Temperature Distribution Within Asphalt Pavements and Its Relationship to Pavement Deflection

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A method has been developed to estimate the temperatures at depth in an asphaltic concrete pavement utilizing the measured pavement surface temperature and the 5-day average air temperature history. Temperature prediction nomographs were developed for each hour between 6 a.m. and 5 p.m. This temperature prediction method is independent of the season of the year. A method for adjusting Benkelman beam deflections for temperature effects has been developed and is presented. This enables the deflections taken at any temperature to be adjusted to a reference temperature, thus making possible direct comparisons of deflections.

An analysis of AASHO Road Test data was made using the Boussinesq and Burmister equations and charts. The results indicate that the temperature-modulus of elasticity relationship is curvilinear, has the same basic shape found by Kallas in the laboratory, and has the same basic shape as the temperature-deflection adjustment factor curve. There appears to be a linear relationship between deflection adjustment factors and modulus of elasticity. Therefore, there seems to be a temperature-deflection-modulus of elasticity correlation between field test data and theory.

•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 that deflect greatly under traversing loads are short-lived. Pavements that undergo minimal deflection at some maximum load are either inherently more rigid or are more firmly supported than those that 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 that causes overt failure, whereas stiffness or rigidity is concerned only with load-deflection (or stress-strain) relationships. It seems reasonable 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 that has a more or less uniform degree of support, deflection and thickness are empirical indicators of strength and structural 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. 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.

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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, because temperatures 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 (a) to develop a method for estimating the temperature at any depth in a flexible pavement up to 12 in. thick, and (b) 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. A study of the data 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.

The data showed that a short period of rain or 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-in. pavement 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, and 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;
3. This method has some precedence in engineering work.

Consideration of air-temperature history provided an interesting and valuable result, as shown in Figures 1 and 2. In Figure 1, a linear relationship between mean pavement temperatures (average of temperatures at the 0.125-, 4.0-, and 8.0-in. depths) and 0.125-in. 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 1 produced Figure 2. 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- and 12-in. 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 analysis were eliminated for one of two reasons: either the recorder was out of operation because of maintenance, or the first two days of recorded pavement temperatures after a missing

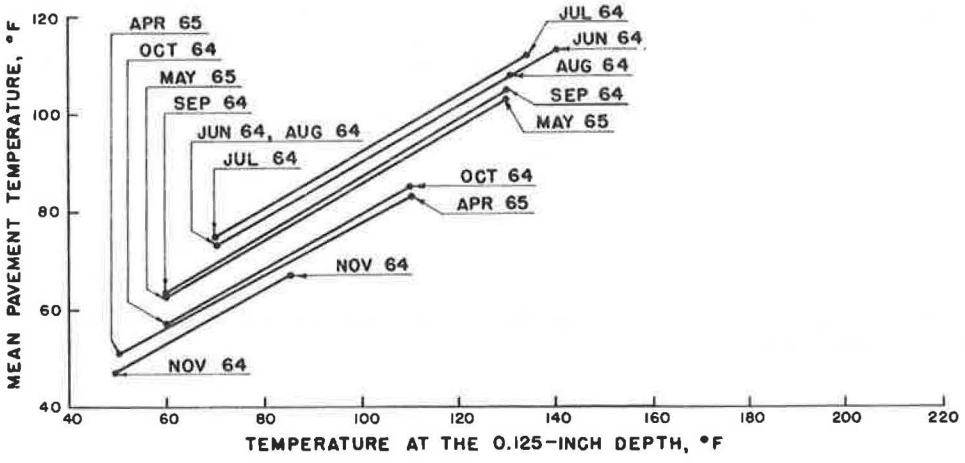

Figure 1. Mean pavement temperature by calendar month for an 8-in. thick pavement at 1:00 p.m. vs temperature at the 0.125-in. depth.

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 taken from 6 a.m. through 5 p.m. were analyzed because 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

$$Y = C_1 + C_2X + C_3X^2 + \ldots + C_nX^{n-1} \tag{1}$$

where

Y = temperature in degrees F at depth X,
X = depth in inches from the pavement surface, and
$C_1, C_2, C_3, \ldots C_n$ = coefficients determined by the method of least squares.

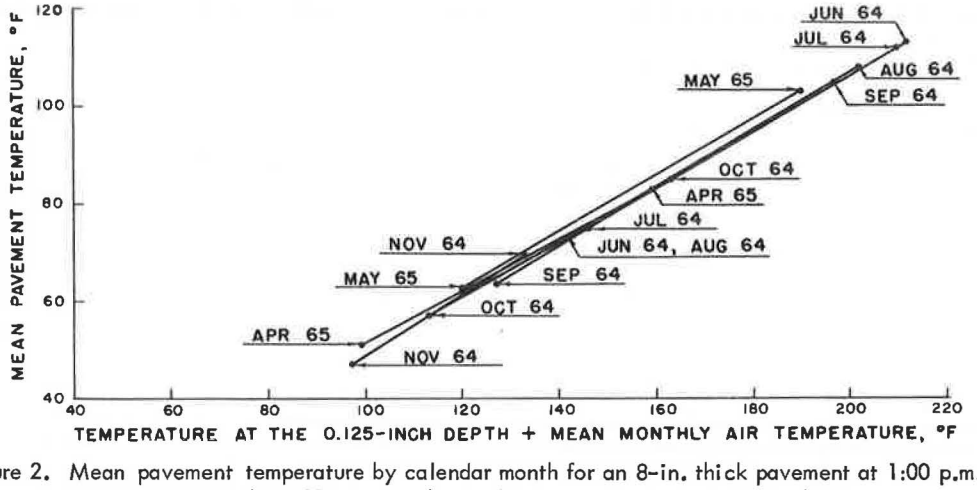

Figure 2. Mean pavement temperature by calendar month for an 8-in. thick pavement at 1:00 p.m. vs temperature at the 0.125-in. depth plus 30-day mean air-temperature history.

Results showed that at 6, 7, and 8 a.m., 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 to approximate data for all hours.

Standard errors of estimate were calculated 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 and 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 measured temperatures at the respective depths.

The temperatures at the surface and at each ½-in. increment of depth through 12 in. were calculated by means of the fourth-order polynomial equation determined for the respective day. Temperatures so calculated were plotted as ordinate values vs 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-in. depth is shown in Figure 3. The average air-temperature history was computed for 5 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 standard error of estimate. The standard error of estimate decreased to a minimum when 2 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-in. depth and for the hours 6 a.m. through 9 a.m. and 6 p.m. and 7 p.m. occurred when a 10-day

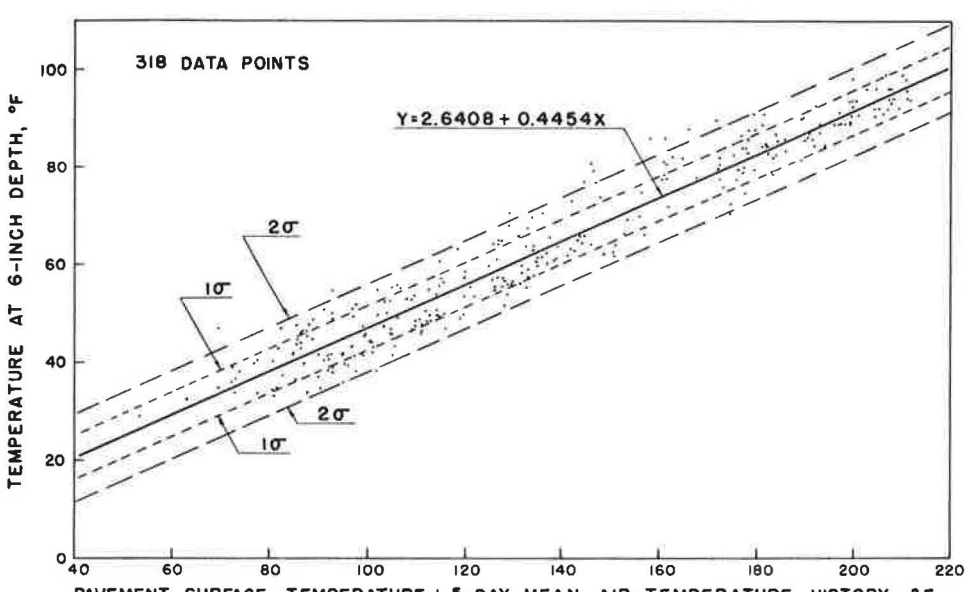

Figure 3. Temperature at the 6-in. depth vs measured pavement surface temperature at 1:00 p.m. plus 5-day mean air-temperature history.

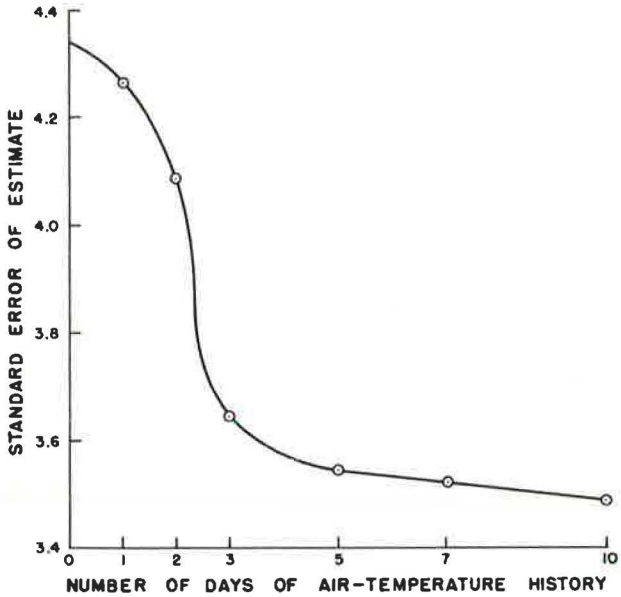

Figure 4. Standard error of estimate for all depths and all hours vs number of days of air-temperature history.

average air-temperature history was added, and for the hours of 10 a.m. through 5 p.m., a 2- to 5-day average air-temperature history was optimum.

Figure 4 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.

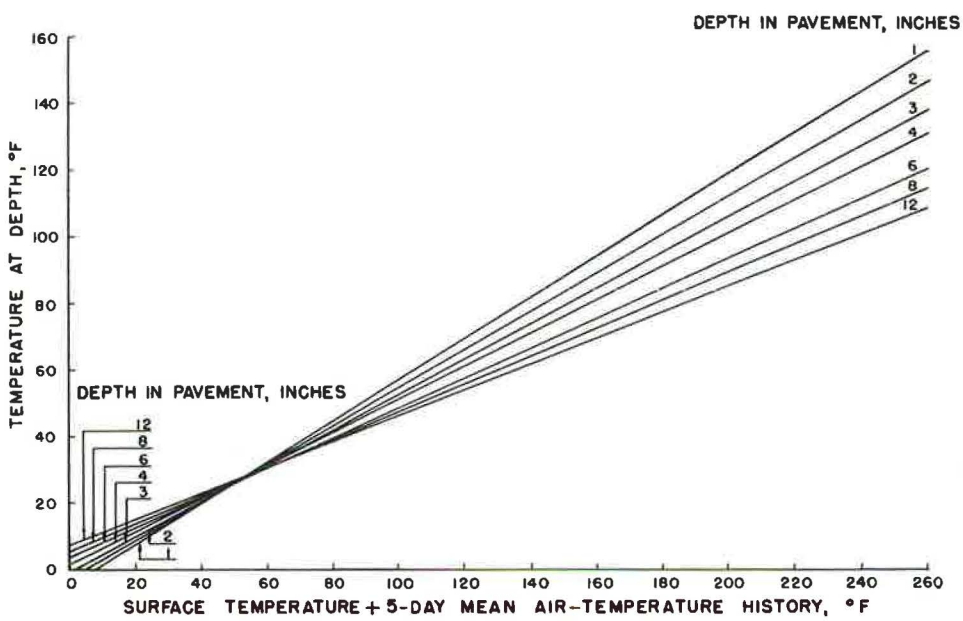

Figure 5. Temperature-depth prediction graph at 1:00 p.m. for pavements greater than 2 in. thick.

As can be seen, accuracy does not increase significantly beyond the 5-day point. Therefore, only the 5 previous days are considered to be significant. Further analysis of the standard errors of estimate showed that the 5-day average air-temperature history sufficed for all depths greater than 2 in. The least standard errors of estimate for the depths 0 in. through 2 in. indicated that the best estimate was obtained by the use of the surface temperature alone. Pavement temperatures in the top 2 in. of the pavement are more directly dependent on the hour of the day and the amount of heat absorption, whereas temperatures at depths greater than 2 in. are assumed to be a function of the surface temperature, amount of heat absorption, and the past 5 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. Because of space limitations, only the set of curves for 1 p.m. is shown in Figure 5 as a typical example.

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, Figs. 89a, 89b, 89c, and 90a) suggested that the dimensionless, multiplicative factor method might be more appropriate. Therefore, in this study, the above AASHO Road Test 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. The equation for the straight lines was

$$M = \frac{Y_2 - Y_1}{\log T_2 - \log T_1} \tag{2}$$

where

M = slope of the straight line,
Y_1, Y_2 = deflection values, and
T_1, T_2 = mean pavement temperatures in degrees 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 of 30 through 150 F, at 10 F-intervals, by the equation

$$Y_3 = Y_1 + M(\log T_3 - \log T_1) \tag{3}$$

where

Y_3 = deflection at the temperature T_3,
Y_1 = same Y_1 used in Eq. 2,
M = slopes as determined in Eq. 2,
T_3 = temperature at which the deflection was computed, and
T_1 = same T_1 used in Eq. 2.

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

The adjustment factors were derived from the equation

$$AF = \frac{Y_{60}}{Y_3} \tag{4}$$

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 Eq. 3, and

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

Table 1 shows the results of calculations for the 4-in. pavement on Loop 5. Each of the 12 adjustment factor curves in Figure 6 are the results of computations according to Eqs. 2, 3, and 4, and the curves are plotted arithmetically with mean pavement temperature, T_3, on the ordinate axis and the adjustment factor, AF, on the abscissa axis. Deflections, Y_3, computed from the 12 individual curves at a given mean pavement temperature, T_3, were added and averaged to obtain the final adjustment factor curve shown in Figures 6 and 7.

Further analysis showed that there may be a relationship among average structures within a given loop—that is, except for the 8.6-in., asphalt-treated base curve, which for some unknown reason was an outlier. There was no consistent relationship between loops and substructures as evidenced by the 2-in. surfacing on Loop 3 and the 6-in. surfacing on Loop 6, where the total structural thicknesses were 9 and 24 in. respectively; yet each had the same adjustment factor curve. The same situation was present with regard to the 4-in. surfacing on Loop 3 and the 16.1-in., asphalt-treated base section that had total structural thicknesses of 11 and 24.1 in. respectively. These structural relationships may have been obscured by the AASHO approach of averaging deflections for a given surfacing thickness within a loop; however, the AASHO structural-equivalency equation showed that in some cases the structural indexes were vastly different. Further analyses might be made of the AASHO data (2, Figs. 89a, 89b, 89c, and 90a) with the raw data grouped according to surfacing thicknesses and structural indexes 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 as long as the deflection is to be adjusted to the reference temperature for that same loading.

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

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

$$Y = \frac{1.5\ Pa}{E} \tag{5}$$

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

TABLE 1

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

Temperature, T_3 (F)	Deflection, Y_3, at Temperature T_3 (in.)	Adjustment Factor	Temperature, T_3 (F)	Deflection, Y_3, at Temperature T_3 (in.)	Adjustment Factor
40	0.01562	1.7106	100	0.04071	0.6563
50	0.02173	1.2293	110	0.04333	0.6167
60	0.02672	1.0000	120	0.04571	0.5846
70	0.03094	0.8636	130	0.04790	0.5578
80	0.03460	0.7723	140	0.04993	0.5351
90	0.03783	0.7063	150	0.05182	0.5156

T_1 = 52 F = average pavement temperature, T_A
T_2 = 80 F = average pavement temperature, T_A
Y_1 = 0.0228 = deflection corresponding to T_1
Y_2 = 0.0346 = deflection corresponding to T_2

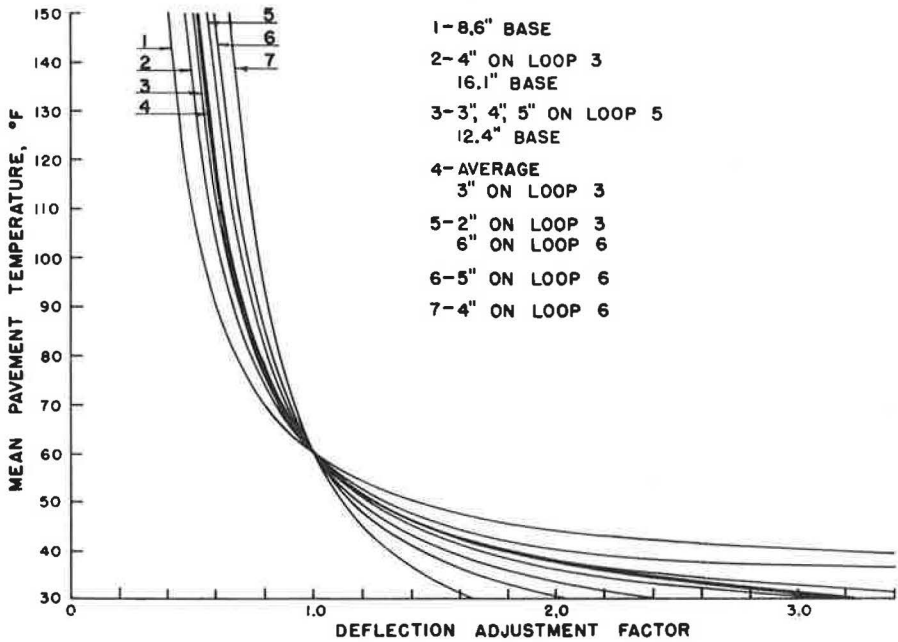

Figure 6. Mean pavement temperature vs deflection adjustment factors for various loops.

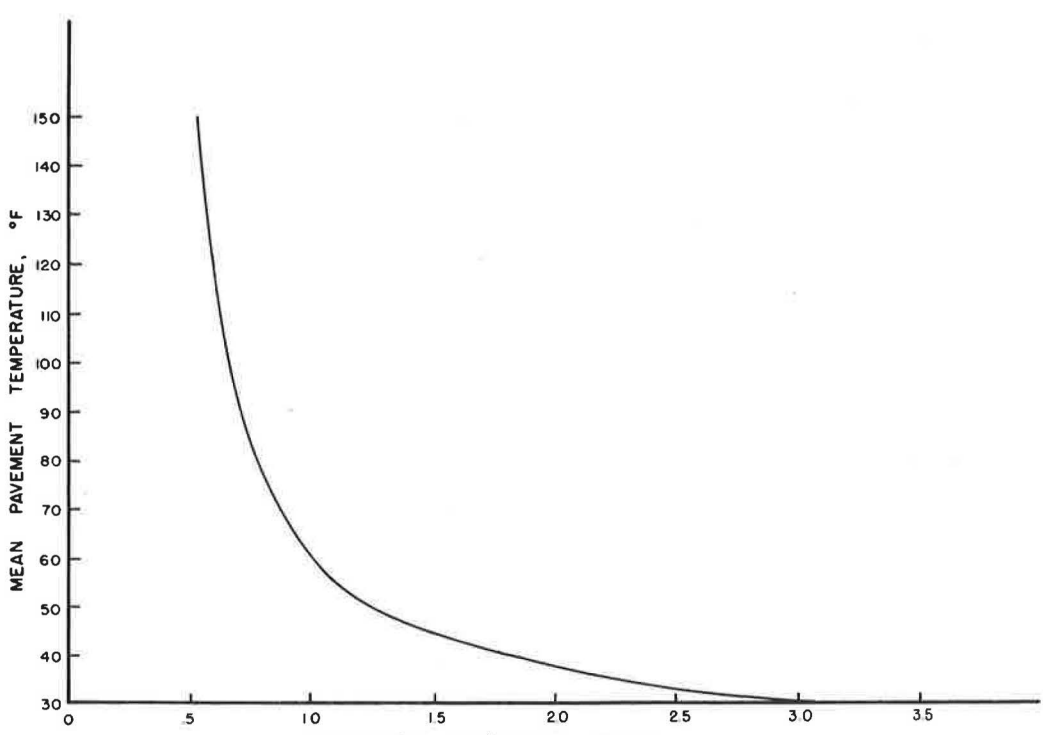

Figure 7. Mean pavement temperature vs average deflection adjustment factor.

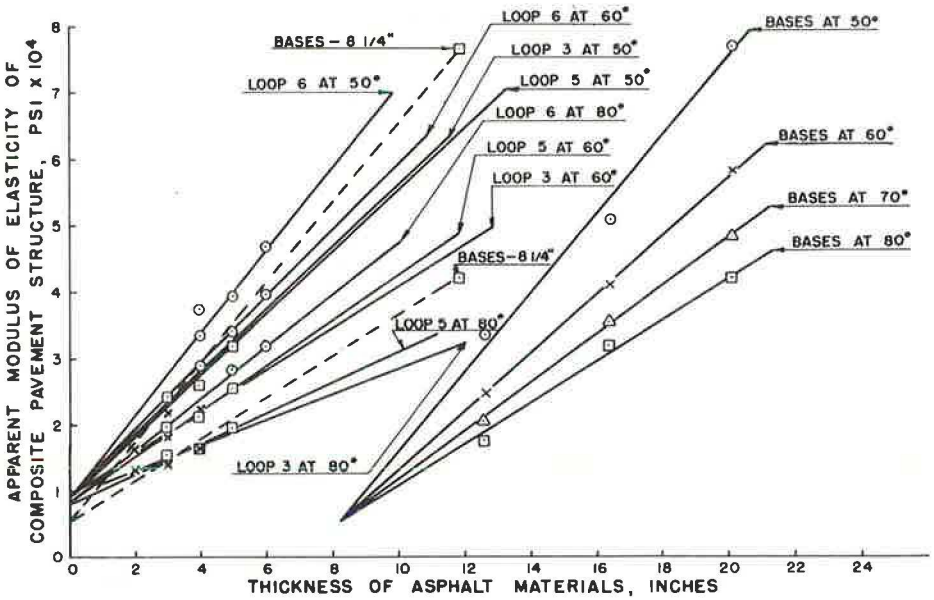

Figure 8. Apparent modulus of elasticity of composite pavement structure vs pavement thickness.

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-layered elastic system (6),

$$Y = \frac{1.5\ Pa}{E_2} F_2 \tag{6}$$

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, Figs. 89a, 89b, 89c, and 90a) were used to calculate the modulus of elasticity by the Boussinesq equation (Eq. 5). This was an apparent modulus, E_c, of the composite structure of the pavement. When these values were plotted against respective thicknesses of asphaltic concrete (Fig. 8), a straight line could be passed through the data points for a given loop section at each temperature; and, upon extrapolation to zero thickness (or temperature-affected thickness, in the case of asphalt-treated bases), the respective lines converged at an approximate value of 8,400 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

$$F_W = \frac{E_2}{E_c} \tag{7}$$

where F_W = Burmister's settlement coefficient.

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

$$E_1 = N \times E_2 \tag{8}$$

where

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

The foregoing calculations were made using the deflections at various temperatures and the E_1 values were avaraged for each temperature. Simultaneous solution of the equation

$$\log_{10} E_1 = \frac{A}{T_A} + B \tag{9}$$

where

T_A = absolute temperature (degrees R = degrees F + 460),
E_1 = average modulus of elasticity of asphaltic concrete at T_A, and
A, B = constants,

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 9 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 7. 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 10. It is seen that the adjustment factor and modulus of elasticity are related at any stated temperature by the equation given in Figure 10.

Comparison of Derived Temperature Distributions and Adjustment Factors With Data From Other Test Roads

Data are being gathered by the Asphalt Institute (7) from a test site at San Diego, California. The flexible pavement at this test site contains thermocouples embedded in

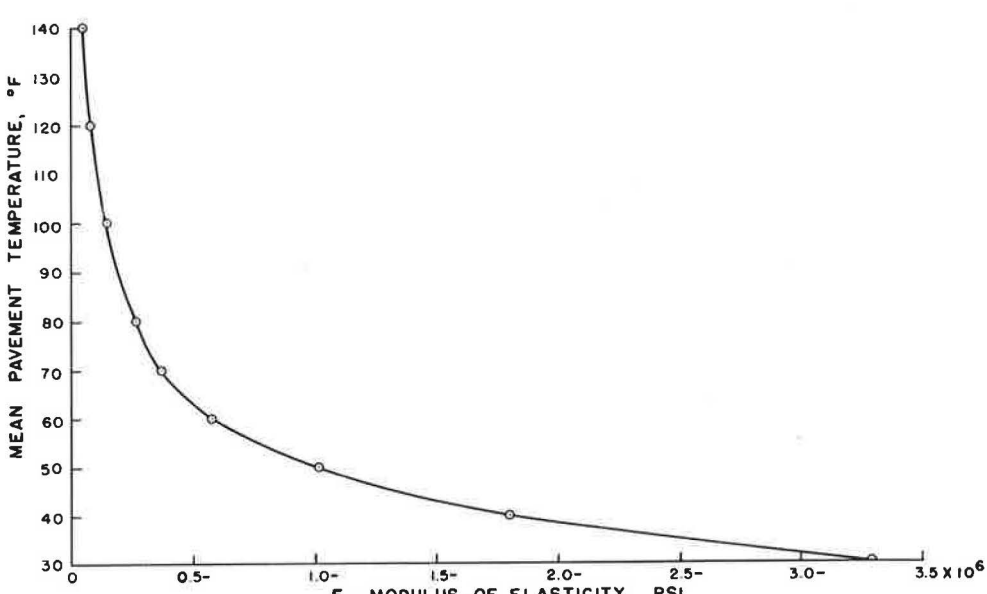

Figure 9. Mean pavement temperature vs modulus of elasticity for asphaltic concrete pavement.

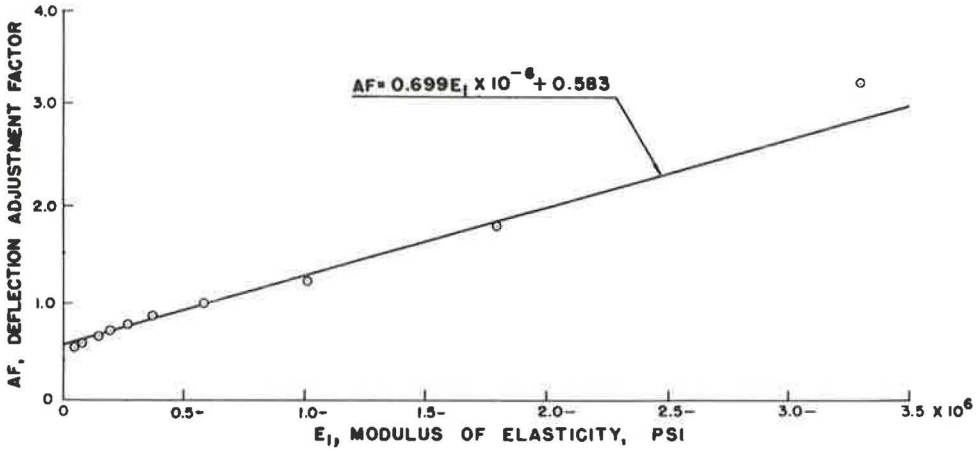

Figure 10. Correlation between deflection adjustment factor and modulus of elasticity for an asphaltic concrete pavement.

the pavement, and temperatures are being recorded. Two days of temperature distributions, October 6, 1966, and February 17, 1967, together with their respective 5 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 ±6 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 California and Colorado data, each compared to the temperatures predicted by the method reported herein and developed from the College Park data. A few temperatures fell outside two standard errors of estimate; however, most of the data are well within these tolerances.

TABLE 2

COMPARISON OF MEASURED PAVEMENT TEMPERATURES AT SAN DIEGO AND COLORADO TEST SITES WITH ESTIMATION OF TEMPERATURES BY METHOD BASED ON COLLEGE PARK DATA

Location	Depth (in.)	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

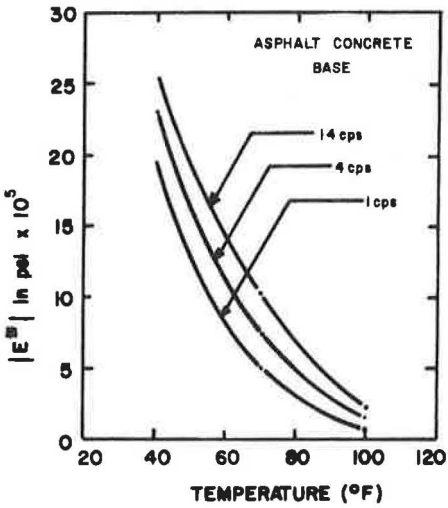

Figure 11. Relationship Between |E*| and temperature for various loading frequencies (8, p. 933).

An interesting comparison between modulus of elasticity of asphaltic concrete, E_1, derived from the AASHO data (Fig. 9) and laboratory measurements of the complex modulus, |E*|, is also provided by Kallas and Riley's tests (8) on asphaltic concretes used on the Colorado test pavement (4). In Figure 11 (from 8, Fig. 3b), showing |E*| plotted against temperature, |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 7 seems extraordinary.

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 altitude on pavement temperatures.

Theoretical analysis of the AASHO Road Test 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.

ACKNOWLEDGMENTS

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Discussion

N. K. VASWANI, Virginia Highway Research Council—The authors are to be complimented on their attempt to account for the effect of temperature on pavement deflection. Clarification of two points may prove to be helpful.

Some of the most important data that led to the authors' conclusions are an analysis of the AASHO data given in Figures 89a, 89b, and 89c and Figure 90a of the AASHO Road Test Report 5. The authors do not seem to have taken the actual data points, but instead the generalized curve for which the correlation and standard deviation values are not known.

In Figure 6 of the paper, seven curves are shown, each based on the AASHO data mentioned. The degree of correlation (or amount of error) existing between the data obtained from the AASHO curves and the curves given in Figure 6 is also not known.

Figure 7 is the average of the seven curves in Figure 6. In Figure 6, the further the distance from the base point (i.e., 60 F of deflection adjustment factor = 1.0), the greater the error in averaging. It is therefore believed that, although this investigation shows the trend, the percentage error is unknown.

The AASHO Road Test and any number of field and laboratory investigations have shown that the pavement strength is the sum of the strengths of each layer, and that this strength can be generalized as

$$\text{deflection, } y, \text{ is a function of } (E_1h_1 + E_2h_2 + \ldots)$$

where E_1 and E_2 are the strength coefficients of the materials in each layer of the pavement with thickness h_1 and h_2 respectively. According to the authors, the modulus of asphaltic concrete, E_1, is a function of the temperature. Thus it follows that, according to the above equation, the change in temperature resulting in the change in the value of E_1 should be an additive quantity for correlating with y, the deflection, as indicated by Kingham and Reseigh (4), rather than a quantity to multiply by $(E_1h_1 + E_2h_2 + \ldots)$, which in effect would change the contributing strength of other layers too. The reason that the authors used the multiplying quantity in their analysis may be the result of the adoption of Burmister's elastic theory.

R. IAN KINGHAM, The Asphalt Institute—Southgate and Deen are to be commended for reducing the enormous bulk of temperature data obtained by Kallas on thick asphalt pavements to a mathematical form that can be used to predict pavement temperatures at any depth in an asphalt pavement layer. With such predictions, a mean pavement temperature can be determined for use in correcting Benkelman beam deflections to a 60 F standard temperature. This discussion is limited to the derivation of the adjustment

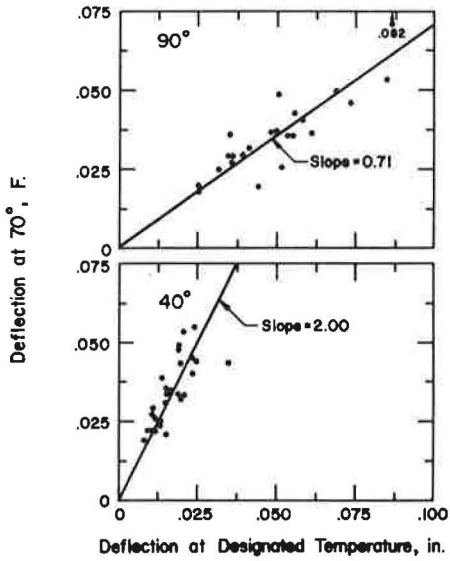

Figure 12. Colorado deflection-temperature data.

factors that the authors suggest can be used to correct beam deflections for temperature.

To derive adjustment factors for correcting beam deflections to 60 F, the authors were limited to data published from the AASHO Road Test. They assumed that the mean pavement temperature for the AASHO data was the average of the top, middle, and bottom of the pavements being tested. It is believed that the top, middle, and bottom temperatures of an asphalt concrete layer 4-in. thick were used. For this reason, temperatures reported for thicker asphalt layers may have been subject to bias.

This would explain in part why the effect of temperature on deflection seemed to decrease at higher temperature ranges. This trend influenced the authors' choice of a mathematical model to fit the data. In order to compute deflection adjustment factors for temperatures other than those measured at the AASHO Road Test, extrapolations from 90 to 140 F had to be made using the mathematical model, and thus the correction factors were highly dependent on the choice of mathematical model. Another limitation of the adjustment factors was the reference temperature of 60 F. It is believed that 70 F would have been a better choice because it represents more nearly the median for the temperatures normally experienced in deflection testing throughout the United States and Canada.

For several years this discussant has been concerned with developing technology for correcting Benkelman beam deflections to a standard temperature (10). Such corrections are very important when deflections are used to determine asphalt concrete overlay thicknesses (11). Data from two full-scale experimental base projects, which were in Colorado (4) and San Diego County, California (12), were collected to explore this problem. These data, plus some published by the Canadian Good Roads Association (5, 13) and the Road Research Laboratory (14), shed further light on the relationship between mean pavement temperature and the Benkelman beam deflection measurement.

All the data considered were obtained by measuring deflections at a point while pavement temperatures varied throughout the course of a day. Deflections plotted against the mean asphalt layer temperature showed a linear relationship for the temperature ranges that can be expected over a 24-hour period. This finding for full-depth asphalt pavements from the Colorado Experimental Base Project has been reported previously by this discussant (10). Also, more nearly linear relationships were found for the AASHO Road Test data when mean temperatures were determined without the known bias. A theoretical analysis also suggested that the relationship is approximately linear for a 30 to 40 F temperature span. For temperatures ranging from 30 to 140 F, however, the trend was curvilinear with greater temperature influence at higher temperatures.

As a result of the field measurements and theoretical studies, this discussant selected a linear mathematical model to fit measurement data for each pavement point. The resulting equations were used to compute deflections for certain designated temperatures. Extrapolations greater than 10 F were avoided. Deflections at these selected temperatures were then plotted against the 70 F deflection as shown in Figure 12. The excellence of fit of the data to a straight line through the origin shows that a multiplying factor, of the type proposed by Southgate and Deen, is a good method of adjusting beam deflections. The slope of the linear fit through the origin is, of course, the adjustment or multiplying factor for the temperature in question.

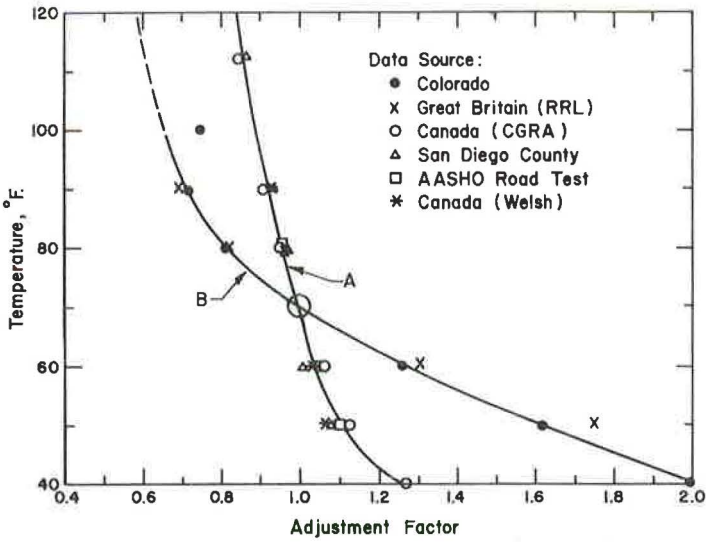

Figure 13. Derivation of adjustment factor curves.

Plots similar to Figure 12 were made for data from each source. The resulting slopes were plotted against their respective temperatures. These results are shown in Figure 13. Two relationships are evident. The Curve A included data primarily from granular base pavements and represents strong support to the thin asphalt layer (less than 4 in.). Curve B represents test data from thick asphalt pavements (4 in. or more) laid directly on weak subgrades.

Figure 13 provides two adjustment factor curves for use in correcting beam deflections to a standard temperature of 70 F. The choice of curves involves some judgment. Considering the data sources for each curve, it is recommended that Curve A, the curve representing the smaller correction factors, be used in the majority of instances. The second curve, Curve B, providing large correction factors, represents an extreme situation where the asphalt layer is thick and weakly supported.

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H. F. SOUTHGATE and R. C. DEEN, Closure—The authors appreciate the interest shown in the paper by Vaswani and Kingham. The comments made by Vaswani are well taken and offer the opportunity to reemphasize points mentioned in the paper.

Because the study reported in the paper was of a feasibility and pilot nature, and because of certain pressing needs to analyze field deflection measurements, the actual data points represented by the curves in Figures 89a, 89b, and 89c and Figure 90a of the AASHO Road Test—Report 5 were not used. Instead, the generalized curves were analyzed and therefore the correlations and deviations are not known. The authors indicated that a more precise analysis might be made in the future by considering the actual data points instead of the generalized curves.

The authors did assume that the definition for surfacing temperature given on page 104 of Report 5 on the AASHO Road Test was correct. Because the term "surfacing temperature" was not redefined for Figures 89 and 90 of the report, it must be assumed that the surfacing temperature was the average of the top, middle, and bottom temperatures of the actual layer thickness rather than of a 4-in. layer.

By definition, the adjustment factor at 60 F was taken to be one and is so indicated in Figures 6 and 7. This does not necessarily suggest that the error in estimating the deflection adjustment factor is less at this temperature than at other temperatures. Much of the scatter indicated by the various curves in Figure 6 may be, in part, due to the averaging effect of the AASHO curves over pavements of various structural thicknesses and components. Selection of the reference temperature seems to be somewhat arbitrary and analyses of deflection measurements should not be altered by use of adjustment factor curves based on different reference temperatures. Figure 7 can be easily adjusted to any other temperature that one desires to use as a reference or base.

It is interesting to note that the adjustment factor curve shown in Figure 7 of the paper falls between Kingham's Curves A and B (Fig. 13), which may be considered extreme cases of pavement construction. Because the adjustment factor curve in the paper was based on Figures 89 and 90 of the AASHO Road Test report, and therefore included averaging effects, it is not surprising that the curve of Figure 7 falls between Curves A and B of Kingham's discussion.

Further analysis of field deflection measurements since the paper was submitted have been made using the deflection adjustment factor curve given in Figure 7 of the paper. Amazingly good agreement has been found between the deflections as adjusted for temperature and the theoretical deflections computed by an n-layered computer program for the analysis of elastic-layered pavement systems. This comparison increased the authors' confidence in the adjustment factor curve and, more importantly, in the shape of the temperature adjustment factor curve.

To repeat what was indicated by the authors in the paper and by Vaswani in his discussion, further analysis of the AASHO Road Test data is needed to determine the actual magnitude of the adjustment factors and to develop the proper and precise relationship between temperature and adjustment factor with respect to the structural makeup of the pavement system. Until this more detailed analysis of actual field data points can be made, it is felt that the adjustment factor curve in Figure 7 provides an adequate first approximation of the temperature effects on pavement deflections.