FINAL REPORT

PAVEMENT DESIGN AND PERFORMANCE STUDY

Phase B: Deflection Study

Evaluation of Pavement Design in Virginia Based on Layered Deflections, Subgrade and Its Moisture Content

by

N. K. Vaswani Highway Research Engineer

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

Studies were conducted to relate the deflection of flexible pavements to such environmental factors as temperature and moisture content of the pavements and their subgrade soils. Also considered were the thickness and the relative positions of the different components making up the pavement systems. Seven pavement designs were studied with respect to the above factors.

The major conclusions of the study are:

- 1. The effect of a weak sandwiched layer in reducing pavement strength needs to be considered during pavement design and evaluation.
- 2. The air temperature considerably affects the pavement modulus. There is a great need for correcting dynaflect deflections for temperature in Virginia.
- 3. Another factor that affects the value of the pavement modulus is the rigidity of the support to the asphaltic concrete; the greater the rigidity, the higher the pavement modulus.
- 4. The temperature sensitivity of the pavement modulus is directly proportional to the pavement modulus and the thickness of the asphaltic concrete layer.
- 5. The primary factor that affects the subgrade modulus appears to be the relative density of the subgrade soil. Low density soils cause high subgrade moisture and low subgrade modulus and high variations in both the moisture and modulus. The reverse is also true.

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INTRODUCTION

Pavement deflection measurements have been utilized in evaluating pavements in Virginia for more than 15 years. Improvements have been made in the methods of measurement during these years but the basic technique remains in use. In fact, reports from other states and countries show that this technique is gaining in popularity.

In this investigation to determine changes in subgrade strength, pavement deflection tests were considered nondestructuve and a most suitable method. To correlate the deflection data with the subgrade moisture, a nuclear method of subgrade moisture measurement was adopted.

PURPOSE

The purpose of this investigation was to evaluate the effect of subgrade moisture on the structural performance of the pavement as influenced by the type of the subgrade soil and the thicknesses and the relative positions of the different layers of the materials in the flexible pavement system.

LIMITATIONS OF THE STUDY

Originally, the study was limited to five projects in the Piedmont area as proposed in the working plan. (1) Later, a project in the Coastal Plain area was added, and data from yet another project are also considered in this report.

Two test sections, one in a cut and one in a fill, were selected for each project; the depths of the cuts and fills varied from about 15 to 40 feet. Each test section was about 1,000 feet long.

A summary of the details of these projects is given in Table 1.

		Pavement Section		Resiliency	h_{av}^{**}	Age (yrs)
	Location	Subbase**	AC**	Value		at Testing
M	'illiamsburg	0.0	10.5"	3.0	9,5	0 to 2
58	harlottesville te. 29 Bypass	6" agg. + 6" CTS	8. 0''	1.0	12.5	0 to 2
N N	prouses Corner te. 15	8** agg.	5. 0"	0.5	7.8	10 to 12
22	ladison te. 29 Bypass	6" agg. + 6" CTS	7.5"	1.0	12.0	0 to 2
22	lassey Corner te. 211	6" agg. + 6" CTS	4.5"	1.0	0°6	2 to 4
2 X	lonroe te. 29	8" CTB	7. 0''	0. 5	15.0	0 to 2
<u>са са</u>	owling Green te. 207	6" CTS	11, 5"	2.5	13.9	2 to 3

TABLE 1 DETAILS OF PROJECTS STUDIED * The project numbers are the same as given in interim reports.⁽²⁾

** See NOTATIONS.

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THEORETICAL DEVELOPMENT OF SUBGRADE AND PAVEMENT EVALUATION CHARTS

In Virginia flexible pavements are designed on the basis of the AASHO Road Test Results whereby the total strength of the pavement is a summation of the strengths of each of the layers. For flexible pavement designs based on this method the strength values for the layers have been converted into thickness equivalency values (a) and the total strength into a thickness index (D). The a and D values have been in use for the last two to three years. (3, 4, 5) These are design methods and do not provide a good means for pavement evaluation.

For the purpose of pavement evaluation by the deflection methods there is a need for developing techniques based on the elastic layered theory developed by Burmister. (7)

The validity of the elastic layered theory for flexible pavements has been verified by various investigators. For example, $Seed^{(8)}$ verified it on prototype pavements and the author⁽⁹⁾ on field pavements.

The easiest and most effective method of pavement evaluation — and even pavement design — is by deflection data. Huang, (10) the Utah State Department Study(11) and the author(12) have shown a need for two deflection parameters to separately evaluate the pavement and its subgrade. One of these two parameters is the maximum deflection directly under the load. The other parameter has varied according to the inclination of the investigator.

In Virginia testing equipment known as the 'dynaflect'' is used for measuring pavement deflections, which consist of the maximum deflection under the wheel load (d_{max}) and four other deflections in the deflected basin. Two parameters are developed from these deflection data. One is the maximum deflection, d_{max} , and the other is the spreadability. (12)

Spreadability could be defined as the average deflection expressed as a percentage of the maximum deflection, and in this investigation it was evaluated by the equation

Spreadability = $S = \frac{d_{max} + d_1 + d_2 + d_3 + d_4}{5 d_{max}} \times 100\%$

where d_{max} , d_1 , d_2 , d_3 , and d_4 are the deflections at 0', 1', 2', 3' and 4' from the center of the applied load, as shown in Figure 1.

For the purpose of evaluating the satellite pavements the author (9, 12) developed pavement evaluation charts based on the maximum deflection and spreadability of a two-layer system as shown in Figure 2. In this two-layer system the strength provided by the top layer — which has an equivalent or average thickness h_{av} and equivalent or average modulus E_{av} — is considered to be equal to the strength provided by the multilayer system of the satellite pavement. The equivalent thickness h_{av} is considered to be the thickness index of the pavement,

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Figure 1. Evaluation of spreadability of a deflected basin.



Figure 2. Two layer system with top layer having average thickness of pavement.

termed D in previous investigations, (3) and is obtained by the following equation

$$h_{av} = D = a_1h_1 + a_2h_2 + \dots$$

where a_1, a_2, \ldots are the thickness equivalencies of the materials defined as the ratios of the strength of the materials in each layer to that of asphaltic concrete while h_1, h_2, \ldots are the thicknesses of the corresponding layers. The equivalent modulus E_{av} is that value of the modulus which for a layer thickness of h_{av} will provide pavement strength equivalent to the pavement on the satellite project. The E_{av} value would therefore be almost equal to that of aspahltic concrete.

in Figure 3 has been used in Virginia for two purposes as follows: (1) To determine what needs to be strengthened — the pavement or the subgrade, and (2) to determine the optimum overlay thicknesses within a project where an average thickness has been approved. This chart has been used for low primary roads by K. H. McGhee, (13)

The application of this chart becomes erroneous for high type primary roads where the pavement thickness is high, and where the ratio of the average moduli of the pavement to that of the subgrade is low. The error in reading takes place where the graphs become curved and hence make it impossible to determine the real value of the subgrade modulus. For example, given $d_{max} = 0.0105$ inch and S = 70, as shown in Figure 3, the subgrade modulus could be erroneously read as equal to 15,000 psi as compared to its actual value of 10,000 psi.

Westergaard (14) and Pickett (15) have theoretically shown relationship between the following five variables for concrete pavements by means of certain equations: (1) The maximum deflection, (2) the volume of the deflected basin, (3) the modulus of the top layer of the pavement, (4) the subgrade modulus, and (5) the pavement thickness. Since such a relationship exists for rigid pavements it was thought that a relationship between similar variables could be at least graphically developed for flexible pavements.

Graphical charts showing a relationship between the following have therefore been developed: (1) The maximum deflection (d_{max}) in inches, and (2) the deflected area (A), which is the area enclosed by half the deflected basin bounded by the pavement surface on top, the deflected basin curve in the bottom, and d_{max} and d_4 as shown in Figure 1. The deflected areas are determined as follows.

A correlation study by Hughes (16) has shown that the deflection under a 9,000 lb. wheel load is equal to 28.6 times the dynaflect deflection. Hence, if d_{max} , d_1 , d_2 , d_3 , and d_4 are the deflections under the dynaflect load, the deflected area under the 9,000 lb. wheel load is as follows:

 $A = 28.6 \times 6 (d_{max} + 2d_1 + 2d_2 + 2d_3 + d_4)$ $= 171.6 (d_{max} + 2d_1 + 2d_2 + 2d_3 + d_4)$

The graphical charts consist of two parts as follows: (1) The subgrade evaluation chart to determine the subgrade modulus at the time of measuring the pavement deflections. This chart, shown in Figure 4, is based on d_{max} and A as discussed previously. (2) The pavement evaluation charts to determine the equivalent or average pavement modulus (E_{av}) at the time of measuring the pavement deflections. These charts; shown in Figures 5 through 10, are based on two-layered theory and are also based on the d_{max} and A values. These pavement evaluation charts are based on two-layered theory and have been drawn for $E_{av} = 500,000$; 400,000; 300,000; 200,000; 100,000; and 50,000 psi.



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Figure 4. Subgrade evaluation chart.



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An example illustrating the use of these graphs is as follows:

A satellite study of a given project showed that the average dynaflect deflection (d_d) of the project was 0.00122 inch and that half the average area of the deflected basin under the dynaflect load = $A_d = 0.028$ sq. inch. The thickness index, D, known from design considerations, is considered to be equal to the average pavement thickness, h_{av} , which is 6 inches.

Based on these data, the average pavement deflection under a 9,000 lb. wheel load = $d_{max} = 0.00122 \times 28.6 = 0.035$ inch and the deflected area A= 0.028 x 28.6 = 0.8 sq. inch, where 28.6 is the correlating factor between dynaflect deflections and deflections due to 9,000 lb.wheel load. (16)

As shown in the subgrade evaluation chart (Figure 4) the subgrade modulus for the above values is 7,100 psi. To determine the E_{av} , locate the point with $d_{max} = 0.035$ and A = 0.8 sq. inch on each of the charts given in Figures 5 through 10 and determine thicknesses for the pavement moduli of 500,000; 400,000; 300,000; 200,000; 100,000; and 50,000 psi. This evaluation is shown by an example in each of these evaluation charts. The pavement thickness corresponding to each of the above moduli respectively are 2.2, 4.0, 4.5, 5.25, 7.5 and 11.0 inches. The pavement thicknesses so obtained are plotted against the pavement moduli as shown in Figure 11. Then this figure shows that the $E_{av} =$ 145,000 psi for a 6-inch pavement.

In drawing the charts given in Figures 4 through 10 two-layer systems were used with the modulus of the top layer, E_{av} , higher than the subgrade modulus. Hence, the charts are applicable when the satellite pavement layered system satisfies this requirement. If this requirement is not satisfied it may so happen that the point of deflection, d_{max} v/s area A, when located in Figure 4, will lie on the base line or in the zone of "very poor pavement needing consideration for replacement." A few cases of such weak pavements are described in Appendix 1.

ANALYSIS OF DATA COLLECTED

As mentioned earlier, data were collected on the seven satellite projects described in Table 1. This table gives the thicknesses and components of the layered system on each project, the resiliency value of the subgrade soils, (4) the equivalent thickness, h_{av} , and the age of the pavement.

All projects except 13 and 15 have rigid subbases consisting of either 6 inches of cement treated subgrade or 8 inches of cement treated stone base. In project 13, full-depth asphaltic concrete is provided directly over the raw subgrade. Project 15 has an untreated aggregate subbase under the asphaltic layer.





All projects are less than four years old except project 15 which is 12 years old. None have been resurfaced.

For the purpose of systematic analysis, the projects were separately analyzed and then combined for an overall analysis as discussed in the following sections. A summary of the data collected for each project is shown in Table 2.

Project 13 - Rte. 31, Williamsburg

The pavement has a full-depth 10.5 inch asphaltic concrete layer placed directly on the subgrade. Since this asphaltic concrete layer lies directly on the subgrade it is considered to contribute 10 percent less strength and hence to have an $h_{av} = 0.9 \times 10.5 = 9.45$.

This project initially was not a part of this study; however, moisture contents were recorded at irregular intervals for a period of about 12 months after construction. The moisture readings did not show much variation. The subgrade moisture varied from about 26 to 27 percent in the fill and 20 to 24 percent in the cut.

Deflection data were taken later. Based on the deflection data, the subgrade modulus, E_s , and the pavement modulus, E_{av} , were determined from the subgrade and pavement evaluation charts. The E_s and E_{av} values so obtained are plotted in Figure 12. To correlate the pavement modulus with the air temperature, a graph of the five-day moving average air temperature is also shown in the figure. This figure shows the following:

- (1) The subgrade modulus in the cut varied from 5,250 to 4,000 psi, and in the fill from 4,750 to 6,000 psi, which indicated a range of about 1,250 psi for each section.
- (2) The average pavement modulus (E_{av}) is inversely proportional to the temperature. It increases with a decrease in temperature and decreases with an increase in temperature.

The pavement modulus varies by 160,000 psi in the cut and by 135,000 psi in the fill for a temperature range of 47°F, giving a temperature sensitivity of 3,400 psi in the cut and 2,900 psi in the fill per degree.

(3) The pavement modulus varies from 90,000 to 250,000 psi in the cut and 65,000 to 200,000 psi in the fill. This pavement is full-depth asphaltic concrete directly over the raw subgrade. Compare the modulus of this pavement with the moduli of the pavements for projects 18 and 19 given in Table 2. In projects 18 and 19 the asphaltic concrete lies over a rigid layer that in one case is cement stabilized subgrade and in the other case cement treated subgrade. The pavement modulus in both these cases varies from 220,000 to 600,000 psi, which is about three times the value obtained on project 13. It therefore appears that the pavement modulus is high when the material directly below the asphaltic concrete is rigid, as is the case with cement stabilization.

TABLE 2

PROJECTS
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SUMMARY

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	Pavement Sectic	a		of Stu	udy	Air Temp.	* 0		Eav ir	ı ksi	*		E _{av} in	ksi
Location			Study	In Mo	ntns	of 5 Davs	Min Max.	Es in ksi			MinMax.	Ee in ksi		
	Subbase	AC	Period	M.C.*	Defl.	Min Max.	(%)	MIDMax.	MIDMAX.	ensiuvity (ksi/oF)	(%)	Min Max.	MID MBX.	censitivity (ksi/ ^o F)
Williamsburg	0.0	10.5"	Aug. 71- Dec. 71	4	4	30-77	20-24	4-5	90-250	3.4	26-27	5-6	65-200	2.9
 Charlottesville Ate. 29 Bypass	6" Agg. + 6" CTS	8.0"	Aug. 70- Dec. 73	ß	29	30-75	12-17	5-7.5	100-175	1.7	24-30	11.5-12.5	95-170	1.7
Sprouses Corner Ate. 15	8" Agg.	5.0"	July 70- Dec. 72	17	29	30-75	26-28	7-8	80-120	0.9	38-42	5-8	85-110	0.6
Madison Rte. 29 Bypass	6" Agg. + 6" CTS	7.5"	Aug. 70- April 72	16	29	30-75	11-21	5-6.5	60-185	2.8	14-26	10-13	65-185	2.8
Massey Corner Rte. 211	6" Agg. + 6" CTS	4.5"	July 70- Dec. 72	I	29	19-72	1	12. 5-17. 4	35-125	1.8	t	7.6-19.5	65-130	1.2
Monroe Rte. 29	8" CTB	7.0"	Jan. 71- Mar. 72	1	14	29-78	1	5.2-6.5	300-640	6,9	1	4-6.5	220-480	5.3
30wling Green Rte. 207	6" CTS	11.5"	June 73- Mar. 74	1	I	I	I	4-5	250-600	5.5	1	4-5	250-600	5.5

*Moisture Content



Figure 12. Location 13 (Williamsburg) — Relationship between (1) pavement modulus (E_{av}) and air temperature, and (2) change in subgrade modulus during the seasons.

The modulus pavement in the remaining four cases is also not high. This is for the following reasons: (1) Three of these pavements, projects 14, 16, and 17, consist of a weak sandwich layer of untreated aggregate directly under the asphaltic concrete layer. The behavior of week sandwiched layers is discussed in Appendix 1. (2) the fourth project has a weak, untreated aggregate over the subgrade, which provides no rigid layers between the subgrade and the asphaltic concrete.

Project 14 – Rte. 29, Charlottesville Bypass

The type of pavement on project 14, which consists of an untreated aggregate layer over a cement treated subgrade, is now commonly used in the Piedmont area of Virginia.

On this project, nuclear subgrade moisture measurements and deflection tests were carried out for about 29 months as shown in Table 2.

Deflections were measured over (1) the raw subgrade, (2) the cement treated soil layer, (3) the untreated aggregate layer, and (4) the asphaltic concrete pavement.

The deflection data over the subgrade, the cement treated soil layer and the untreated aggregate layer were obtained by combining the cut and fill sections. Those over the cement treated subgrade were obtained when the treatment was about 25 days old. Those over the untreated aggregate were obtained at two different times: about two to three days after it was laid and about five and a half weeks after it was laid. The data so obtained are given in Table 3.

TABLE 3

d_{max} (inches) Date Top Layer A (sq.in.) Subgrade 0.0530 0.917 May 1, 1969 6" cement treated subgrade 0.0357 0.747 May 7, 1969 Aggregate base 0.0400 0.776 June 13, 1969 Aggregate base 0.0269 0.606

MAXIMUM DEFLECTION AND DEFLECTED BASIN AREA ON PROJECT 14

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Analysis of the raw subgrade deflection data showed the subgrade modulus to be 8,000 psi. Analyses of the deflection data over cement treated soil showed that the modulus of elasticity of the cement treated soil was 62,000 psi for a thickness of 6 inches. As can be observed from Table 3 on May 7, 1969, after the untreated aggregate was provided, the values of d_{max} and A increased instead of decreasing. This trend of a reduction in the pavement strength immediately after the untreated aggregate has been provided has been observed on other projects. One example of this was given in the working plan for this investigation. (14) It has also been noticed that after some time the untreated aggregate recovers its strength and d_{max} and A decrease as shown by the data given in Table 3 for June 13, 1969.

The initial decrease in strength immediately after the addition of untreated aggregate can be explained by the principle of a weak layer overlying a stronger layer or layers as explained in Appendix 1. Untreated aggregate, immediately after construction, probably contains a high quantity of moisture which considerably decreases its strength. Thus after a few days, when the moisture evaporates, the strength is regained. If this is really the case, then it is possible that if during the life of the pavement the untreated aggregate layer picks up a high quantity of moisture, it will again lose strength and the pavement will behave like a weak sandwiched layer system, as explained in Appendix 1.

If the above mentioned probabilities do exist, the untreated aggregate layer should be used with restraint, and its thickness should be as low as possible. This precaution is explained in Appendix 1.

Based on the deflection data taken after the completion of the pavement, the subgrade modulus, E_s , and pavement modulus, E_{av} , were determined from the subgrade and pavement evaluation charts. The E_s and E_{av} values so obtained during different test times are plotted in Figure 13.

The subgrade moisture content determined by a nuclear depth probe during this investigation is also plotted in this figure. A five-day moving average of the air temperature for the period of deflection testing was determined and is also shown in Figure 13.

The following conclusions are made from the study of the correlation of the variables plotted in Figure 13: (1) The pavement modulus is inversely proportional to the temperature. It increases with a decrease in temperature and decreases with an increase in temperature. The curves for pavement modulus and temperature are sine curves with a 90° phase difference. For a temperature range 30° to 75° F, the pavement modulus in the fill and cut areas changes from 170,000 to 95,000 psi, giving a temperature sensitivity of asphaltic concrete of 1.7 ksi per degree. In comparing the rate of change of the E_{av} on this new project with the rate of change of the E_{av} on other new projects it appears that the change is similar to the one on project 17, but is about half of that on projects 13 and 16.



Figure 13. Location 14 (Rte. 29 Bypass, Charlottesville) – Relationships between (1) pavement modulus (E_{av}) and air temperature, and (2) subgrade modulus and subgrade moisture.

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(2) The change in subgrade modulus seems inversely proportional to the change in subgrade moisture. It increases with a decrease in moisture content and decreases with an increase in moisture content. This relationship is not as precise as the one observed between the pavement modulus and air temperature. It is therefore probable that in addition to moisture content there are other factors which affect the subgrade modulus. Since the pavement is new the other factors could include construction variables such as compaction.

The soil density, soil grading, and soil drainage would affect the overall value of the subgrade modulus. This is probably the reason why the moisture content and hence the subgrade modulus in the cut is lower than in the fill. The relative effects of each of these variables affecting subgrade moisture are further discussed in the following pages.

Project 15 - Rte. 15, Sprouses Corner

The pavement on project 15 is about 12 years old and has not been resurfaced. It is located in the Piedmont area and consists of a 5-inch asphaltic concrete layer over an 8-inch untreated aggregate.

On this project, nuclear subgrade moisture measurements and deflection tests were carried out for a period of about 29 months as shown in Table 2.

Based on the deflection data taken, the subgrade modulus and pavement modulus were determined from the subgrade and pavement evaluation charts, and are plotted in Figure 14. Figure 14 also gives the subgrade moisture content and the five-day moving average air temperature during the testing time. The following relationships are very evident from the study of the correlation of the variables plotted in Figure 14.

(1) The pavement modulus is inversely proportional to the temperature, and the curves for the pavement modulus and temperature are sine curves with a phase difference of 90°. For a temperature variation of 30° to 75° F the pavement modulus in the cut changes from 80,000 to 120,000 psi and in the fill from 85,000 to 110,000 psi, giving a temperature sensitivity of 900 psi in the cut and 600 psi in the fill per degree. This change in temperature sensitivity is even smaller than half of the lowest value observed on the remaining six satellite projects in this investigation. The two obvious reasons for this small change could be age and/or the thickness of the asphaltic concrete. Age is probably the predominant factor because the asphaltic concrete thickness of 4.5 inches. The sensitivity per degree of temperature on this project is lowest among the remaining six projects, which justifies the speculation that though age may be the prime factor the lower thickness of asphaltic concrete could also lead to a reduction in temperature sensitivity.

SUBGRADE MODULUS - 2<mark>6</mark> - pei 10,00 FILL O -0 7,500 -0 5,000 % MOISTURE CONTENT - M. C. 60 FILI 40 -CUT 20 80 AIR TEMPERATURE (5 DAY AVG.) ^OF 5 DAY AVERAGE 60 40 20 PAVEMENT MODULUS - Ea - pei 150,000 æ 100,000 CUT 7.7-50 000 FILI 6-1-'70 C 7-1-'70 8-1-'70 9-1-170 11-1-70 10-1-.70 12-1-'70 17'-1-1 2-1-71 3-1-'71 4-1-'71 5-1-'71 6-1-'71 17'-1-7 8-1-'71 17'-1-9 10-1-171 17'-1-11 12-1-11 1-1-'72 2-1-'72 3-1-'72 4-1-'72 5-1-'72 6-1-172 7-1-'72 8-1-'72 9-1-172 10-1-72 11-1-'72 12-1-'72 1-1-73 2-1-'73

1927

Figure 14. Location 15 (Rte. 15, Sprouses Corner) – Relationship between (1) pavement modulus (E_{av}) and air temperature, and (2) subgrade modulus and subgrade moisture.

TEST DATES

(2) There is very little change in the subgrade moisture content on this project. The reason for this could be that with age the subgrade moisture has stabilized.

The subgrade modulus in the cut varies from 7,000 to 8,000 psi, which is a very small variation. The small change in both the subgrade moisture and the subgrade modulus in the cut indicates a certain correlation between these two variables. A similar correlation does not seem to hold for the fill area, where the subgrade modulus varies from 5,000 to 8,000 psi. No information is available to justify this amount of change.

Project 16 - Rte. 29, Madison Bypass

The section of the pavement on this project is similar to that of project 14, in that it has a cement treated subgrade overlaid by 6 inches of untreated aggregate and 7.5 inches of asphaltic concrete. Like project 14, it was recently built.

The duration of the study on this project was about 29 months, as shown in Table 2. Deflections measured over the cement treated subgrade were obtained when the cement treatment was more than one month old. The analysis of these deflection data showed that the modulus of the 6-inch cement treated subgrade was 115,000 psi in the cut area and 100,000 psi in the fill area. The modulus of the 6-inch cement treated subgrade layer in project 14 is 62,000 psi, which indicates that the modulus of soil-cement varies depending upon the type of soil, construction techniques, and other factors. However, since the strength will increase with time, for design purposes an average modulus value of 100,000 psi for cement treated subgrade may be reasonable.

Based on the deflection data taken after the compaction of the pavement, the E_s and E_{av} values were determined from the subgrade and the pavement evaluation charts, and are plotted in Figure 15. The subgrade moisture content determined by the depth nuclear probe and the five-day moving average air temperature recorded for the period of deflection testing are also shown.

From the study of these variables, the following conclusions are made:

- (1) The pavement modulus is inversely proportional to the temperature, and the curves for pavement modulus and temperature are sine curves with a phase difference of 90°. For a temperature variation of 30° to 75°F the pavement modulus in the cut and the fill area changes from 60,000 to 185,000 psi, giving a temperature sensitivity of 2,800 psi per degree.
- (2) In both the cut and the fill areas the subgrade modulus is inversely proportional to the subgrade moisture. Though this is true but unlike the pavement modulus and air temperature relationship, no definite pattern seems to exist between the relationship of these two variables. This is probably because the temperature curve follows a sine curve while the moisture curve does not follow any systematic variation.

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Figure 15. Location 16 (Rte. 29 Bypass, Madison) – Relationship between (1) pavement modulus (E_{av}) and air temperature, and (2) subgrade modulus and subgrade moisture.

Project 17 - Rte. 211, Masseys Corner

The strength of the project 17 pavement is similar to that of projects 14 and 16, except that the thickness of the asphaltic concrete layer in this project is less. Project 17 has a 6-inch cement treated subgrade overlaid by 6 inches of aggregate and 4.5 inches of asphaltic concrete.

This pavement, about two years old when the study was started, is located at the foot of a mountain and in rocky terrain. The location is probably the reason why the subgrade moduli - as shall be seen later - are high.

From the deflection data taken, E_s and E_{av} values were determined from the subgrade and pavement evaluation charts and are plotted in Figure 16.

The subgrade modulus in the fill increases with a decrease in the subgrade moisture and remains low when the subgrade moisture is high. The variations in subgrade moisture are very little while the variations in the pavement modulus are high. It is therefore probable that the variations in the subgrade modulus are not due to the changes in the subgrade moisture alone.

A correlation between the subgrade soil density and moisture content at different depths of the subgrade is shown in Figure 17. Figures 16 and 17 show that the moisture content is lower in the cut than in the fill. Further, Figure 17 shows that the density is higher in the cut than in the fill and that the moisture content is inversely dependent on the subgrade soil density. Figure 16 shows that the subgrade modulus is usually higher in the cut than in the fill.

Based on this comparison it could be concluded that the relative density of the soil is one of the most important factors on which the pavement modulus depends and that as the soil density increases the pavement modulus increases.

Further, the subgrade moisture content and the variations therein are dependent on the density of the subgrade soil. If the density is low, the moisture content and the variations therein are high, and the subgrade modulus and the variations therein are also high, while if the density is high, the reverse is true.

The above statement is justified by the subgrade modulus data for this project, which shows a variation of 19,500 to 7,600 = 11,900 psi for the fill and 17,400 to 12,500 = 4.900 psi for the cut, for an average soil density of 118 pcf in the fill and 132 pcf in the cut. The average moisture content in the fill is 18 and in the cut it is 14.

Project 18 - Rte. 29, Monroe

The cross section of the pavement on project 18 consists of a 7-inch asphaltic concrete layer over an 8-inch cement treated aggregate base. The modulus of this type of base is much stronger than that of the cement treated subgrade usually provided in Virginia. The project is located in a very highly resilient soil of the Piedmont area.



Figure 16. Location 17 (Rte. 211, Massey Corner) – Relationship between (1) pavement modulus (E_{av}) and air temperature, and (2) subgrade modulus and subgrade moisture.

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or **1932**





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The study on this project was started just after the construction was completed.

From the deflection data taken the E_s and E_{av} values were determined from the subgrade and pavement evaluation charts and are plotted in Figure 18, which also shows the five-day moving average air temperature recorded for the project.

The following conclusions are made for this project:

The pavement modulus is inversely proportional to the temperature, and the curves for the pavement modulus and temperature are sine curves with a phase difference of 90°. For a temperature variation of 29-78°F the pavement modulus in the cut varies from 300,000 to 640,000 psi, giving a temperature sensitivity of 6,900 psi per degree; and the pavement modulus in the fill varies from 220,000 to 480,000 psi, giving a temperature sensitivity of 5,300 psi per degree. These are the highest sensitivity values obtained among the seven satellite projects considered in this investigation. The construction specifications for this project are similar to those of the other projects. As previously discussed, the reason for the high sensitivity value could be that the asphaltic concrete lies on a rigid subbase.

Project 19 - Rte. 207, Bowling Green

Project 19 was not originally a part of this investigation and was added to permit further study of certain behaviour observed in the other projects. The pavement section consists of 11.5 inches of asphaltic concrete over 6 inches of cement treated subgrade.

Data collected on four different days for this project are summarized in Table 4.

TABLE 4

Section	Date	d _{max} (inches)	A (sq. inches)	E _s (psi)	E _{av} (psi)
A A	4-5-73 3-12-74	$0.0077 \\ 0.0064$	$\begin{matrix}0.2905\\0.2421\end{matrix}$	4,000 4,000	600,000 650,000
B B	7-2-73 3-12-74	$0.0162 \\ 0.0082$	0.5323 0.3193	5,000 4,000	225,000 500,000

MAXIMUM DEFLECTION d_{max} AND DEFLECTED BASIN AREA A ON PROJECT 19



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Figure 18. Location 18 (Rte. 29, Monroe) – Relationship between (1) pavement modulus (E_{av}) and air temperature, and (2) change in subgrade modulus during the seasons.

Table 4 shows the seasonal changes in the pavement modulus. Thus, section A had an E_{av} of 600,000 psi in April 1973 and an E_{av} of 650,000 psi in March 1974, a difference of 50,000 psi. Similarly, section B had an E_{av} of 225,000 psi in July 1973, i.e., during the summer, and an E_{av} of 500,000 psi in March 1974, i.e., the value almost doubled due to the change of season.

GENERAL EVALUATION

- 1. For the purpose of evaluating relevant parameters, the following charts were developed in this investigation:
 - (a) A subgrade and pavement evaluation chart based on the maximum deflection and spreadability. (See Figure 3.)
 - (b) Subgrade evaluation charts based on the maximum deflection and the deflected area. (See Figure 4.)
 - (c) A pavement evaluation chart based on the maximum deflection and the deflected area. (See Figures 5 through 10.)

The chart from (a) above could be utilized for low type primary flexible roads. Charts from (b) and (c) could be used for all types of flexible pavements.

2. This investigation has shown that when the strength of any one layer in the pavement system is less than that of the layers below it, the advantages of the layered system decreases with an increase in weakness and increase in the thickness of the weaker layer. Hence such a system should be used with caution.

As discussed under project 14, it is probable that the untreated aggregate layer provided under the asphaltic concrete layer and over the cement treated soil layer may provide a weak layer, especially if it contains a high percentage of moisture. It is therefore desirable that the thickness of this layer be as low as possible.

3. All seven projects have shown that the pavement modulus changes with the five-day moving average air temperature. Both the temperature and the pavement modulus curves are sine curves with a phase difference of 90°.

An example of the temperature effects during a given day is given below to further clarify the temperature effects.

On project 13, deflection tests were carried out on a morning in March 1974 and repeated in the afternoon. In the morning the air temperature was 60° F and the pavement surface temperature was 54° F; in the afternoon the air temperature was 90° F and the pavement surface temperature 91° F.

It was found that in the morning the d_{max} was 0.0179 inch and A was 0.5788 sq. inch; and in the afternoon the d_{max} was 0.02174 inch and A was 0.6167 sq. inch.

The subgrade and pavement evaluation charts (Figures 4 through 10) show that the subgrade moduli in the morning and the afternoon were the same and were 7,000 psi. The pavement modulus in the morning was about 300,000 psi and in the afternoon it was about 200,000 psi.

The above example shows that even the daily changes in temperature cause changes in the pavement modulus. A need for a temperature correction factor for pavement deflections is therefore evident.

- 4. All projects show differences in the pavement moduli for cuts and fills. These difference generally are not great, which indicates that they are minor effects of construction techniques.
- 5. The pavement support in all seven satellite projects can be divided into two classifications as follows:
 - (a) Those having a strong rigid support such as projects 18 and 19 wherein an asphaltic concrete overlies rigid layers such as 8 inches of CTB or 6 inches of CTS, and
 - (b) those having a weaker support or a weaker sandwiched layer system wherein an asphaltic concrete lies over a raw subgrade as in project 13, or over untreated aggregate subbase as in project 15, or over a weaker untreated aggregate sandwich layer as in projects 14, 16, and 17.

The evaluation of the projects and Table 2 shows that the pavement moduli are higher in cases where the asphaltic concrete layers have strong supports than in the cases where they have weak supports. This has been previously discussed under project 13.

- 6. Figures 19 and 20, drawn from the data given in Table 2, show that the temperature sensitivity of the pavement modulus is directly proportional to the pavement modulus and thickness of the asphaltic concrete. The pavement sensitivity increases with an increase in the pavement modulus and asphaltic concrete thickness, and vice versa. Also, as discussed under project 15, the temperature sensitivity is related to age. As age increases, the temperature sensitivity decreases.
- 7. As discussed under project 16, the modulus of the cement treated soil varies depending upon the type of soil, percent cement, etc.; however, an average modulus value of 100,000 psi for the material may be taken if the actual value is not known.



Sensitivity of pavement modulus v/s asphaltic concrete thickness for rigid and nonrigid subbases of the satellite projects. Figure 19.

5 O 9 8 0 Pavement Modulus Sensitivity per $^{\rm OF}$ x 10^3 ഹ 4 က ୦ନ 2 0 8 T Ò 0 0 4 0 600,000 500,000 100,000



8. As discussed under project 17, the relative density of the subgrade soil appears to be the most important factor on which the subgrade modulus depends, and the subgrade modulus increases with increased soil density. The subgrade moisture content and the variations therein are dependent on the density of the subgrade soil. If the subgrade soil density is low, the moisture content and the variations therein are high, and the subgrade modulus and the variations therein are also high. The reverse is also true. This statement is further supported by data obtained from project 15, on which the subgrade soil should have been fully compacted in its 12 years of life. On this project, the subgrade moisture varied very little.

CONCLUSIONS

- 1. The subgrade and pavement evaluation charts developed in this investigation could be utilized in a pavement rehabilitation program.
- 2. The effect of a weak sandwiched layer in reducing pavement strength should be considered during pavement design and evaluations.
- 3. The air temperature considerably affects the pavement modulus. There is a great need for correcting dynaflect deflections for temperature in Virginia.
- 4. The other factor that affects the value of the pavement modulus is the rigidity of the support for the asphaltic concrete. The greater the rigidity, the higher the pavement modulus.
- 5. The temperature sensitivity of the pavement modulus is directly proportional to the pavement modulus and thickness of the asphaltic concrete layer and inversely proportional to age.
- 6. The primary factor that affects the subgrade modulus appears to be the relative density of the subgrade soil. The subgrade moisture appears to be dependent upon the density of the subgrade soil. Low density soils cause a high subgrade moisture, a low subgrade modulus, and high variations in both the subgrade moisture and subgrade modulus. The reverse is also true.

RECOMMENDATIONS FOR RESEARCH

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1. Correlations between temperature and pavement modulus should be determined to make corrections in the deflection data obtained at different times in Virginia.

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2. Since the introduction of an untreated aggregate layer between the rigid subbases (such as cement treated soil or cement treated aggregate) and the asphaltic concrete considerably reduces the modulus of the overlying asphaltic concrete, it is necessary to investigate means of preventing cracking in cement stabilized subbases, which causes reflection cracks.

An alternative approach is to look into the use of certain materials other than untreated aggregate to prevent reflection cracks. As an example, high strength fabrics between asphalt concrete layers and cement stabilized subbase could provide ultimate economy in pavement cost.

NOTATIONS

a	= Thickness equivalency values of a material in a given layer.
Α	= Area of $1/2$ the deflected basin under 9,000 lb. wheel load in square inches.
A _d	= Area of $1/2$ the deflected basin under the dynaflect load in square inches.
Agg.	= Untreated aggregate.
СТВ	= Cement treated aggregate base.
CTS	= Cement treated subgrade soil.
d ₀ , d	1, d_2 , d_3 , d_4 = Deflections at 0, 1, 2, 3, and 4 feet from the center of the two applied loads.
D	= Thickness index of a pavement.
d _d	= Dynaflect deflection in inches.
d _{max}	= Maximum deflection under 9,000 lb. wheel load in inches.
Е	= Modulus of elasticity measured by deflection tests in psi.
Eav	= Equivalent modulus of the pavement measured by deflection tests in psi.
Em	= Modulus of the weak sandwiched layer in psi.
$E_{\mathbf{s}}$	= Equivalent modulus of the subgrade soil measured by deflection tests in psi.
h _{av}	= Equivalent thickness of the pavement in inches.
$h_{\mathbf{m}}$	= Thickness of the weak sandwiched layer in inches.
M.C.	= Moisture content.
S	= Spreadability.
Uav	= Average Poissions ratio of the pavement materials.
$\mathbf{U}_{\mathbf{S}}$	= Poissions ratio of the subgrade material.

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APPENDIX 1

CONDITIONS WHEN REQUIREMENTS OF SUBGRADE EVALUATION CHART ARE NOT SATISFIED

There are two conditions when requirements of the subgrade evaluation chart are not satisfied:

- (1) When the average modulus of the pavement is lower than the subgrade modulus; i.e., when E_{av} is lower than E_{s} .
- (2) When a weaker layer is sandwiched between two or more stronger layers.

The above conditions are explained by a set of three examples. An additional three examples are given for the type of sandwiched layered pavements used in Virginia.

- 1. Three examples of weaker layer over stronger layer:
 - (A) Weaker overlying layer E = 30,000 psi, U = 0.47 and h = 3 in. Stronger underlying layer - E = 100,000 psi, U = 0.47 andh = semi-infinite.
 - (B) Weaker overlying layer E = 30,000 psi, U = 0.47 and h = 6 in. Stronger underlying layer - E = 100,000 psi, U = 0.47 and h = semi-infinite.
 - (C) Weaker overlying layer -E = 30,000 psi, $U = 0.47 \text{ and } h_{av} = 9 \text{ in}$. Stronger underlying layer -E = 100,000 psi, U = 0.47 and h = semi-infinite.

These examples are shown by points A, B, and C in Figure A1, the subgrade evaluation chart. As can be seen they lie in the zone of "very poor pavements and need consideration for replacement." If the top weak pavement layer is replaced by a stronger layer, the pavement will have a much longer life. The subgrade evaluation chart shows that the mere removal of the top layer will increase the subgrade strength value to E = 100,000 psi. The remedy therefore could be either removal or stabilization of the weak layer.

If a stronger layer is provided over this weak layer, a weak sandwich layer system will be developed that could provide a weaker pavement system.

In the case of a weak sandwiched layer system the values of d_{max} and A depend on the following factors: (1) The thickness of the weak layer and the thickness of the layers above and below it, and (2) the ratio of the modulus of the weak layer to the moduli of the stronger layers in the pavement system.

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These conditions are explained by examples D, E, and F below. In these examples, the two-layer system in example C is covered with another layer of material having an E_{av} of 300,000 psi, which is higher than the modulus of the layer underneath it. The thicknesses of the overlying top layers are 3, 6 and 9 inches, respectively.

- 2. Three examples of sandwiched layer system:
 - (D) Top layer -E = 300,000 psi, U = 0.47 and h = 3 in. Middle layer -E = 30,000 psi, U = 0.47 and h = 9 in. Subgrade $-E_s = 100,000$ psi, U = 0.47 and $h_s = semi-infinite$
 - (E) Top layer E = 300,000 psi, U = 0.47 and h = 6 in. Middle layer - E = 30,000 psi, U = 0.47 and h = 9 in. Subgrade $- E_S = 100,000 \text{ psi}$, $U = 0.47 \text{ and } h_S = \text{semi-infinite}$
 - (F) Top layer -E = 300,000 psi, U = 0.47 and h = 9 in. Middle layer -E = 30,000 psi, U = 0.47 and h = 9 in. Subgrade $-E_S = 100,000 \text{ psi}$, $U = 0.47 \text{ and } h_S = \text{semi-infinite}$

These examples are shown by points D, E, and F in Figure A1.

Point D (with a 3-in. overlying layer) lies in the zone of "very poor pavements and need consideration for replacement." Hence from the location of point D (with a 3 in. strong layer over 9-in. weak layer) it is obvious that it would be economical to remove the weak layer before providing a 3-in. layer of a higher modulus material. The addition of strong layers of 6- and 9-in. thicknesses as shown in examples E and F above and as shown by points E and F in Figure A1, removes the pavement from the zone of "very poor pavements and need consideration for replacement" to a zone where no consideration for replacement is necessary. However, it should be noted that in between points D and E in Figure A1, i.e. with about a 4.5 in. thickness of the top overlying layer, the pavement as a whole has a strength equivalent to that of a mere subgrade having a modulus of 70,000 psi and zero pavement strength. This is a result of a 12-in. thick pavement over a subgrade strength of 100,000 psi when a weak sandwiched layer is introduced in the pavement system.

The above examples show the effect of the weaker and thicker sandwiched layers by which the pavement strength is reduced instead of being increased. Weak sandwiched layers, if adopted, should therefore be used with caution.

In Virginia, in order to avoid reflection cracks from the cement treated subgrade soil, an untreated stone aggregate layer is provided over the soil-cement and under the top asphaltic concrete. In some cases the untreated stone aggregate layer is found to be very weak, which decreases the pavement strength instead of increasing it. The thickness of the untreated stone aggregate layer should therefore be kept as low as possible, only as thick as needed to prevent reflection cracks. Three examples, G, H, and I, of such layered systems are given below.

3. Three examples of sandwiched layer systems usually practiced in Virginia to eliminate the effect of reflection cracks from cement treated subgrades.

In these examples the E of the asphaltic concrete has been taken as equal to 300,000 psi based on the data obtained from projects 18 and 19, which have asphaltic concrete layers directly over the cement or stone treated subgrade. The E value of untreated aggregate is taken as 30,000 psi based on the evaluation of the satellite projects. The E value of cement treated subgrade is taken as 100,000 psi based on the evaluation of project 16. The subgrade modulus values are based on the data obtained for projects in the Piedmont area. In fact, asphaltic concrete as shown would give still higher moduli if laid without an untreated aggregate layer below it, i.e. directly over the cement treated soil.

- (G) Top layer (AC) E = 300,000 psi, U = 0.47 and h = 3 in. Middle weak sandwiched layer (Agg.) - E = 30,000 psi, U = 0.47 and h = 6 in. Underlying layer (CTS) - E = 100,000 psi, U = 0.47 and h = 6 in. Subgrade -E = 5,000 psi, U = 0.47 and h = semi-infinite
- (H) Top layer (AC) E = 300,000 psi, U = 0.47 and h = 6 in. Middle weak sandwiched layer (Agg.) - E = 30,000 psi, U = 0.47 and h = 6 in. Underlying layer (CTS) - E = 100,000 psi, U = 0.47 and h = 6 in. Subgrade - E = 5,000 psi, U = 0.47 and h = semi-infinite
- (I) Top layer (AC) E = 300,000 psi, U = 0.47 and h = 9 in. Middle weak sandwiched layer (Agg.) - E = 30,000 psi, U = 0.47 and h = 6 in. Underlying layer (CTS) - E = 100,000 psi, U = 0.47 and h = 6 in. Subgrade - E = 5,000 psi, U = 0.47 and h =semi-infinite

These examples are shown by points G, H, and I in Figure A1 (subgrade evaluation chart) and Figure A2 (pavement evaluation chart for $E_{av} = 300,000$ psi). The pavement evaluation chart shows that for the 3-in. top layer (in example G) the equivalent pavement thickness = 6 in. By adding another 3-in. thickness, i.e. by providing a total thickness 6 in. of the layer having E = 300,000 psi in example H, the pavement evaluation chart shows that the equivalent pavement thickness has increased by only 2 in. (i.e. from 6 to 8 in.) instead of the additional 3 in. provided. Similarly by adding 6 in. of E = 300,000 psi to the thickness has increased by only 4 in. (i.e. from 6 to 10 in.) at point I instead of the additional 6 in. provided.

These examples therefore show that the effectiveness of the 3-in. asphaltic concrete reduces to 2-in. of the same material.

If the thickness of the weak sandwiched layer having E = 30,000 psi was decreased from 6 in. to 4 in., the decreased cost of 2 in. of material will outweigh the advantage of the change in strength. The economics would further improve if the thickness was further decreased. Thus, with a noncracking cement treated subgrade — and hence, no provision for untreated aggregate stone — the advantages will be very high.



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