

RESEARCH REPORT

TEMPERATURE DISTRIBUTION WITHIN ASPHALT
PAVEMENTS AND ITS RELATIONSHIP
TO PAVEMENT DEFLECTION

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INTRODUCTION

Asphalts "soften" as the temperature increases and "stiffen" as the temperature decreases, and measurements have shown that the deflection and rebound of asphalt pavements in response to loads are affected to a significant degree by temperature. Historically, pavements which deflect greatly under traversing loads are short-lived. Pavements which undergo minimal deflection at some maximum load are either inherently more rigid or are more firmly supported than those which undergo greater deflection. The rigidity or "stiffness" of asphaltic concrete is not a direct measure of strength, nor is deflection an inverse measure of the strength of a pavement structure. Strength is usually expressed as the load or stress which causes overt failure; whereas stiffness or rigidity

is concerned only with load-deflection (or stress-strain) relationships. It seems reasonable to say that the deflection of a pavement decreases as the thickness of the asphaltic concrete is increased and that the strength of the pavement structure is thereby increased. Therefore, in the case of a pavement which has a more-or-less uniform degree of support, deflection and thickness are empirical indicators of strength and structure adequacy. For lesser but uniform degrees of support, greater thicknesses of asphaltic concrete are compensating -- effectively reducing deflection and strengthening the pavement system. Of course, the supporting capabilities of underlying soil or base courses may be improved and(or) thickened to accomplish the same effect. Indeed, a multiplicity of inter-relationships is evident in a vast array of research literature concerning pavement design and performance. Elastic and viscoelastic theories have been extended and perfected, fatigue theories of failure have been studied, and each of these has been related with some degree of confidence to load and deflection.

Surface deflection (or rebound) remains the most measurable response of a pavement to an applied load. Adjustment of measured deflections to a common (or base) temperature offers further hope of reducing the temperature variate and improving the correlation between load-deflection and classical theory.

Pavement surface temperature alone does not suffice to account for the dependency of deflection on temperature; and, since temperature at depths are known to influence deflections, subsurface temperatures must be either measured in situ or estimated from other correlations. The purpose of this research (1) is as follows:

1. To develop a method for estimating the temperature at any depth in a flexible pavement up to twelve inches thick, and
2. To analyze the temperature-deflection data generated in the AASHO Road Test (2) to show that temperature adjustment factors are generally applicable to Benkelman beam deflection measurements of bituminous pavements and to determine the magnitude of these adjustment factors.

METHOD AND ANALYSIS

Analysis of Temperature Records

The data used to develop the temperature distributions and the prediction criterion were those recorded in 1964 and 1965 at the Asphalt Institute's laboratory at College Park, Maryland (3).

In this analysis, data for 12 consecutive months were punched on cards to facilitate data processing and analysis. All thermocouple readings had reasonable relationships to other thermocouples; thus all data were considered in further analyses. These data could be sorted into categories of general weather conditions, such as:

1. A normal sunny day, illustrated by Figure 1,
2. A passing cloud, causing a dip in the surface temperature, illustrated by Figure 2,
3. A rain shower, causing a sharp decrease in the slope of the curves, and
4. An overcast or rainy day, causing the surface temperature to be consistently lower than the temperatures at depths.

The data also revealed that once the disturbing influence was passed, the temperature distribution pattern resumed its normal shape (see

Figure
1

Figure
2

Figure 2), usually within six hours or less. They also revealed that in normal weather and at a given hour, the temperature at a given depth was approximately the same percentage value of the surface temperature, even though the surface temperatures fluctuated from day to day. For a given depth, temperature fluctuations followed an orderly pattern and were influenced primarily by the surface temperature -- which, in turn, was influenced by such factors as:

1. Solar radiation
2. Site features
3. Time of day
4. Weather conditions
 - a. Degree of sunshine
 - b. Amount of rain
 - c. Snow
 - d. Cloud cover
 - e. Wind
5. Air temperature
6. Subsurface temperature.

The data showed that a short period of rain and extensive cloud cover reduced the surface temperature and influenced the temperatures at shallow depths; however, extended periods of inclement weather reduced the surface temperature to nearly the level of the air temperature and proportionately decreased the temperature throughout the 12-inch thickness. Air temperatures generally dropped and recovered more slowly than the pavement surface temperature. Therefore, air-temperature history was an indication of previous long-term influences on the temperatures at various depths.

Mean daily air temperatures, a measure of the air-temperature history, were computed as the average of the highest and lowest air temperatures for each day. This particular method was chosen for the following reasons:

1. The U. S. Weather Bureau uses this system for each reporting weather station, thus air temperature data would be readily available,
2. The U. S. Weather Bureau report does not contain air temperatures for each hour of the day, and
3. This method has some precedence in engineering work.

Figures
3 & 4

Consideration of air-temperature history provided an interesting and valuable result as shown in Figures 3 and 4. In Figure 3, a linear relationship between mean pavement temperatures (average of temperatures at the 0.125-, 4.0-, and 8.0-inch depths) and 0.125-inch depth temperatures is shown for each calendar month. The relationship of the months, their temperature ranges, and the seasonal changes in temperatures can be readily seen. The addition of mean-monthly air temperature to each respective monthly line in Figure 3 produced Figure 4. The addition of air-temperature history to each respective month reduced the scatter of the data such that one straight line could replace all of the monthly lines. Similar analyses for 4-inch and 12-inch thick pavements indicated the same general relationships.

Regression Analysis of Temperatures with Respect to Depth

The only daily temperature data that were deleted prior to regression analyses were eliminated for one of two reasons, as follows:

1. Recorder was out of operation due to maintenance, or

2. The first two days of recorded pavement temperatures after a missing day of data were eliminated because the antecedent air temperatures were also missing from the source data. This resulted in the elimination of 47 days of data. Therefore, data for 318 days were used in the final analysis.

To develop relationships to be used in later analyses, a regression analysis was made of the temperature-depth data. Because the method of estimating temperatures would ultimately be used to adjust Benkelman beam deflections, data for 0600 through 1900 hours were analyzed since most deflection tests would be performed during these hours.

To approximate the temperature-depth relationships for a given hour, a review of the data suggested the need for a polynomial equation of the form

$$Y = C_1 + C_2X + C_3X^2 + \dots + C_nX^{n-1} \quad (1)$$

where Y = temperature in °F at depth X ,

X = depth in inches from the pavement surface, and

$C_1, C_2, C_3, \dots, C_n$ = coefficients determined by the method of least squares.

Results showed that for the hours 0600, 0700, and 0800, a third-order polynomial provided the best fit, and a fourth-order polynomial was very nearly as accurate. For the remaining hours, a fifth-order polynomial gave the best fit, and again the fourth-order was very nearly as accurate. Therefore, a fourth-order polynomial was chosen for data representing all hours.

Standard errors of estimate were calculated by a computer program and the maximum difference between the observed temperature value and the value calculated from the polynomial was recorded. Analysis showed that the average standard error of estimate was approximately 0.50°F -- the least being 0.09°F and the maximum being 2.20°F . The maximum difference between the observed and calculated temperatures ranged from 0.17°F to 4.54°F and an average of 318 values yielded 0.95°F . The large differences, such as the 4.54°F , were verified by inspection of the temperature-depth data, which revealed that the real distribution was erratic. Days of data were picked at random, and further checks between observed and calculated values indicated that the curves were smooth and in close agreement with real temperatures at the respective depths.

The temperatures at the surface and at each half-inch increment of depth through 12 inches were calculated by means of the fourth-order polynomial equation determined for the respective day. Temperatures so calculated were plotted as ordinate values versus the measured surface temperature plus an average air-temperature history preceding the day of record (a separate graph for each depth was prepared). The plot for the 6-inch depth is presented in Figure 5; there, the average air-temperature history was computed for five days prior to the day of record. The optimum number of days for the air-temperature history was determined by further investigations described below.

The addition of an average air-temperature history to the surface temperatures was found to produce a favorable shift in the abscissa values in relation to the fixed ordinate values. Average air temperatures were computed for 1, 2, 3, 5, 7, and 10 days preceding each day of record; each set of data was adjusted and evaluated in terms of

Figure
5

standard error of estimate. The standard error of estimate decreased to a minimum when two days of air-temperature history were added and then increased as the number of antecedent days increased. The minimum standard error of estimate for the 6-inch depth and for the hours 0600 through 0900 and 1800 and 1900 occurred when a ten-day average air-temperature history was added; and for the hours of 1100 through 1700 a two- to five-day average air-temperature history was optimum.

Figure
6

Figure 6 was drawn to find the number of days of average air-temperatures that gave the least standard error of estimate for all depths and all hours under consideration. Ordinate values are the averages of all standard errors of estimate for all depths and for all hours under consideration, and the number of days considered is plotted on the abscissa. As can be seen, accuracy does not increase significantly beyond the five-day point. Therefore, only the five previous days are considered to be significant. Further analysis of the standard errors of estimate showed that the five-day average air-temperature history sufficed for all depths greater than 2 inches. The least standard errors of estimate for the depths 0 inches through 2 inches indicated that the best estimate was obtained by the use of the surface temperature alone. Pavement temperatures in the top 2 inches of the pavement are directly dependent upon the hour of the day and the amount of heat absorption whereas temperatures at depths greater than 2 inches are assumed to be a function of the surface temperature, amount of heat absorption, and the past five days of temperature history.

A complete set of curves giving the best estimate of temperature at the several depths and by hour of the day was developed and the set of curves for 1300 hours is shown in Figure 7 as a typical example.

Figure
7

Development of Deflection Adjustment Factors for Temperature Effects

Two types of adjustment factors were considered. The first was to assign an incremental deflection to each degree of temperature difference between the pavement temperature and the reference or standard temperature. This type of correction was employed by Kingham and Reseigh (4) and by Sebastyan (5); however, the magnitude of suggested corrections differed. The second method considered was the use of a dimensionless, multiplicative factor that could be applied to a measured deflection at some known surface temperature or a known mean temperature of the pavement. No known reference in the literature mentions the second method.

Inspection of the AASHO Road Test curves (2, Figures 89a, b, c, and 90a) suggested that the dimensionless, multiplicative factor method might be more appropriate. Therefore, in this study, the above AASHO curves were transformed to semilogarithmic plots, temperature being the logarithmic scale. The data plotted as straight lines, and the slopes of the individual curves for each loop were very nearly parallel; however, the slopes for the several loops were not parallel. Each surfacing thickness was the average of three structural cross sections. The equation for the straight lines was

$$M = \frac{Y_2 - Y_1}{\log T_2 - \log T_1} \quad (2)$$

where M = slope of the straight line,

Y_1, Y_2 = deflection values, and

T_1, T_2 = mean pavement temperatures in °F corresponding to the Y_1 and Y_2 deflection values, respectively.

After the slope had been determined, the deflections were computed for mean pavement temperatures 30°F through 150°F, on 10°F-intervals, by the equation

$$Y_3 = Y_1 + M(\log T_3 - \log T_1) \quad (3)$$

where Y_3 = deflection at the temperature T_3 ,

Y_1 = same Y_1 used in Equation 2,

M = slopes as determined in Equation 2,

T_3 = temperature, °F, at which the deflection was computed, and

T_1 = same T_1 used in Equation 2.

A mean temperature of 60°F was chosen as the reference temperature, T_{60} .

The adjustment factors were derived by the equation

$$AF = \frac{Y_{60}}{Y_3} \quad (4)$$

where AF = the adjustment factor used to adjust measured deflections due to temperature effects,

Y_{60} = computed deflection, in inches, for the mean pavement temperature 60°F from Equation 3, and

Y_3 = computed deflection, in inches, for a particular mean pavement temperature T_3 from Equation 3.

Table
1

Thus, the adjustment factor is a pure number. Table 1 shows the sample calculations for the 4-inch pavement on Loop 5. Each of the twelve adjustment-factor curves was computed according to Equations 2, 3, and 4 and the curves plotted arithmetically (Figure 8) with mean pavement temperature, T_3 , on the ordinate axis and the adjustment factor, AF , on

Figure
8

the abscissa axis. Deflections, Y_3 , computed from the twelve individual curves at a given mean pavement temperature, T_3 , were added and averaged to obtain the final adjustment-factor curve shown in Figures 8 and 9.

Figure
9

Further analysis showed that there may be a relationship among average structures within a given loop -- that is, except for the 8.6-inch, asphalt-treated base curve, which for some unknown reason was an outlier. There was no consistent relationship between loops and sub-structures as evidenced by the 2-inch surfacing on Loop 3 and the 6-inch surfacing on Loop 6, where the total structural thicknesses were 9 inches and 24 inches respectively; yet each had the same adjustment-factor curve. The same situation was present in regard to the 4-inch surfacing on Loop 3 and the 16.1-inch, asphalt-treated base section which had total structural thicknesses of 11 and 24.1 inches, respectively. The above structural relationships may have been obscured by the AASHTO approach of averaging deflections for a given surfacing thickness within a loop; however, the AASHTO structural-equivalency equation showed that in some cases the structural indices were vastly different. Another analysis might be made of the AASHTO data (2, Figures 89a, b, c, and 90a) with the raw data grouped according to surfacing thickness and structural index without regard to locations.

The adjustment-factor curve for temperature effects is applicable only to creep-speed deflections because the source data used in the analysis were taken at creep speed. Further analysis would be required to establish applicability to deflections taken at other than creep speed.

The adjustment-factor curve is applicable to any loading so long as the deflection is to be adjusted to the reference temperature for

Relationship Between Temperature-Adjustment Factors and Modulus of Elasticity of Asphaltic Concrete

Reflection upon the Boussinesq equation for deflections at the center of a flexible plate,

$$Y = \frac{1.5 Pa}{E} \quad (5)$$

where Y = surface deflection in inches,

P = unit load on circular plate,

a = radius of plate, and

E = modulus of elasticity of the material,

discloses that the deflection is a linear function of load as well as the modulus of elasticity of the material -- which may be affected by temperature. In turn Burmister's equation for deflections under a flexible plate, using a two-layer elastic system (6),

$$Y = \frac{1.5 Pa}{E_2} F_2 \quad (6)$$

where E_2 = modulus of elasticity of lower layer, and

F_2 = dimensionless factor depending on the ratio of moduli of elasticity of the subgrade and pavement as well as the depth-to-radius ratio,

indicates that deflections are also a function of pavement thickness and the modulus of elasticity of the pavement layer and the underlying material. The load and the radius of contact area could be considered constant for a given axle load and tire pressure.

The surface deflections (2, Figures 89a, b, c and 90a) were used to calculate the modulus of elasticity by the Boussinesq equation (Equation 5). This was an apparent modulus, E_c , of the composite

Figure
10

structure of the pavement. When these values were plotted against respective thicknesses of asphaltic concrete, Figure 10, a straight line could be passed through the data points for a given Loop section at each temperature; and, upon extrapolation to zero thickness (temperature-affected thickness, in the case of asphalt-treated bases), the respective lines converged at an approximate value of 8400 psi. This was considered to be the subgrade modulus E_2 of Burmister's two-layered, elastic theory equation. The F_W factors were obtained by

$$F_W = \frac{E_2}{E_C} \quad (7)$$

where F_W = Burmister's settlement coefficient.

Burmister's influence curves (6) were used to obtain the ratio of E_1/E_2 . The modulus of elasticity of the asphaltic concrete was obtained from

$$E_1 = N \times E_2 \quad (8)$$

where

$$N = \frac{E_1}{E_2}$$

The above calculations were made using the deflections at various temperatures and the E_1 -values were averaged for each temperature.

Simultaneous solution of the equation

$$\log_{10} E_1 = \frac{A}{T_A} + B \quad (9)$$

where T_A = absolute temperature ($^{\circ}R = ^{\circ}F + 460^{\circ}F$),

E_1 = average modulus of elasticity of asphaltic concrete at T_A , and

A, B = constants,

Figure
11

for two different temperatures determined the values A and B. Extrapolated values for E_1 at 30°F, 40°F, 100°F, 120°F and 140°F were then calculated. Figure 11 shows that the resulting modulus of elasticity of the asphaltic concrete pavement has a curvilinear relationship with temperature. Note that the shape of the curve is very similar to the adjustment-factor curve shown in Figure 9. The shape of the temperature-modulus curve derived by elastic theory clearly substantiates the adjustment-factor curve derived by statistical procedures. A correlation graph is shown in Figure 12. It is seen that the adjustment factor and the modulus of elasticity are related, at any stated temperature, by the equation given in Figure 12.

Figure
12

Comparison of Derived Temperature Distributions and Adjustment Factors with Data from Other Test Roads

Data are being gathered now by the Asphalt Institute (7) from a test site at San Diego, California. The flexible pavement at this test site contains thermocouples embedded in the pavement, and temperatures are being recorded at this time. Two days of temperature distributions, October 6, 1966, and February 17, 1967, together with their respective five days of high and low air temperatures have been received from the Asphalt Institute and checked by the temperature prediction procedure described in this report. The predicted temperatures varied generally within $\pm 6^\circ\text{F}$ from the observed temperatures at the various levels. The Asphalt Institute also furnished temperature distribution data for the Colorado test pavement reported by Kingham and Reseigh (4). Table 2 contains the summary of the analyses for both San Diego and Colorado data, each compared to the temperatures predicted by the method reported herein and developed from the College

Table
2

Park data. A few temperatures fell outside two standard errors of estimate; however, most of the data are well within these tolerances.

An interesting comparison between modulus of elasticity of asphaltic concrete, E_1 , derived from the AASHO data, Figure 11, and laboratory measurements of the complex modulus, $\{E^*\}$, is also provided by Kallas' tests (8) on asphaltic concretes used on the Colorado test pavement (cf. 4). Kallas' Figure 3a (8), showing $\{E^*\}$ plotted against temperature is shown here as Figure 13. $\{E^*\}$ was determined by sinusoidal tension and compression loading. The most favorable agreement is with respect to the 1-cps loading frequency. The similarity between this curve and the curve in Figure 9 seems extraordinary.

Figure
13

SUMMARY AND RECOMMENDATIONS

A practical and reasonably accurate method of estimating the temperature distributions within flexible pavements has been developed. This method can be used to analyze deflection data at any time if the hour of the day and the surface temperature are included in the recorded data.

The relationship between mean pavement temperature and deflection allows any deflection test value to be adjusted to a reference temperature if the mean temperature of the pavement at the time of testing is known or is estimated by the method outlined herein.

Further study is needed to test the assumption that the average air-temperature history allows this system of estimating pavement temperature distributions to be used in other areas of the world. Additional data are needed to determine whether the average air-temperature history adequately takes into account the effects of latitude and alti-

Theoretical analysis of the AASHO pavement deflection data by the two-layered elastic theory shows a curvilinear relationship between modulus of elasticity of asphaltic concrete and temperature: the magnitude of the moduli are such that a straight-line relationship exists between moduli and the multiplicative, temperature-deflection, adjustment factors.

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4. R. I. Kingham and T. C. Reseigh, "A Field Experiment of Asphalt-Treated Bases in Colorado," Preprint Volume, Second International Conference on the Structural Design of Asphalt Pavements, University of Michigan, 1967, pp. 767-790.

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Table 1

SAMPLE CALCULATIONS SHOWING DEVELOPMENT OF DEFLECTION
ADJUSTMENT FACTORS FOR THE 4-INCH PAVEMENT ON LOOP 5
OF THE AASHO TEST ROAD

TEMPERATURE, T_3 ($^{\circ}$ F)	DEFLECTION, Y_3 , AT TEMPERATURE T_3 (INCHES)	ADJUSTMENT FACTOR
40	0.01562	1.7106
50	0.02173	1.2293
60	0.02672	1.0000
70	0.03094	0.8636
80	0.03460	0.7723
90	0.03783	0.7063
100	0.04071	0.6563
110	0.04333	0.6167
120	0.04571	0.5846
130	0.04790	0.5578
140	0.04993	0.5351
150	0.05182	0.5156

$T_1 = 52^{\circ}$ F = Average Pavement Temperature, T_A
 $T_2 = 80^{\circ}$ F = Average Pavement Temperature, T_A
 $Y_1 = 0.0228$ = Deflection Corresponding to T_1
 $Y_2 = 0.0346$ = Deflection Corresponding to T_2

Table 2

COMPARISON OF MEASURED PAVEMENT TEMPERATURES AT SAN DIEGO AND
 COLORADO TEST SITES TO ESTIMATION OF TEMPERATURES BY METHOD
 BASED UPON COLLEGE PARK, MARYLAND, DATA

LOCATION	DEPTH (INCHES)	NUMBER OF OBSERVATIONS	AVERAGE DIFFERENCE BETWEEN OBSERVED AND ESTIMATED TEMPERATURES (°F)	STANDARD DEVIATION (°F)
COLORADO	2.00	59	-2.68	5.03
	4.60	4	-4.75	6.61
	5.50	5	-1.40	3.55
	5.75	25	+1.72	5.51
	6.00	25	+1.96	5.94
	7.50	4	-0.25	3.71
	9.00	5	+1.60	4.24
	10.50	50	+2.82	7.09
SAN DIEGO	3.00	2	0.00	0.00
	3.10	2	-2.00	1.41
	3.40	2	-6.00	6.00
	3.50	11	-3.50	4.69
	6.50	2	-2.50	2.55
	9.40	11	+0.09	2.50
	9.50	2	-2.50	2.55
	10.80	2	-2.50	2.55
	11.50	2	-3.50	3.54

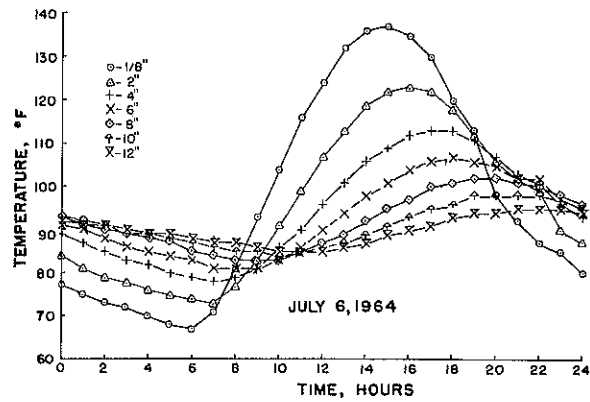


Figure 1 Temperature Distribution in an Asphaltic Concrete Pavement vs. Time, Illustrating a Normal Sunny Day

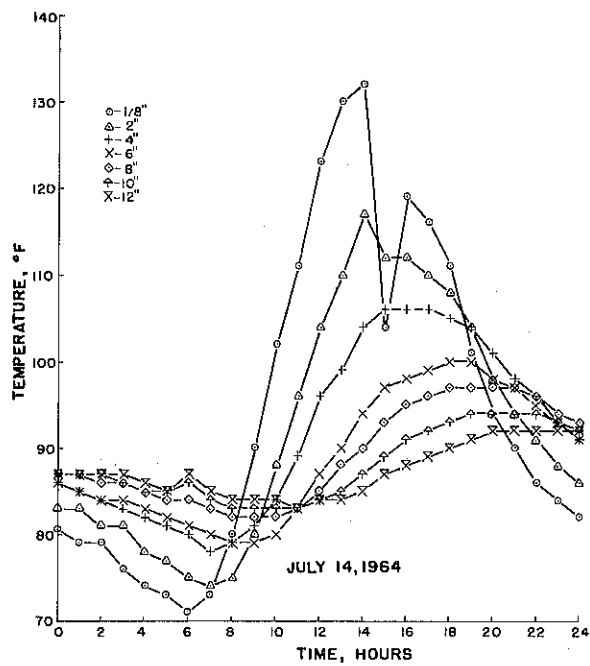


Figure 2 Temperature Distribution in an, Asphaltic Concrete Pavement vs. Time, Illustrating the Effects of a Passing Cloud

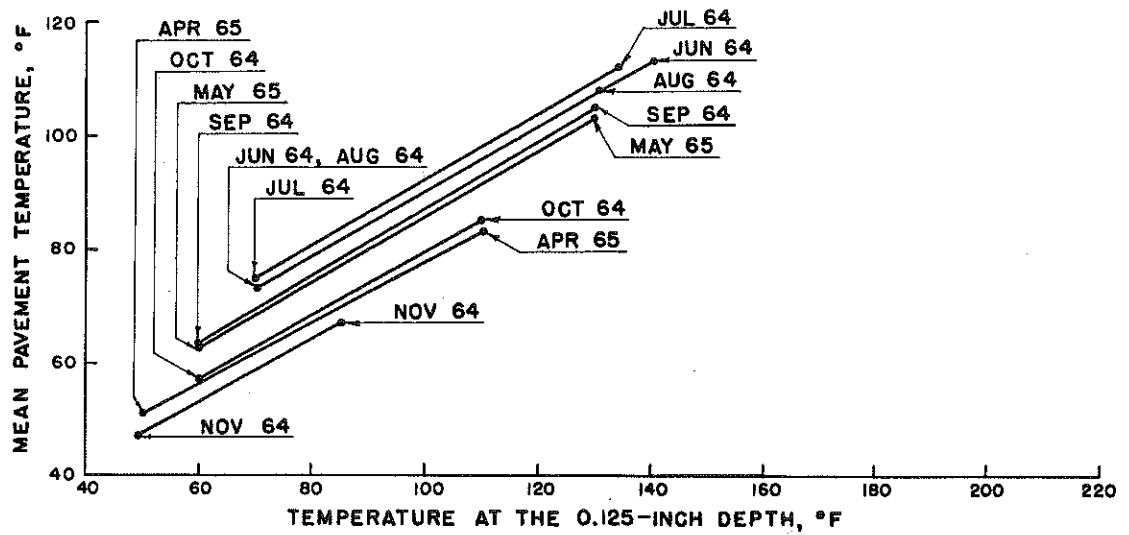


Figure 3 Mean Pavement Temperature by Calendar Months for an 8-inch Thick Pavement at 1300 Hours vs. Temperature at the 0.125-Inch Depth

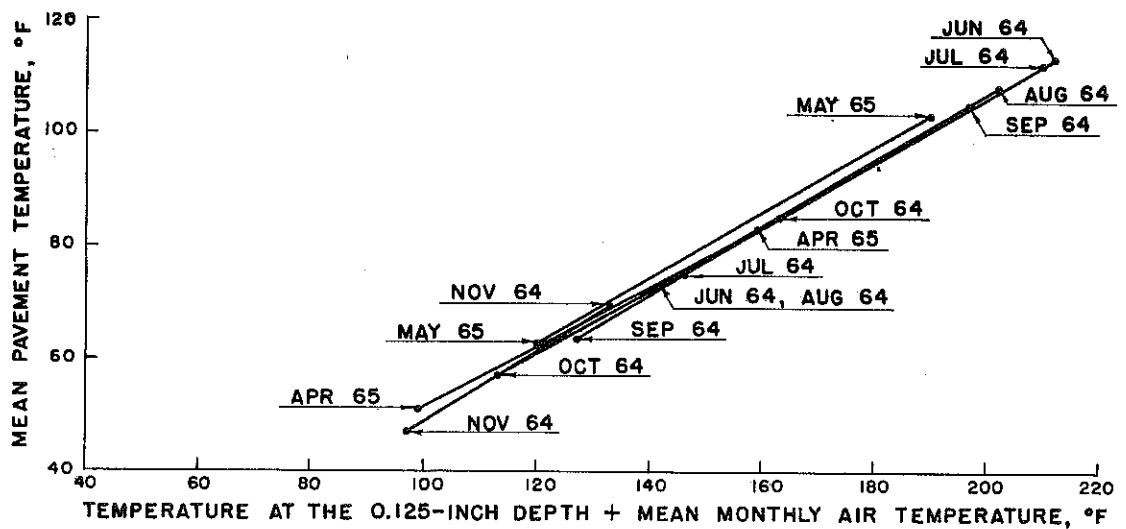


Figure 4 Mean Pavement Temperature by Calendar Month for an 8-Inch Thick Pavement at 1300 Hours vs. Temperature at the 0.125-Inch Depth Plus 30-Day Mean Air-Temperature History

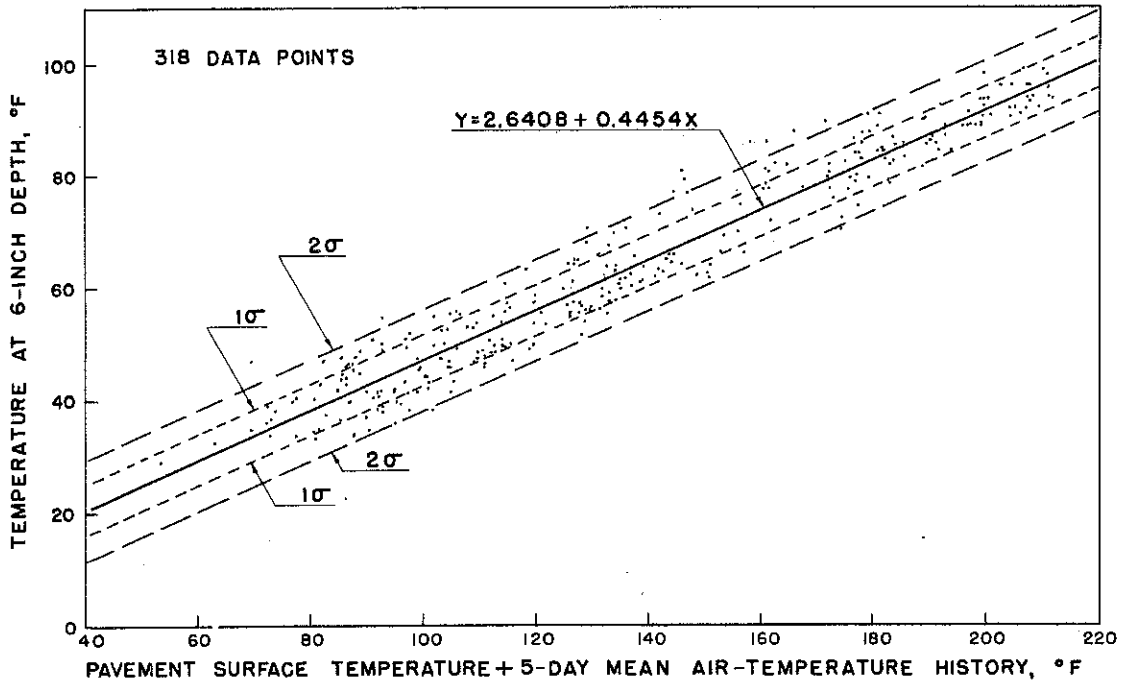


Figure 5 Temperature at the 6-Inch Depth vs. Measured Pavement Surface Temperature at 1300 Hours Plus 5-Day Mean Air-Temperature History

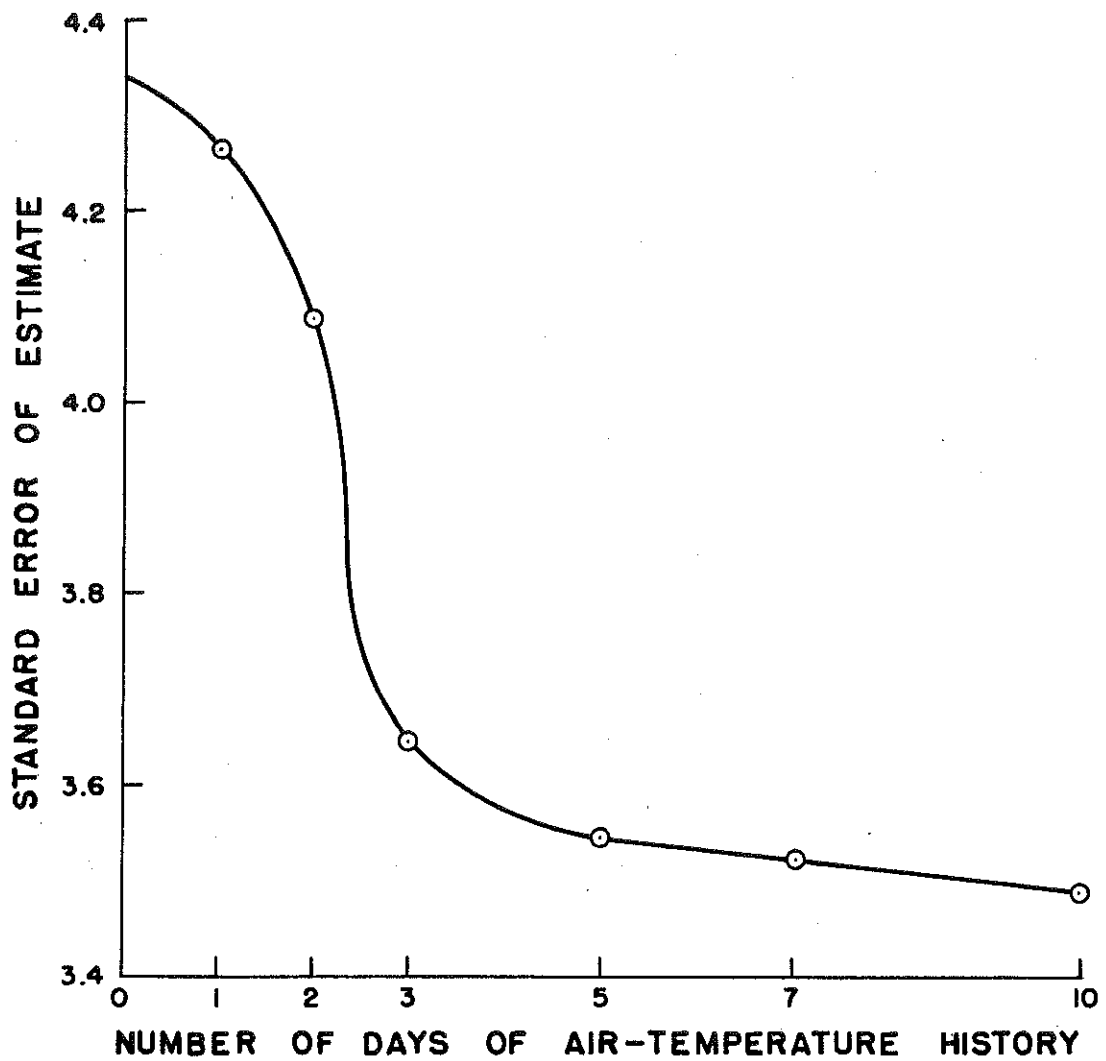


Figure 6 Standard Error of Estimate for All Depths and All Hours vs. Number of Days of Air-Temperature History

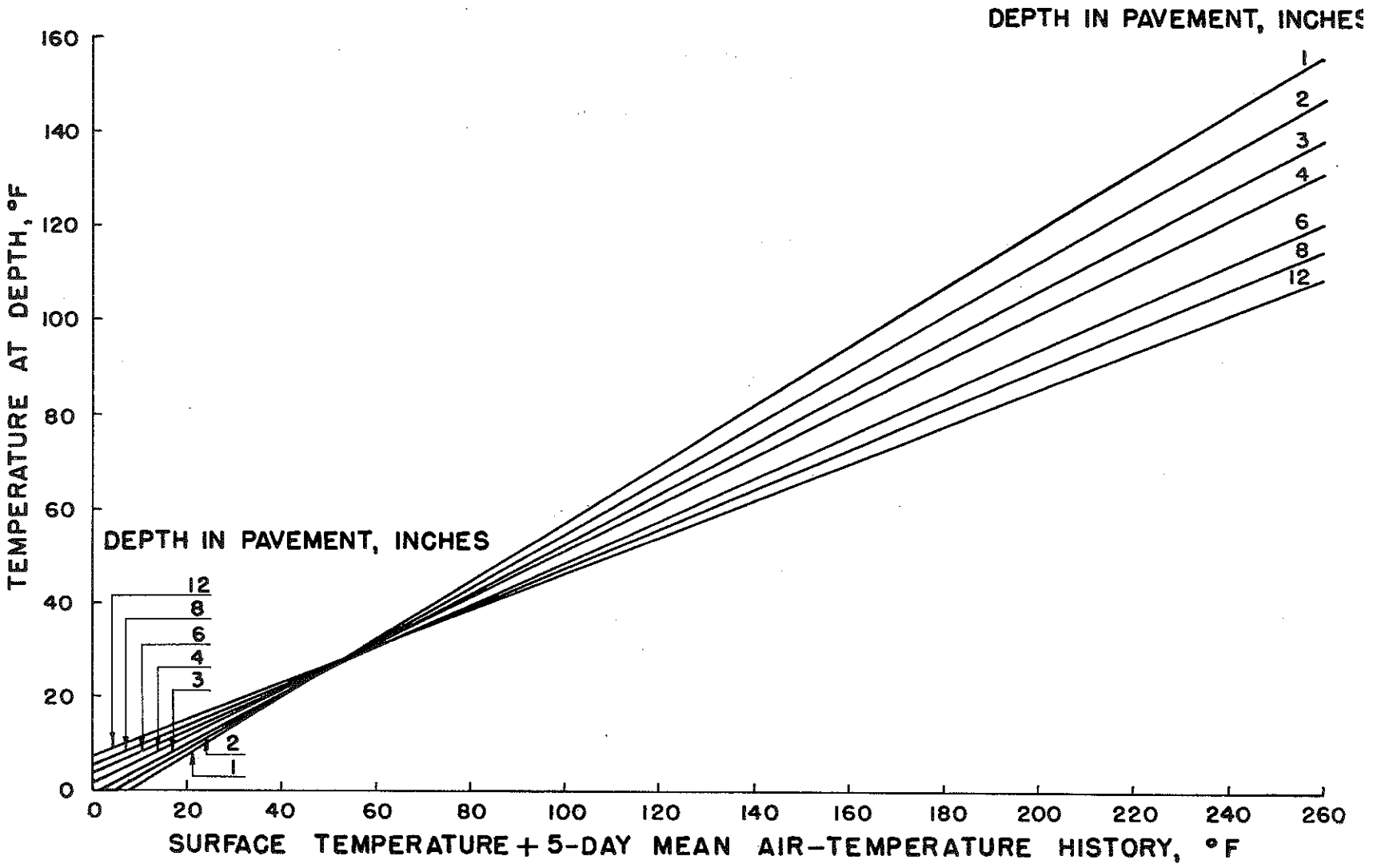


Figure 7 Temperature-Depth Prediction Graph at 1300 Hours for Pavements Greater Than 2 Inches Thick

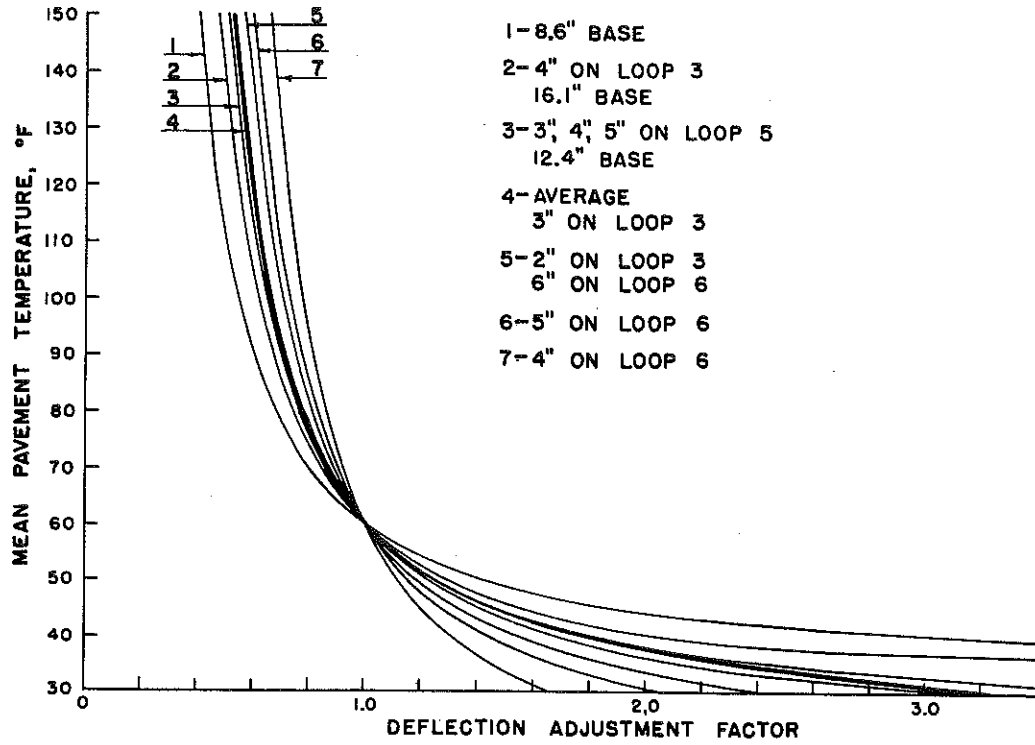


Figure 8 Mean Pavement Temperature vs. Deflection Adjustment Factors for Various Loops

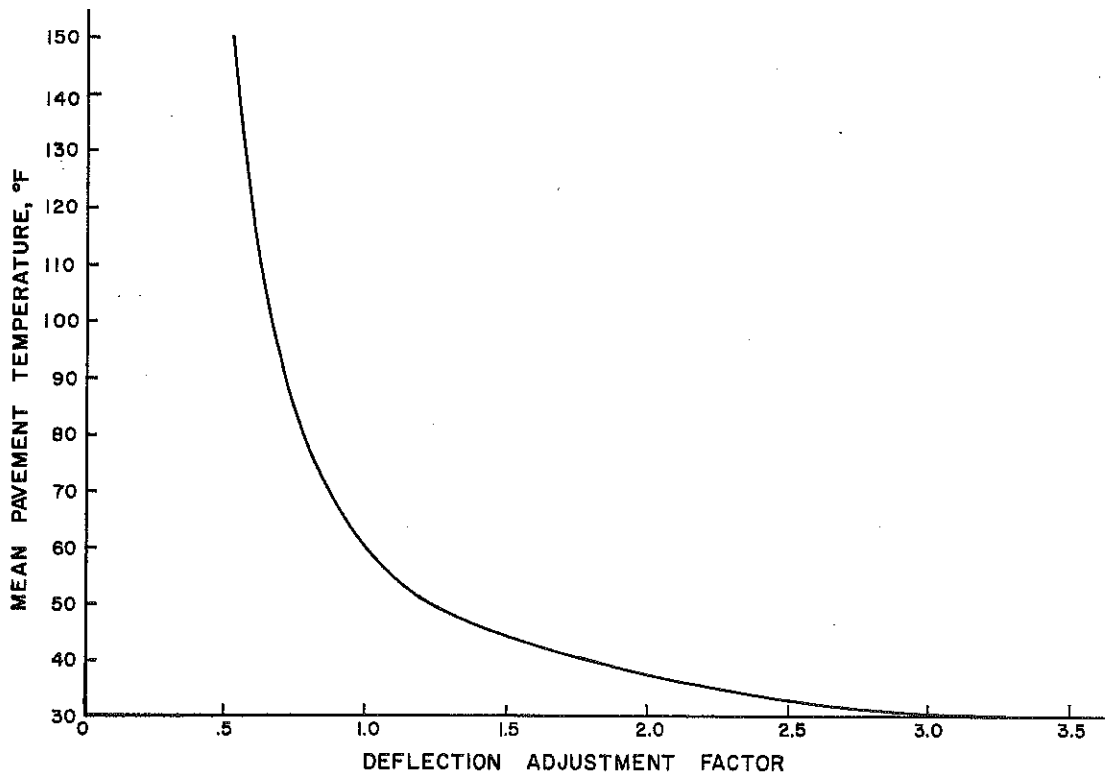


Figure 9 Mean Pavement Temperature vs. Average Deflection Adjustment Factor

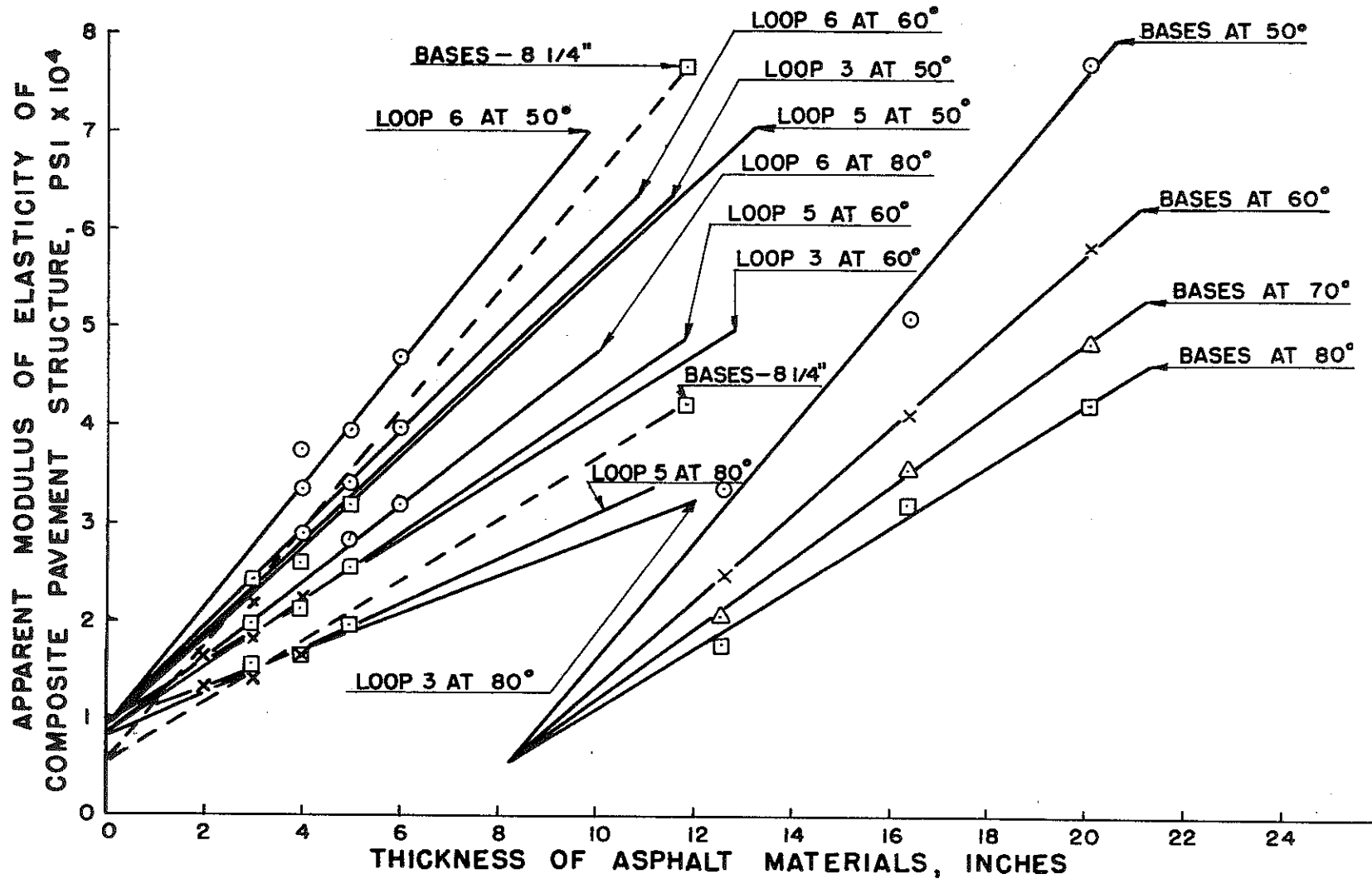


Figure 10 Apparent Modulus of Elasticity of Composite Pavement Structure vs. Pavement Thickness

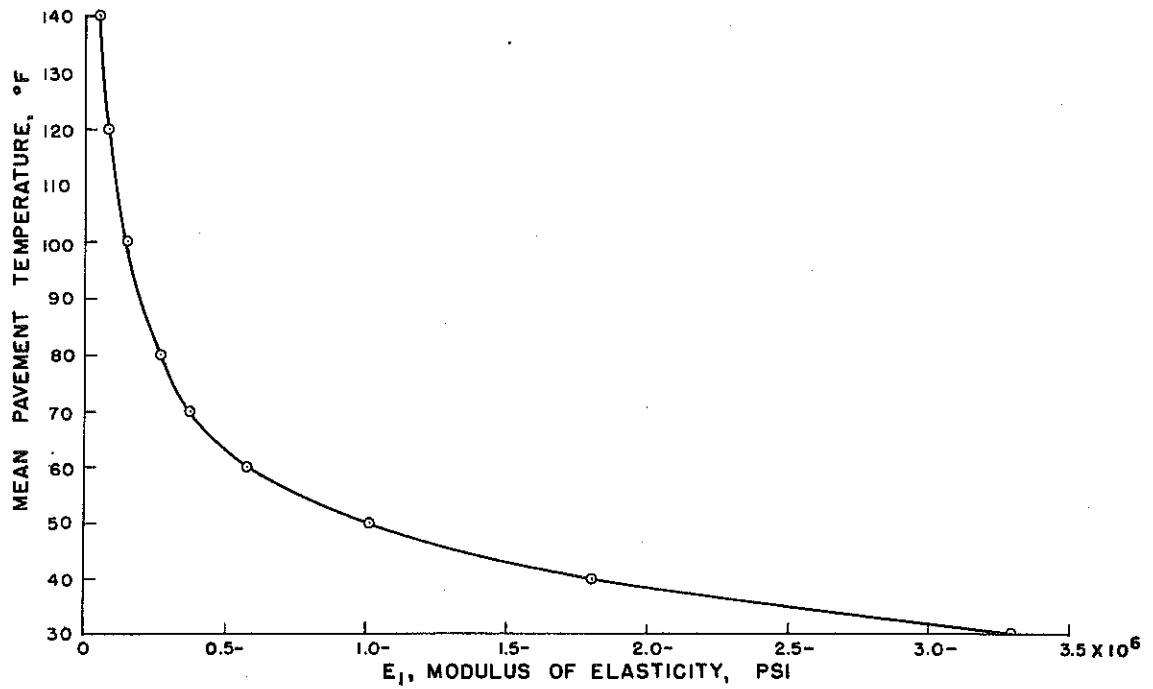


Figure 11 Mean Pavement Temperature vs. Modulus of Elasticity for Asphaltic Concrete Pavement

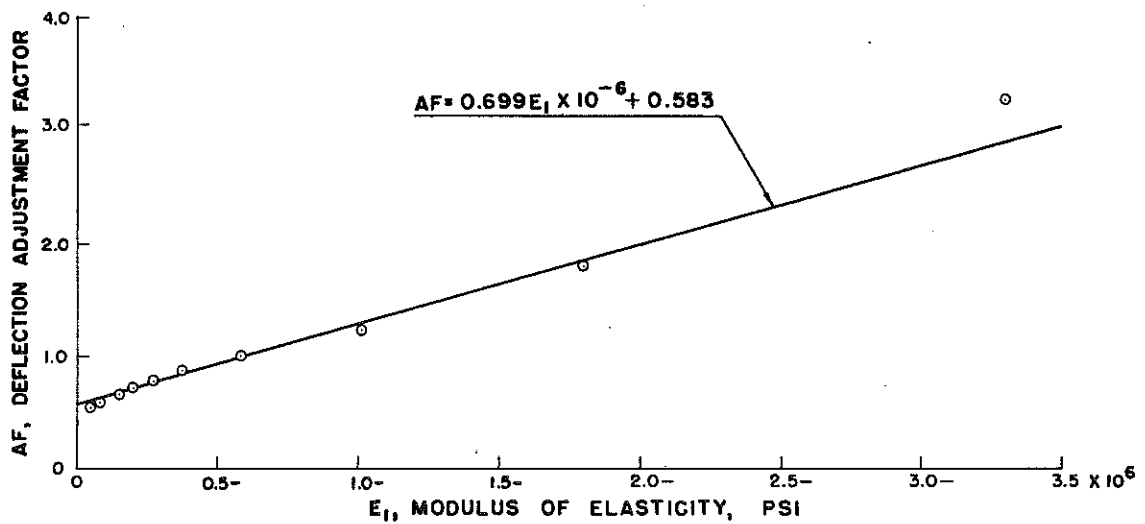


Figure 12 Correlation Between Adjustment Factor and Modulus of Elasticity for an Asphaltic Concrete Pavement

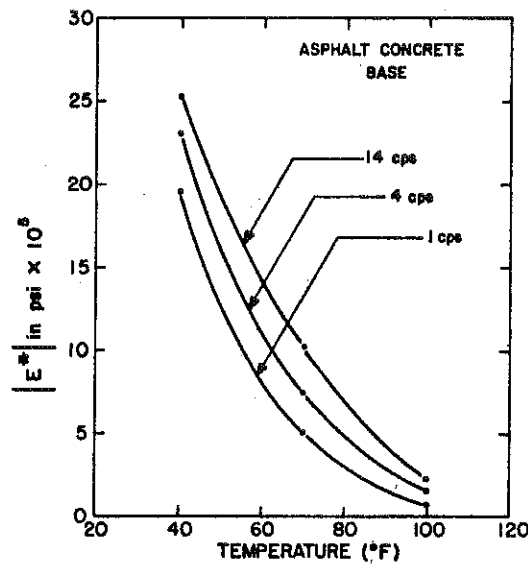


Figure 13 Relationship Between $|E^*|$ and Temperature for Various Loading Frequencies (8, p. 794)