Seasonal Effects on the Strength of Pavement Structures

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ABSTRACT

Results are presented from monitoring and predicting changes in subgrade resilient modulus with season of the year for test sites on the U.S. Forest Service road system. Data collection involved measuring deflection, subgrade moisture content, and soil suction over an 18-month period at four test sites located in Washington and Oregon. In addition the pavement materials (asphalt concrete and base and subgrade materials) were sampled and a series of laboratory resilient modulus tests was conducted on each sample. The laboratory and field data were used to develop methods of predicting changes in subgrade stiffness (strength) over time. The two most promising methods were those obtained from regression equations developed from the laboratory test data for the pavement materials and appropriate elastic-layered computer programs and a hand-calculation method based on deflection measurements.

In analyzing pavement performance, seasonal variations caused by environmental conditions pose a difficult problem. These variations, particularly freezing and thawing and the associated soil moisture changes, result in the deterioration of the pavement structure because of a decrease in its stiffness and associated strength. This deterioration has economic impacts including maintenance and rehabilitation costs as well as user costs.

The overall objective of the study being reported was to evaluate the effect of seasonal environmental variations on pavement stiffness and strength. More specifically, the objectives were to

1. Measure changes in subgrade resilient modulus with changes in season and
2. Develop an algorithm to predict seasonal change in modulus from easily measured field data.

Easily measured field data include deflections, soil moisture content, soil suction, and weather information.

To meet these objectives, computer programs and a hand-calculation method were tested to see whether modulus values could be predicted from deflection measurements such as those obtained with a Benkelman beam or from deflection basins measured by the Dynaflect or similar equipment. In addition an attempt was made to correlate modulus with soil type, weather data, soil moisture, and soil suction.

FIELD STUDY

Site Selection

To meet the study goals, extensive use of existing U.S. Forest Service (USFS) roads was made. Several criteria were used as a basis for roadway test-site selection. They were that

1. The site must represent USFS Region 6 soil conditions, climate, and topography;
2. The site must be easily accessible; and
3. Weather data from a nearby source must be available.

Based on these criteria, four test sites were chosen: in the Olympic and Wenatchee National Forests in Washington and the Deschutes and Willamette National Forests in Oregon. Table 1 provides a summary of the site characteristics. To illustrate the differences between test sites during winter conditions, design freezing indices (1,2) were compared as follows [t°F = (t°C ÷ 0.55) + 32]:

Site	Degree-Days
Olympic	150
Wenatchee	1,000
Deschutes	800
Willamette	200

Instrumentation

A main objective of this study was to measure changes in subgrade moduli during a 2-year period. To this end, each site was instrumented with Soiltest MC-310A soil cells to measure subgrade moisture content, soil suction, and temperature (typical locations shown in Figure 1); frost tubes to measure depth of freezing (schematic view shown in Figure 2); and pavement station markers to facilitate repeatable deflection measurements. A typical schematic view of the location of the deflection points, frost tubes, and moisture-temperature cells for one of the four test sections (Olympic National Forest) is shown in Figure 3.

In addition to measurements obtained with the Dynaflect and Benkelman beam, the falling-weight deflectometer (FWD) (Dynatest Consulting, Inc.) was used to measure deflections at both the Olympic and Willamette sites.

Data-Collection Procedures

Field data were collected at all four sites over an 18-month period beginning in January 1981 with special emphasis on the spring thaw period. The following data were collected during each site visit:

1. Pavement deflection,
2. Pavement temperature,
3. Air temperature,
4. Subgrade temperature,
5. Soil cell resistivity (for moisture content), and
6. Frost penetration depth.

Tensiometer suction measurements and gravimetric water contents were also recorded at the Deschutes and Willamette sites.

TABLE 1 Summary of the Characteristics of the Four Test Sites

Forest	USFS Road No.	Elevation (ft above sea level)	Yearly Rainfall (in.)	Pavement Material	Base-Course Material	Subgrade Material
Olympic	220	≃ Sea level	150	5-in. ACP	Crushed aggregate (8 in.)	Clean silty sand with 5 percent gravel
Wenatchee	2451	2,450	24	4-in. CSS-1	Granitic sand (4-6 in.)	Granitic sand
Deschutes	2301	4,400	25	5-in. open-graded emulsion	Crushed aggregate (4.5 in. GW)	SW-SM light-brown pumice ash
Willamette	2233	2,200	70	2.4-in. ACP	Crushed aggregate (14.4 in. GP)	MH clayey silt, residual soil

Note: 1 in. = 2.54 cm; 1 ft = 0.3 m; GW, GP, SW, SM, MH = groups from Unified Soil Classification of U.S. Corps of Engineers and U.S. Bureau of Reclamation.

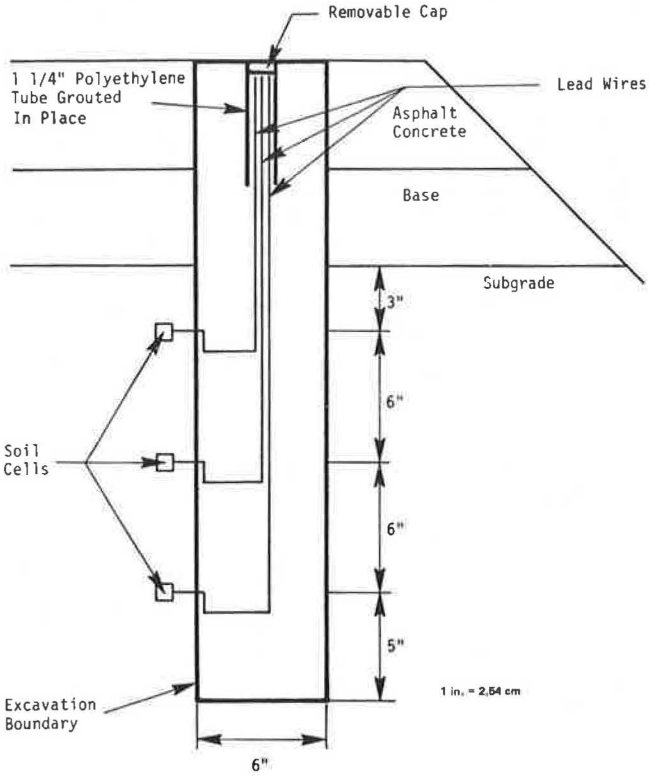

FIGURE 1 Typical soil-cell layout.

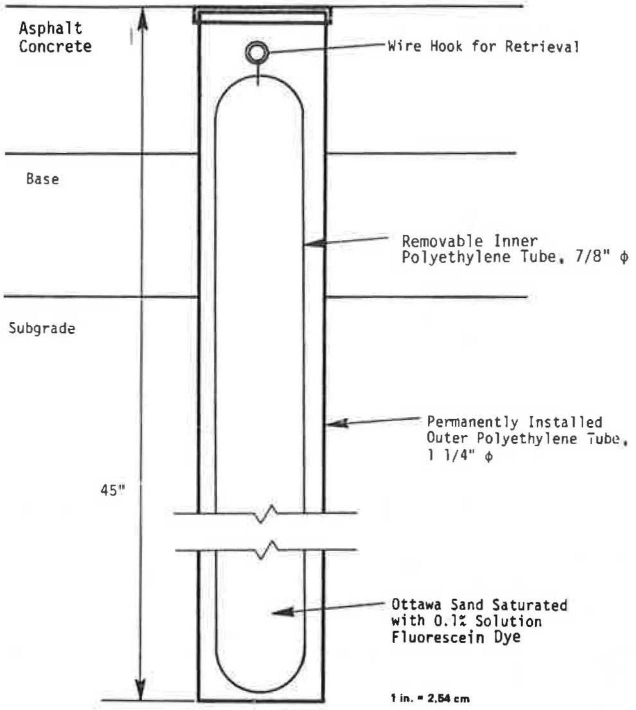

FIGURE 2 Schematic of in situ frost tube.

LABORATORY STUDY

Pavement cores and grab samples of the base and subgrade materials were obtained from each test site. Samples of each were taken for laboratory testing and moisture content determination. The moisture content samples were placed in plastic bags and sealed to prevent evaporation. In situ dry density of each soil was also determined at the time of sampling.

The laboratory testing included sieve analysis (ASTM D421 and D422), hydrometer analysis (ASTM D421 and D422), Atterberg limits (ASTM D423), and specific gravity (ASTM D854) for each soil. These tests were done to provide basic identification of the base and subgrade materials. The optimum density and moisture content for the soils was also determined by AASHTO T-99 (Standard Proctor). Much of the laboratory testing was conducted at the Department of Civil Engineering, Oregon State University.

In addition to the standard soil tests, the resilient moduli of the bases and subgrades were also determined. The soil samples were tested at several moisture contents and densities to bracket in situ conditions. The resilient moduli were then used as inputs for computer programs to predict subgrade modulus. The resilient moduli of the pavement cores were also determined by using a repeated-load diametral test apparatus at 70°F (21°C).

DATA ANALYSIS

This section contains a description of the methods used and the results obtained in predicting modulus from easily measured field data. The relationships examined were those of predicting subgrade modulus from soil moisture content and measured deflections. Soil suction was not investigated as an alternative because suction data were not available for the Olympic and Wenatchee test sites and it was determined that soil suction was no better a predictor of modulus than subgrade moisture content and was more difficult to measure.

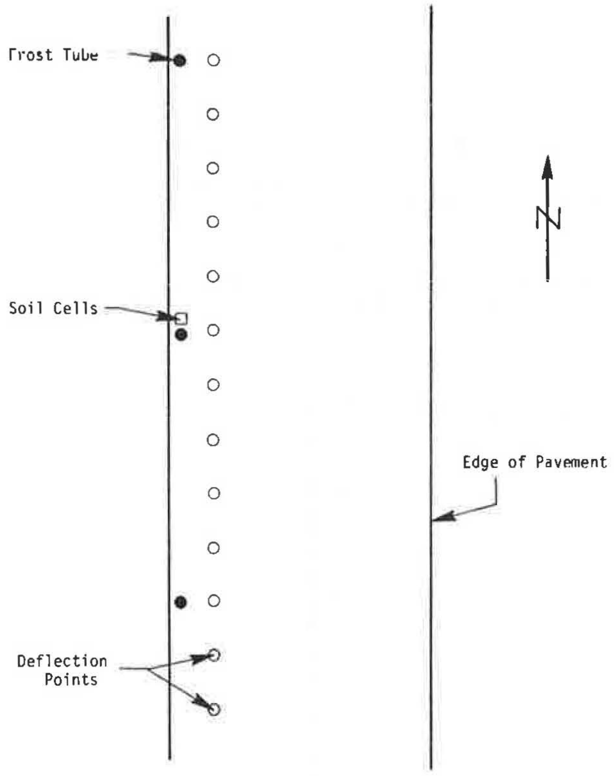

FIGURE 3 Schematic of Olympic National Forest, USFS Road 220.

Prediction of Resilient Modulus from Moisture Content

The regression equations developed from the laboratory resilient modulus test results (Table 2) can be used directly to predict resilient modulus. Equations were developed for the base course and subgrade soils of the four test sites. To use the equations, three quantities must be known:

1. Dry density of the soil,
2. Stress appropriate to a given load (either bulk or deviator depending on whether the soil is granular or fine-grained), and
3. Moisture content.

The dry density of the soil is considered to be a constant and can be determined either from the initial construction records or from field measurement. The stress required is either bulk or deviator stress. These stresses vary depending on the surface loading conditions and can be determined by use of computer programs such as PSAD2A (3) or ELSYM5(3). The loading conditions and the appropriate pavement layer data are input into the programs. Layer data include the thickness, dry density, Poisson's ratio, and the stress relationship ($M_R = K_1\theta^{K_2}$, and so on) for each. The programs will then output stresses at the points requested, including bulk and deviator stresses. Alternatively, bulk and deviator stresses at a point in a layered system can be estimated by using other methods such as those developed by Jones and Peattie (4,5).

Once the bulk or deviator stress for a particular loading is known, along with the dry density, the regression equations can be used to calculate modulus at a given moisture content. The moisture content to input can be determined by sampling to determine gravimetric water content or obtaining resistivity measurements with instrumentation such as the Soiltest cells. To use the latter method, calibration curves of resistivity versus moisture content for the soil must be developed in the laboratory.

Such equations can be used to predict change in modulus with moisture content variation throughout the year; however, the equations are only valid for the range of stresses at which the soils were tested. The laboratory deviator stress range was from 1 to 12 psi (7 to 83 kN/m²) for the subgrade soils and 1 to 20 psi (7 to 138 kN/m²) for the base-course soils. The bulk stress range was 7 to 30 psi (48 to 207 kN/m²) for the subgrade soils and 4 to 64 psi (28 to 448 kN/m²) for the base-course soils. The behavior of the soils at lower stresses has not been determined.

Prediction of Subgrade Modulus from Deflection Measurements

To predict subgrade resilient modulus from measured deflections, three methods were chosen for analysis. Two were computer programs, PSAD2A (3), developed at the University of California, Berkeley, and BISDEF (6), developed at the U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi. The third, a hand-calculation method, was the dual parametric approach (7), refined at the Texas Transportation Institute by Little. Each of these will be discussed.

PSAD2A Computer Program

PSAD2A is the computer program used to analyze Benkelman beam loads. The program uses an iterative approach to determine moduli of the different layers. Several inputs are required for the program. Each layer must be characterized by

1. Poisson's ratio,
2. Dry density,

TABLE 2 Multivariate Regression Equations Developed from Laboratory Data for Predicting Resilient Modulus from Bulk or Deviator Stress, Moisture Content, and Dry Density

Site	Layer	Regression Equation	r^2
Olympic	Subgrade	$\log M_R = 0.749 + 0.673(\log\theta) - 0.0286(w/c) - 0.0008(\gamma_d)$	0.837
Olympic	Base	$\log M_R = -0.102 + 0.796(\log\theta) - 0.0124(w/c) + 0.0053(\gamma_d)$	0.845
Wenatchee	Subgrade	$\log M_R = -0.266 + 0.551(\log\theta) - 0.0554(w/c) + 0.0097(\gamma_d)$	0.894
Wenatchee	Base	$\log M_R = -0.636 + 0.581(\log\theta) - 0.0254(w/c) + 0.0102(\gamma_d)$	0.877
Deschutes	Subgrade	$\log M_R = -0.850 + 0.671(\log\theta) - 0.0122(w/c) + 0.0182(\gamma_d)$	0.895
Deschutes	Base	$\log M_R = 0.473 + 0.584(\log\theta) - 0.0324(w/c) + 0.0022(\gamma_d)$	0.930
Willamette	Subgrade	$\log M_R = 1.61 - 0.213(\log\sigma_d) - 0.0346(w/c) + 0.0130(\gamma_d)$	0.419
Willamette	Base	$\log M_R = -0.0143 + 0.645(\log\theta) - 0.0304(w/c) + 0.0035(\gamma_d)$	0.928

Note: M_R in ksi; θ and σ_d in psi (1 psi = 7 kN/m²); w/c in percent; γ_d in pcf (1 pcf = 0.16 kN/m³).

3. Thickness,
4. Stress relationship, and
5. Initial estimate of modulus.

Poisson's ratios for the individual layers were determined from average values found in the literature for similar material (8). The dry density of the asphalt concrete was assumed to be 150 pcf (24 kN/m³), and the dry densities for the soils were as measured in the field. The thicknesses of the layers were the actual thicknesses of the pavement components. The input values for each site are summarized in Table 3. The stress relationships to input were obtained from the regression equations presented in Table 2.

TABLE 3 Summary of the Layer Characteristics for the Four Test Sites

Site	Layer	Thickness (in.)	Dry Density (pcf)	Poisson's Ratio
Olympic	Asphalt	5.0	150	0.30
Olympic	Base	8.0	137	0.35
Olympic	Subgrade	212	115	0.40
Wenatchee	Asphalt	4.0	150	0.30
Wenatchee	Base	4.0	124	0.40
Wenatchee	Subgrade	212	129	0.40
Deschutes	Asphalt	5.0	150	0.30
Deschutes	Base	4.5	114.5	0.35
Deschutes	Subgrade	212	65	0.40
Willamette	Asphalt	2.4	150	0.30
Willamette	Base	14.4	127	0.35
Willamette	Subgrade	∞	–	0.45

Note: 1 in. = 2.54 cm; 1 pcf = 0.16 kN/m³.

The base-course moisture contents were not measured in the field. For each site, the in situ base and subgrade moisture content were measured at the time of material sampling. The percentage of change in moisture content between that measured at sampling and those determined by the soil cells was assumed to be the same for the subgrade and base-course materials. In other words, the same percentage of increase or decrease in moisture content was assumed for both layers.

Because asphalt-concrete modulus changes with temperature, a temperature-corrected modulus was required. The pavement surface temperature was measured during each visit. To determine the asphalt-concrete temperature at the layer middepth, Southgate and Deen's method was used (9). This method uses air and pavement surface temperatures. Once this temperature had been determined, the correction factor (10) was multiplied by the laboratory asphalt-concrete modulus to provide the appropriate asphalt-concrete modulus at the time of deflection testing.

The load inputs were two loads of 4,500 lbf (20 kN) each, 12.7 in. (32.2 cm) apart center to center. The load radius was assumed to be 4.2 in. (10.8 cm), which corresponds to a tire pressure of 80 psi (552 kN/m²).

The output of the program consists of stresses, strains, and deflections. The outputs of primary interest were the surface deflection between the two tires, the modulus of each layer, bulk stress at the middle of the base course, bulk or deviator stress at the top of the subgrade, horizontal tensile strain at the bottom of the asphalt-concrete layer, and the vertical compressive strain at the top of the subgrade. Several runs were made for each test site, each one representing the subgrade moisture content and asphalt-concrete modulus for a particular site visit.

BISDEF Computer Program

BISDEF is a program that uses the concept of minimizing the differences between the computed and measured deflection basins to determine resilient moduli. This program was used to analyze the Dynaflect and the FWD data.

The inputs required by the program for each layer are

1. Poisson's ratio,
2. Thickness,
3. Range of allowable modulus, and
4. Initial estimate of modulus.

Poisson's ratios and layer thicknesses were the same as those used in PSAD2A.

The load inputs were those representative of Dynaflect loading, two 500-lbf (2.2-kN) loads 20 in. (51 cm) apart center to center. The loaded area per force wheel was assumed to be 4 in.² (25 cm²), giving a load radius of 1.13 in. (2.87 cm) (7). Four geophone inputs were used for all analyses.

The outputs of the program are the modulus of each layer and the stresses at any predetermined point. So that bulk and deviator stress could be determined, stress output was requested at the middle of the base and the top of the subgrade.

Dual Parametric Approach

This method is a graphical approach for subgrade modulus determination from Dynaflect deflections based on layered-elastic theory. It uses two deflection basin parameters. They are maximum deflection and spreadability.

Spreadability is defined as follows:

$$S = (d_{max} + d_1 + d_2 + d_3 + d_4)/5d_{max} \quad (1)$$

where d_{max} is the maximum pavement deflection and d_1, d_2, d_3, d_4 are deflections at 1, 2, 3, and 4 ft (0.3, 0.6, 0.9, and 1.2 m) from the center of the applied load. This approach is a modification of the Vaswani method (11).

One of the major assumptions in this method is that the spreadabilities for the deflection basin measured under Dynaflect and Benkelman beam are identical. This allows the subgrade modulus to be estimated under normal load conditions rather than under the light Dynaflect loads by obtaining only Dynaflect data.

To use the method to predict subgrade modulus a composite or average modulus of elasticity for the layers above the subgrade must be calculated. The equation used is as follows:

$$E_{avg} = (E_1h_1 + E_2h_2 + \ldots)/(h_1 + h_2 + \ldots) \quad (2)$$

where E_1, E_2, and so on, are the elastic moduli of the layers and h_1, h_2, and so on, are the corresponding thicknesses of the layers.

Once the composite modulus, spreadability, and maximum deflection are known, the subgrade modulus can be determined. This is done by using a graph such as that shown in Figure 4. For example, assume E_{avg} = 200,000 psi (1 380 000 kN/m²), the spreadability = 60, and the maximum deflection (Dynaflect converted to Benkelman beam, BB = D x 16.2) = 22.6 milli-in. This results in a subgrade modulus (E_S) of 10,000 psi (69 000 kN/m²) as illustrated in Figure 4. Moduli can be interpolated between lines.

Composite moduli were determined by using the temperature-corrected asphalt modulus and the PSAD2A-determined base-course modulus for the date being investigated.

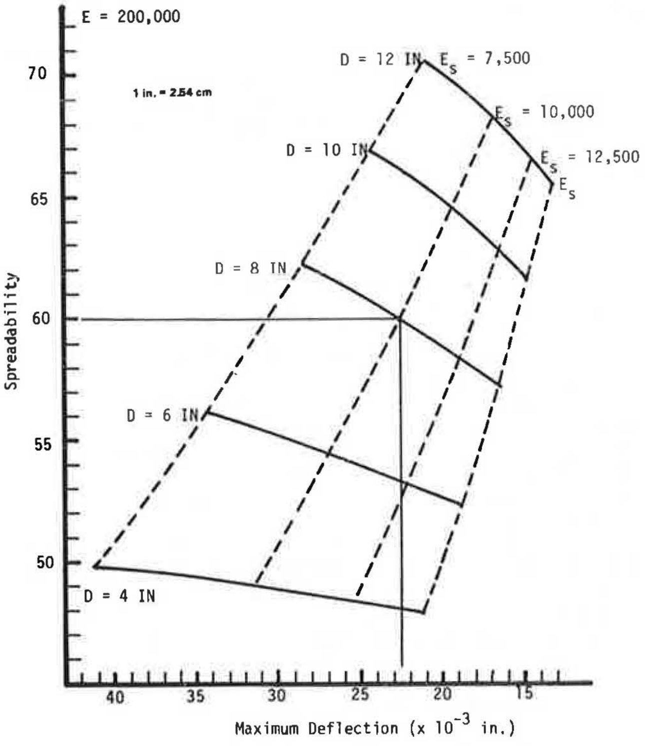

FIGURE 4 Typical graph for use with the dual parametric approach *(7)*.

Comparison of Subgrade Modulus Prediction Methods

To make comparisons it is necessary to examine the loading conditions used or assumed in the method. Benkelman beam loads were used in PSAD2A. The dual parametric approach uses Dynaflect deflections converted to Benkelman beam values. The FWD can be used to approximate essentially any loading condition. Even though all three measurement systems can be in terms of Benkelman beam loading conditions, stress-sensitive layers will not necessarily react similarly. Given this shortcoming, comparisons are presented in Table 4.

With the exception of the Olympic test site the dual parametric approach and PSAD2A results matched well. A difficulty with the dual parametric approach is that it does not, as currently developed, predict moduli less than 7,500 psi (51 800 kN/m²); however, the procedure can be easily extended to overcome this limitation.

In a comparison of the modulus predicted by using FWD data in BISDEF with that predicted by using PSAD2A, the results were favorable. This indicates that the regression equations are a good predictor of subgrade modulus because they were the basis for the output of PSAD2A. Another indication that the equations reasonably predict modulus is that the actual and predicted deflections are similar. This indicates that the equations (derived from laboratory data) reasonably matched the in situ soil conditions.

As an additional check on how well the laboratory-based equations predict modulus, the deviator stress resulting from FWD loading was placed in the regression equation for the Willamette subgrade in order to predict subgrade modulus. By using a moisture content of 51.7 percent as measured by the soil cells and a dry density of 66 pcf (10.57 kN/m³), the equation predicted a modulus of 3,370 psi (23 240 kN/m²) as compared with that of 3,410 psi (23 540 kN/m²) for BISDEF. To see whether the same predictive capability existed for the base-course equation for Willamette, it too was analyzed. By using a bulk stress of 11.4 psi (78.4 kN/m²), a moisture content of 5.2 percent, and a dry density of 127 pcf (20.34 kN/m³), the equation predicted a base-course modulus of 8,970 psi (61 890 kN/m²). This can be compared with the BISDEF-predicted modulus of 6,600 psi (45 530 kN/m²). Again the comparison was reasonable.

To see whether this trend continued, the same analysis was completed for the Olympic National Forest FWD data. Three stress levels were used at this site; thus more comparisons could be made (results are shown in Table 5). As shown, the base-course moduli are similar, whereas the equations predict subgrade moduli one-third those predicted by BISDEF. Recall that the dual parametric approach

TABLE 4 Comparison of Predicted Subgrade Modulus Values for the Four Test Sites

Date	PSAD2A (psi)	Dual Parametric Approach (psi)
USFS Road 220, Olympic National Forest		
01/29/81	12,410	26,100
11/06/81	10,510	27,000
01/28/82	9,260	31,500
02/25/82	9,060	32,000
05/11/82	10,620	32,300
USFS Road 2451, Wenatchee National Forest		
11/05/81	18,230	20,000
04/15/82	13,750	13,750
05/11/82	16,480	15,850
USFS Road 2301, Deschutes National Forest		
01/28/81	2,970	<7,500
03/24/81	4,450	<7,500
05/19/81	4,460	<7,500
11/19/81	4,090	<7,500
02/22/82	4,340	8,470
04/21/82	4,780	<7,500
05/17/82	4,850	<7,500
USFS Road 2233, Willamette National Forest		
01/27/81	1,420	<7,500
03/25/81	2,120	<7,500
04/20/81	3,280	<7,500
05/18/81	1,540	<7,500
07/16/81	3,350	
11/18/81	2,890	<7,500
04/22/82	3,260	<7,500
05/17/82	2,560	<7,500

Note: Subgrade modulus values measured with the FWD on 4/16/81 in the Olympic National Forest and 6/23/81 in Willamette National Forest, were 34,503 and 3,410 psi, respectively. 1 psi = 7 kN/m².

TABLE 5 Comparison of Moduli Predicted by BISDEF for FWD Loading and by the Regression Equations, Olympic National Forest, USFS Road 220

Base θ (psi)	Subgrade θ (psi)	Base M_R from BISDEF (psi)	Base M_R from Equation[a] (psi)	Subgrade M_R from BISDEF (psi)	Subgrade M_R from Equation[b] (psi)
15.6	11.5	29,130	29,740	37,390	11,010
15.0	11.2	23,850	28,830	34,500	10,820
19.5	14.4	48,630	35,520	37,380	12,810
19.8	14.8	33,550	35,960	34,160	13,050
25.1	18.8	46,210	43,430	35,540	15,330
30.6	18.2	62,550	50,850	38,470	15,000

Note: 1 psi = 7 kN/m²; 1 pcf = 0.16 kN/m³.

[a] Using γ_d = 137 pcf, w/c = 8.1 percent.

[b] Using γ_d = 115 pcf, w/c = 11.5 percent.

also predicted subgrade moduli in the range of 30,000 psi (207 000 kN/m²), which indicates that possibly the Olympic subgrade equation is not representative of the subgrade soil behavior.

SEASONAL VARIATIONS OF MATERIAL PROPERTIES

By referring to Table 4, it is observed that the amount of change in the predicted subgrade moduli varies between test sites and with time of the year (both as one would expect). The subgrade soils at the test sites were generally coarse-grained (Olympic, Wenatchee, and Deschutes) and hence (as the predictions show) vary only small to modest amounts throughout the year. Based on the PSAD2A-predicted moduli, the percentage differences given in Table 6 were found for the four test sites. As shown in Table 6, the fine-grained subgrade at the Willamette test site varied by 40 to 50 percent during the data-collection period. Thus, a road structure designed without consideration of such variation could be easily underdesigned. However, the modest subgrade variations at the other test sites were much lower, primarily because of more granular gradation of the subgrade soils.

Table 4 also reveals another interesting observation: The critical (or weakest) period for the Deschutes test site did not occur in the early spring but in November (however, the moduli variations from that test site are low). Further, the critical period for the remaining test sites ranged from February through May. This is quite reasonable given that the frost penetration at all of the test sites was minor. Thus, the predicted moduli are primarily a function of rainfall, not of the formation and subsequent thawing of ice lenses in frost-susceptible soils.

SUMMARY AND CONCLUSIONS

Seasonal variations in pavement strength caused by environmental conditions pose difficult problems. These variations can cause deterioration of the pavement structure, which results in maintenance, rehabilitation, and higher user costs. This study was undertaken to evaluate the effect of seasonal variations on pavement stiffness and strength and to develop a method to predict seasonal changes in modulus from easily measured field data.

To accomplish these goals, four USFS roads were chosen to be monitored over an 18-month period beginning in January 1981 (two in Washington and two in Oregon). Surface deflections were measured by using a Dynaflect and Benkelman beam, subgrade moisture content was measured by using Soiltest moisture-temperature cells, and weather data were collected from nearby weather stations. In addition soil samples and pavement cores were obtained and subjected to resilient modulus testing.

Two major relationships were explored:

1. Prediction of subgrade resilient modulus from soil moisture content and
2. Prediction of subgrade resilient modulus from measured surface deflections.

Predicting subgrade modulus from soil moisture content was accomplished through the use of regression equations developed from the laboratory resilient modulus testing. In the equations resilient modulus is a function of soil moisture content, dry density, and bulk or deviator stress.

To predict subgrade modulus from measured deflections, three analysis methods were chosen. Two were computer programs, PSAD2A and BISDEF, and the third, a hand-calculation method, was the dual parametric approach. PSAD2A was used to analyze the Benkelman beam data and BISDEF and the dual parametric approach were used to analyze the Dynaflect data because they use deflection basins.

TABLE 6 Percentage Differences for Moduli at Four Test Sites

	Percentage Differences	
Site	Between Maximum and Minimum Values	Between Mean and Minimum Values
Olympic	27	13
Wenatchee	25	15
Deschutes	16[a]	9
Willamette	54	43

[a] First observation not used.

In addition to predicting modulus, percentage changes in modulus over time were calculated to determine seasonal variations in pavement strength for the four test sites.

The following conclusions are appropriate:

1. The regression equations (based on moisture content, soil dry density, and bulk or deviator stress) developed from laboratory resilient modulus data can be used to reasonably predict subgrade and base-course resilient modulus.
2. The dual parametric approach is an easy-to-use and accurate method of predicting subgrade modulus by using Dynaflect data. The method, however, needs to be extended to accommodate subgrade modulus values below 7,500 psi.
3. Fine-grained subgrade soils exhibit larger variations in resilient modulus throughout the year than do the more granular subgrade soils encountered in this study.
4. When frost penetration into the pavement structure is minimal, variation in modulus is primarily a function of rainfall and the minimum modulus for the year does not necessarily occur during the spring.

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Stresses in Full-Depth Granular Pavements

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ABSTRACT

Highway pavements for moderate to low-volume traffic often consist of granular materials topped with thin bituminous surfacing. The particulate bases transfer the stresses to the underlying layer by grain-to-grain interaction and cannot resist tensile stresses. The usual analysis of multilayer pavements requires the granular layers to possess tensile strength. A finite-element solution is presented for determination of stresses in pavements made up of full-depth granular layers. In this method the tensile stresses computed in the elements of the granular material by the elastic approach are eliminated during each iteration until the solution converges. The vertical stresses on the subgrade are found to be significantly higher than those obtained from linear-elastic analysis.

Design of highway and airfield pavements involves selection of materials and determination of the thickness of various layers that should be used in pavement construction so that the pavement layers are stable and carry the traffic during the design period without any major maintenance. Highway pavements in India and elsewhere for moderate to low-volume traffic consist essentially of granular materials in the form of water-bound macadam or crushed rock with thin bituminous surfacing. The pavements in such cases are practically full-depth granular construction if the strength of the thin bituminous surfacing is ignored. Analysis of such pavements requires special consideration because of the particulate nature of the materials and the absence of confinement for want of a thick bituminous surfacing.

Various organizations have developed computer programs such as BISAR (1), CHEVRON (2), ELSYM 5 (3), and so on, based on multilayer elastic theory, which requires the granular materials to withstand tensile stresses. Materials like crushed rock or water-bound macadam have little or no strength in tension. The little tensile strength that they may have is because of the interlocking and the intergranular friction. Hence the linear or nonlinear elastic analyses used by different researchers require modification to account for the limited tensile strength of granular layers of flexible pavements.

Some of the design procedures (4-6) assign definite values of elastic moduli to the granular bases depending on the thickness of the layers, and the pavement is analyzed as an elastic-layered system. The maximum tensile strain in asphalt concrete and the vertical stress or strain on the subgrade are evaluated in order to ensure the safety of the pavement from fatigue and rutting, respectively.

In this paper the development of an analytical method for estimating stresses in full-depth granular pavements is described that takes into account the limited tensile strength of granular materials.

DEVELOPMENT OF COMPUTER PROGRAM

A finite-element technique has been adopted to develop computer programs for calculation of stresses in granular pavements. A program designated EPAVE