measured parameters. (Compare Table 2 with Figs. 8, 9, 10, and 11 for the I-70 project.)

The findings show that the subgrade undergoes seasonal changes in moisture and density detected from undisturbed samples, field nuclear measurements, and Dynaflect data. Most subgrades gained moisture and suffered loss of modulus and density after construction. Typical results are given in Tables 1, 2, and 3.

The moduli predicted by using Dynaflect measurements directly on the subgrade show close agreement with laboratory measured values (Table 4). Measurements on completed pavements showed seasonal trends but resulted in moduli somewhat higher than expected from this test. This can be attributed to the difference in the deviatory stress in each case and to the slab effect of pavement layers that will eliminate lateral movements that increase confining pressures. In addition, the Dynaflect measures the average subgrade support within a considerable depth, whereas those undisturbed field samples are obtained at the top of the subgrade and will only reflect variations in the upper few feet. Further research is in progress to establish the exact correlation between actual subgrade moduli and those obtained from Dynaflect measurements on pavement surfaces.

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