Temperature Correction of Deflections and Backcalculated Asphalt Concrete Moduli

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A temperature correction procedure for deflections and backcalculated asphalt concrete (AC) moduli for flexible pavements in North Carolina is presented. The data used in developing this procedure were collected from four pavements in the Piedmont area of North Carolina with various types of layer materials and thicknesses. Four trips, one in each season, were made to each of these pavements so that deflections in the maximum range of temperatures could be obtained without significant structural deterioration of the pavements. During each trip deflection testing was conducted on an hourly basis for 1 full day per test section. Pavement surface and depth temperatures were measured at the time of deflection testing with a falling weight deflectometer. The measured deflection and temperature values were used to validate the temperature correction procedure presented in the 1993 *AASHTO Guide for Design of Pavement Structures*. It was found that the AASHTO procedure produced significant errors in the corrected deflections. The main reasons for these errors were that the AASHTO mean temperature cannot account for the difference in temperature-depth gradients during heating versus cooling cycles and that the AASHTO temperature correction factors overcorrect the deflections at higher temperatures. A new temperature correction procedure for deflections and backcalculated moduli was developed on the basis of the fact that the middepth temperature of the AC layer is an effective AC layer temperature. The accuracy of this procedure was validated with deflection and surface temperature data collected from four other pavement sections in North Carolina.

The overlay design analysis in the 1993 *AASHTO Guide for Design of Pavement Structures* (*1*) introduces nondestructive dynamic deflection testing as a means of evaluating the in situ structural capacity of existing pavements. Two general approaches to carrying out this evaluation are the pavement layer moduli prediction technique and the direct structural capacity prediction technique. The first approach backcalculates the in situ moduli of all the layers by using the deflection basin measured from falling weight deflectometer (FWD) testing. The second technique determines the overall structural capacity of the pavement from the subgrade modulus and the peak deflection at the center of the loading plate of the FWD.

In either of the approaches deflection measurements or backcalculated layer properties must be corrected to a particular type of loading system and a standard set of environmental conditions for use in the overlay design analysis. Loading system-related factors are the type of nondestructive testing device, the frequency of loading, and the load level. The most important environmental factor affecting the surface deflections of flexible pavements is the temperature of the asphaltic layers.

The 1993 AASHTO guide (*1*) presents a temperature correction procedure for FWD deflections and backcalculated asphalt concrete (AC) moduli (Figure 1). A set of curves, originally developed by Southgate and Deen (*2*) and modified empirically by using AASHO Road Test data, was recommended in the AASHTO guide to correct the measured deflection at a test temperature to a deflection value at a standard temperature of 21°C (70°F). This procedure determines the effective temperature of the AC layer by calculating the mean value of temperatures from the near surface, the midlayer, and the bottom of the AC layer. These temperatures are predicted from the sum of the measured pavement surface temperatures and the average air temperature for the previous 5 days by using the relationships presented in Figure 1. It has been reported by many practitioners that the AASHTO procedure is inaccurate, especially at temperatures over 38°C (100°F) (*3*).

Johnson and Baus (*3*) recently developed an alternative technique based on the AC temperature-stiffness relationships developed by Ullidtz (*4*) and the elasticity relations used in Appendix PP of the AASHTO guide (*1*) to calculate the composite modulus of multilayered pavements. Although the proposed method by Johnson and Baus (*3*) was reported to provide more consistent results than the AASHTO procedure, the development of a more accurate method

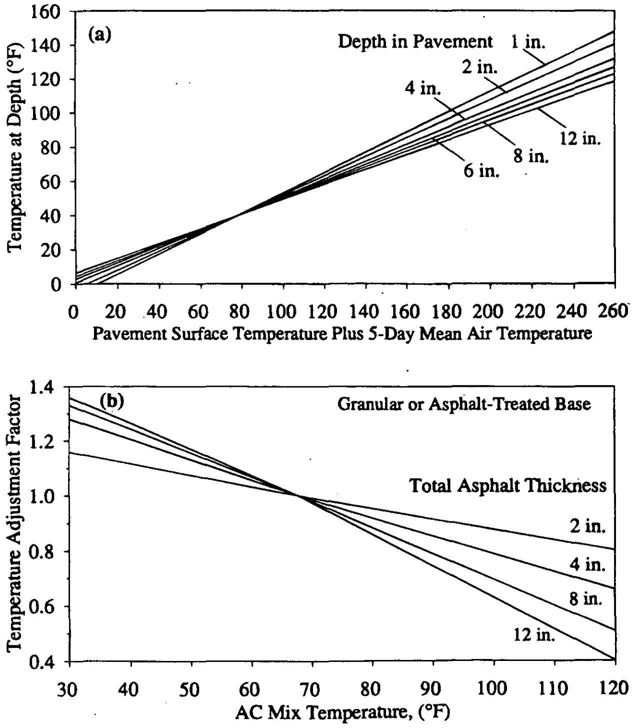

FIGURE 1 AASHTO temperature correction procedure (*1*): (*a*) prediction of pavement depth temperatures; (*b*) temperature adjustment factors for pavements with granular or asphalt-treated base [1 in. = 25.4 mm; °C = (°F − 32)/1.8].

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of estimating pavement temperatures was recommended as the most important future research topic.

Based on the urgent need to develop a more realistic temperature correction procedure for the overlay designs in North Carolina, research was conducted at North Carolina State University in which a new temperature correction procedure for FWD deflections and backcalculated AC moduli was developed by means of periodic FWD testing and temperature measurements from pavement sections in service. This procedure is based on the middepth temperature of asphaltic layers as an effective temperature and has two parts: (a) prediction of the AC middepth temperature and (b) adjustment of the measured deflections or backcalculated AC moduli to a reference temperature. In this paper field data collected from the test sections are first used to check the accuracy of the AASHTO procedure, and the newly developed temperature correction factors are presented along with a summarized description on the entire temperature correction procedure. Then this procedure is validated with the deflection and surface temperature data collected from four pavement sections in North Carolina. A prediction method for the AC middepth temperature cannot be included here because of space limitations; a description of the method can be found elsewhere (*5*).

TEST SITE SELECTION

Four test sites with pavement characteristics and at geographic locations that would highlight the factors under investigation were chosen in the Piedmont area of North Carolina: three on US-421 north of Siler City and one on US-70 east of Clayton. The major selection criteria were the thicknesses of the AC layers, the types of base course materials, and the structural conditions of these pavements. The compositions of the four sections are summarized in Table 1.

TEMPERATURE GAUGE INSTALLATION

To determine the change in temperatures within the AC layer during the testing period a method had to be devised to repeatedly measure temperatures from various depths of the AC layer without direct influence from ambient air conditions. This was achieved by first coring a 75-mm (6-in.)-diameter hole through the entire depth of the AC layer. After the core was removed a drill with a pivoting nose was placed in the 75-mm core hole to horizontally drill holes for the thermocouples. The thermocouple holes were placed in the AC layer from top to bottom at intervals of 25 to 50 mm (1 to 2 in.), depending on the depth of the section.

Epoxy was injected into each horizontal hole, and then the thermocouple attached to strands of insulated wire was injected. These thermocouples were checked in the laboratory by comparing the readings from the individual thermocouples at 25°C (77°F). The wires were taken across the pavement through a trench slit cut transversely from the core hole to the pavement edge. The wires were carried to the shoulder until it reached a junction box where the wire end connections were stored. The core hole was backfilled with hot mix, and the trench in the pavement was filled with epoxy. The wire end connections were plugged into a switch box and a digital meter that displays the temperatures given by each thermocouple. Air and pavement surface temperatures were determined with an infrared thermometer.

FIELD TESTING AND DATA COLLECTION

In each test section two areas with minimum damage were selected to avoid any errors due to location-specific variations in the strengths or stiffnesses of the pavements. In each area one temperature hole was installed and two locations were marked for FWD testing, one in the outer wheelpath and the other in the center of the outer lane. The test sections were an average of 24 m (80 ft) in length.

Testing was conducted during each season of the year (early September, October, early February, and late May). FWD deflections, temperatures (air, pavement surface, and depth), and climatic data were collected on an hourly basis over an entire day for each section. The underlying assumption was that this testing plan would allow evaluation of the effects of temperature change on deflection measurements by keeping other variables (such as the moisture contents of subsurface layers, damage state of the AC layers, and aging) relatively constant. In addition to the field temperature data, the highest and lowest air temperatures for the previous 5 days before each FWD test were acquired from the National Climatic Data Center.

FWD testing was conducted at four points in each test section, two under the wheelpath and two at the lane center, to evaluate the effect of damage in the AC layer on the temperature correction of deflections. Four different load levels, 2722, 4082, 4990, and 7711 kg (6,000, 9,000, 11,000, and 17,000 lb), were used to study the effects of load level on backcalculated moduli of different types of layer materials.

TABLE 1 Compositions of Pavement Test Sections

	Thickness, mm (in.)			
	Section 17	US 70	Section 13	Section 20
Surface Course	51 (2.0)	51 (2.0)	51 (2.0)	51 (2.0)
Binder Course	38 (1.5)	89 (3.5)	38 (1.5)	38 (1.5)
Asphalt Base	-[a]	-	102 (4.0)	140 (5.5)
Aggregate Base	203 (8.0)	279 (11.0)	-	-
Lime-Stabilized Subgrade	178 (7.0)	-	178 (7.0)	-
Total AC Layer	89 (3.5)	140 (5.5)	191 (7.5)	229 (9.0)
Subgrade Type	A-7	A-3	A-6	A-7

[a] Data not applicable.

DISCUSSION OF RESULTS

Temperature Measurements

Figure 2 presents the change in temperature gradients recorded in May from a 140-mm (5.5-in.)-thick AC layer (US-70 section). Surface temperatures moved considerably, whereas temperatures at lower depths maintained greater consistency, resulting in cone shapes on the pavement depth-versus-temperature graph. It must be noted here that the slope of the temperature gradients changes as the time of day moves from the heating cycle (before 2 p.m.) to the cooling cycle (after 2 p.m.). The significance of this observation is that one may get vastly different middepth temperatures if the change in the slope of the temperature-pavement depth curves is not taken into consideration. For example, although the surface temperatures measured at noon and at 4:02 p.m. in Figure 2 are essentially the same, the middepth temperatures differ by 7°C (13°F). Therefore, a meaningful pavement temperature prediction method requires the time of FWD testing as an input variable and a means of accounting for the temperature gradient along pavement depths.

When determining the effective temperatures of the AC layer at different times of the same day, the AASHTO mean temperature becomes a function of pavement surface temperature only, because the average air temperature for the previous 5 days remains constant for FWD testing within the same day. The problem of using the AASHTO mean temperature in correcting deflections will be presented later by analyzing deflection-temperature data obtained from the same day. In the present study the temperature at the middepth of the AC layer was selected as the effective temperature.

Validation of AASHTO Temperature Correction Procedure

One of the major strengths of the present study is the availability of deflection and temperature data at various depths measured at different times of the same day. The data from US-70 and Section 20 were used to check the accuracy of the AASHTO temperature-deflection correction procedure. Figure 3(*a*) presents the results from the AASHTO procedure. The first point to be made from Figure 3(*a*) is the increasing trend of the corrected deflections as the mean temperature increases. This trend is more significant in Section 20, which has a thicker AC layer [229 mm (9 in.) compared with 140 mm (5.5 in.) in US-70]. Since it was assumed that other variables affecting the deflection measurements except the temperature remained almost constant during a day, the corrected deflections should theoretically be the same for different times (and therefore different mean temperatures) of the same day if the correction procedure is accurate. The significantly different corrected deflections shown in Figure 3(*a*) indicate the problems with the AASHTO temperature-deflection correction procedure.

Another important observation can be made by comparing points A and B in Figure 3(*a*). Points A and B represent the data collected from the US-70 section in May 1993 at noon and 4:02 p.m. of the same day, respectively. The measured temperatures of this trip were presented earlier (Figure 2). Since the surface temperatures at these times were about the same and the average air temperature for the previous 5 days remains constant during the same day, the AASHTO mean temperatures for Points A and B are essentially the same. However, the corrected deflections are significantly different because the AASHTO mean temperature cannot account for the difference in temperature gradients in the heating versus cooling cycle of a day, which was demonstrated earlier (Figure 2). This difference in temperature gradients results in different effective temperatures of the AC layer and therefore different deflection values.

The same corrected deflection data in Figure 3(*a*) were plotted against the measured middepth temperatures in Figure 3(*b*). Although the variation in corrected deflections was reduced by using the middepth temperature, a strong temperature dependency of the corrected deflections was still observed. Some improvement in Points A and B was made in Figure 3(*b*). In general, the use of the middepth temperature improved the AASHTO-corrected deflection-versus-pavement temperature relationship, but not to a satisfactory level. The discrepancies shown in Figure 3(*b*) may be because the AASHTO mean temperature, which is heavily dependent on the surface temperature, was used to calculate the temperature

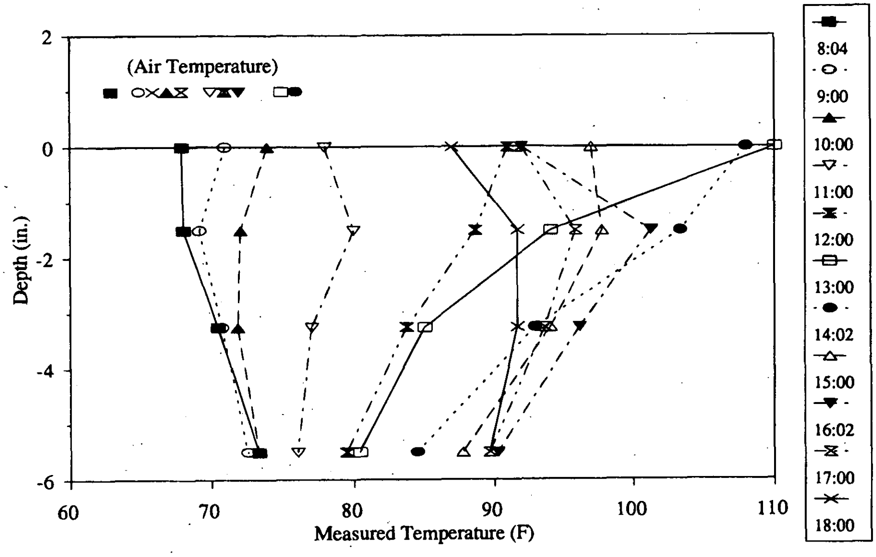

FIGURE 2 Temperature change monitored on US-70 section in May 1993.

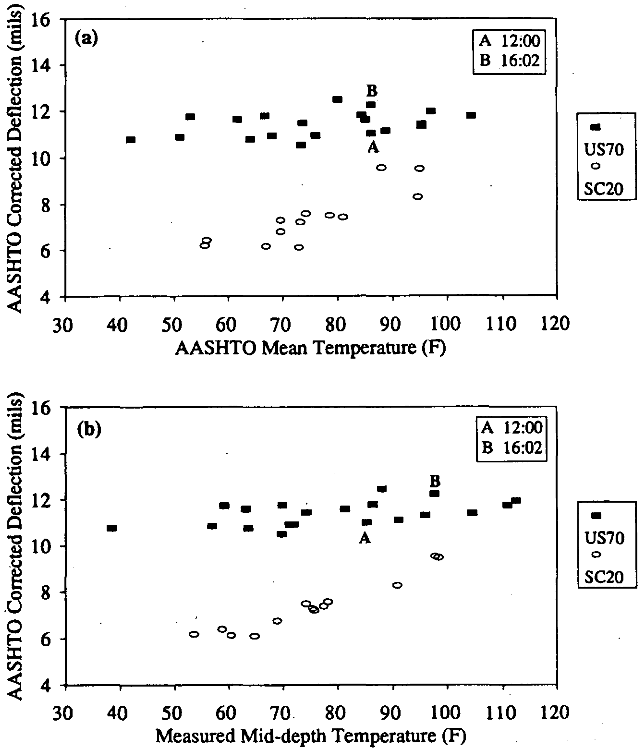

FIGURE 3 (*a*) **AASHTO-corrected deflection versus AASHTO mean temperature;** (*b*) **AASHTO-corrected deflection versus measured middepth temperature (1 mil = 25.4 μm).**

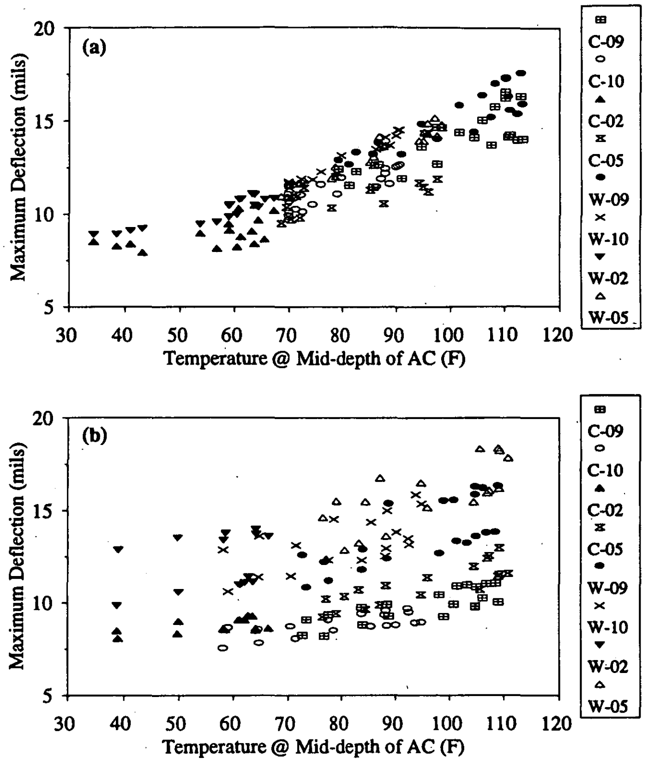

FIGURE 4 Maximum deflection versus middepth temperature: for (*a*) US-70; (*b*) Section 17 (C, W, and numbers represent lane center, wheelpath, and months, respectively).

adjustment factors and because the relationships used to determine temperature adjustment factors are inaccurate.

Temperature Correction of FWD Deflections

Maximum deflection values under 4082-kg (9,000-lb) load drops are plotted in Figure 4(*a*) against the middepth temperatures of the AC layer for the US-70 section. Two variables contributed to the variation of the maximum deflections in Figure 4(*a*). One was different damage levels between the lane center and the wheelpath, and the other was random variations in pavement stiffnesses and strengths between the two FWD testing areas within the same section. This location-specific structural difference may be due to variations in layer thicknesses, compaction, material properties, moisture conditions of sublayers, and so forth. Nevertheless, it was found that the increasing trends of the maximum deflection versus the middepth temperature from each trip were superposed quite nicely, as long as the superposition was performed on the deflection data from the same FWD testing location.

The largest deflection variation was observed from Section 17 with an 89-mm (3.5-in.)-thick asphaltic layer [Figure 4(b)]. The primary reason for this variation is due to the differences in structural conditions between the two FWD testing areas and between the lane center and the wheelpath, the effect of which is probably amplified in sections with thin AC layers.

Temperature correction factors for FWD deflections can be developed by calculating the deflection ratios by dividing the measured deflection value at a specific temperature by the deflection at 20°C (68°F). Since there existed some variation in the measured deflections at a constant temperature, as shown in Figure 4, a regression curve had to be developed to pick up the representative deflection for a specific temperature. The AASHTO correction curves express the relationship between temperature correction factor and temperature as a linear function. A more detailed study of the measured deflections as a function of the middepth temperature, however, suggested that the relationship is better expressed as a nonlinear function. Knowing that the temperature correction factor must be equal to 1 at the reference temperature of 20°C (68°F), it was found that the following equation represents the relationship fairly well:

$$D_{68} = 10^{\alpha(68 - T)} \times D_T \qquad (1)$$

where

D_{68} = adjusted deflection to the reference temperature of 20°C (68°F),
D_T = deflection measured at temperature T (°F),
$\alpha = 3.67 \times 10^{-4} \times t^{1.4635}$ for wheelpath and
$= 3.65 \times 10^{-4} \times t^{1.4241}$ for lane center,
t = thickness of AC layer (in.), and
T = the AC layer middepth temperature (°F) at the time of FWD testing.

By using this relationship the temperature correction factors for deflections under the 4082-kg (9,000-lb) FWD load were calculated and are plotted in Figure 5(*a*) for different locations (wheelpath versus lane center) and for various AC layer thicknesses. Figure 5(*a*) indicates that the difference in deflections between the lane center and the wheelpath observed from Figure 4 has been significantly reduced by using the deflection ratio. Also, the pavements with thicker AC layers demonstrated a greater temperature dependency of the deflection ratio.

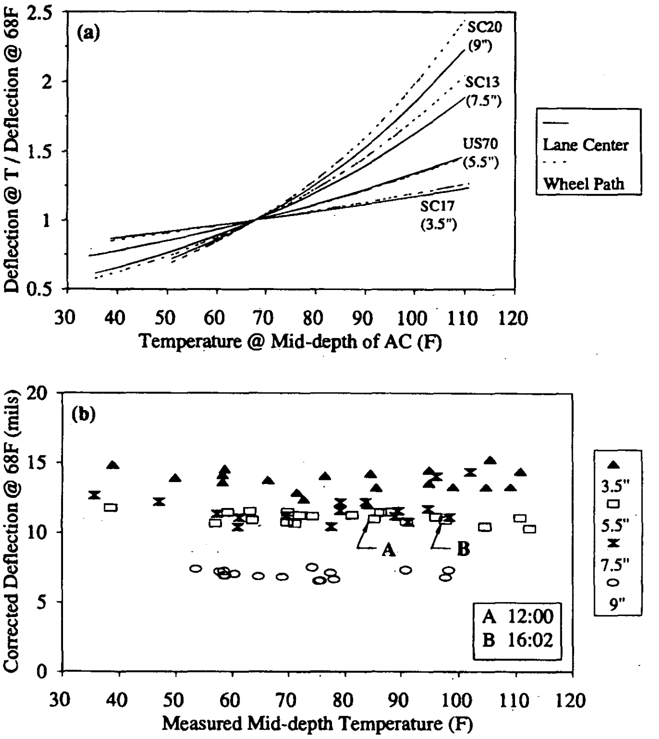

FIGURE 5 **(*a*) Temperature correction factors for deflections; (*b*) corrected deflection versus middepth temperature using the deflection correction factors.**

The temperature correction curves generated by Equation 1 were used to recalculate the corrected deflections presented in Figure 3. The corrected deflections were then plotted against the middepth temperatures in Figure 5(*b*) for all four seasons. Overall, the corrected deflections for the individual section were relatively constant, regardless of the middepth temperature. Points A and B displayed almost the same corrected deflections, demonstrating the accuracy of the new temperature correction procedure. Compared with Figures 4(*a*) and 4(*b*) resulting from the AASHTO procedure, substantial improvement has been made in Figure 5(*b*).

Effect of Load Level on Backcalculated Moduli

The layer moduli were backcalculated from measured deflection basins by using the MODULUS 4.0 program. Moduli values backcalculated from the 4082-kg (9,000-lb) load drop on the US-70 section are plotted in Figure 6 against the middepth temperature as an example showing typical variation in backcalculated AC moduli.

The backcalculated AC moduli were relatively the same, regardless of the FWD load levels. However, the moduli of the aggregate base course increased as the FWD load increased [Figure 7(*a*)]. This trend can be explained by the well-known effect of confining pressure or bulk stress on the modulus of granular materials. The moduli of lime-stabilized subgrade tended to decrease as the load increased [Figure 7(*a*)]. It was found that the effect of the FWD load level on the subgrade modulus was different, depending on the location of the test sections [Figure 7(*b*)]. Subgrade moduli from all of the Siler City sections (Sections 13, 17, and 20) decreased as FWD load increased, whereas the reverse trend was observed from the Clayton section (US-70). Further investigation on subgrade type provided the reason for these trends. As shown in Table 1, subgrades in the Siler City sections are classified as A-6 or A-7, indicating highly plastic clayey materials, whereas the subgrade in the Clayton section is A-3 soil, which is a granular sandy material. Therefore, the same effect of stress state as described earlier for the granular base course can be expected for the granular subgrade of the Clayton section. However, unlike the effect for granular materials, the modulus for fine-grained soils rapidly decreases as the deviator stress is increased up to a certain value and then increases very slightly with increasing deviator stress. This explains the conflicting trends in Figure 7(*b*).

Temperature Correction of Backcalculated AC Moduli

The relationship between the modulus ratio versus the middepth temperature was found to be similar for all sections (Figure 8), although larger discrepancies were found at lower temperatures. It is noted that the backcalculation for Section 17 required a fixed analysis because of the thin surface layer. This analysis determines the AC

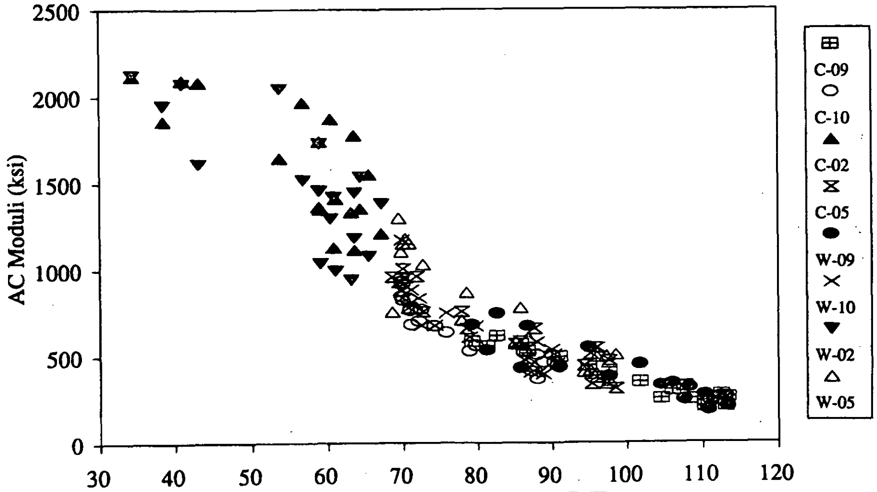

FIGURE 6 **Backcalculated AC moduli as a function of middepth temperature from US-70 (1 ksi = 6.89 MPa).**

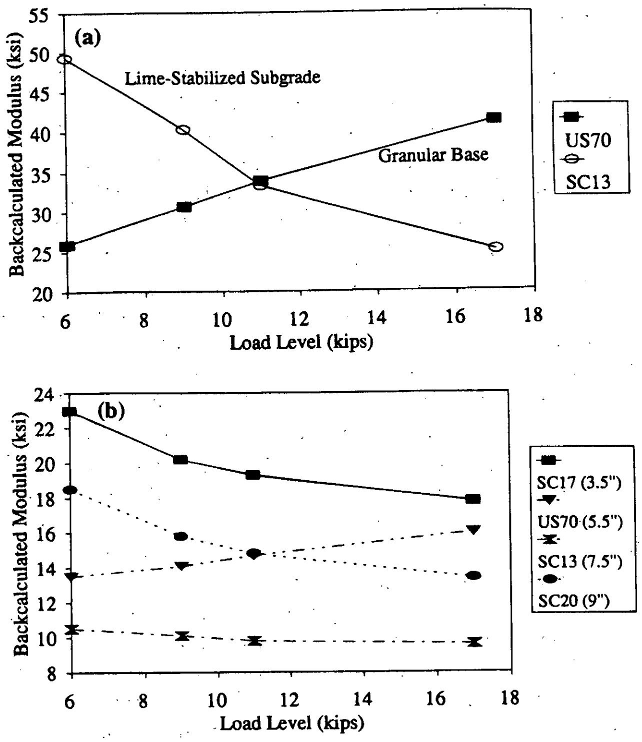

FIGURE 7 Effects of load level on backcalculated moduli: (*a*) granular base and lime-stabilized subgrade; (*b*) unbound subgrade.

modulus on the basis of the aggregate type and temperature by using the modulus-temperature relationship developed from laboratory testing and already resident in the MODULUS program. Therefore, it seemed that the AC modulus-versus-temperature relationship in the MODULUS program represents the temperature dependency of the mixtures investigated in the present study quite well.

Because the stiffness of AC is a strong function of temperature, only by specifying the corresponding temperature will the measured stiffness be meaningful. Therefore, it is important to adjust the measured modulus to a reference temperature. Since the modulus ratio curves in Figure 8 are similar for all seasons of the four test sections, the following relationship can be derived on the basis of regression analysis.

$$E_{68} = 10^{0.0153(T-68)} \times E_T \tag{2}$$

where

E_{68} = corrected AC modulus to the reference temperature of 20°C (68°F),
E_T = backcalculated AC modulus from FWD testing at temperature T (°F), and
T = the middepth temperature (°F) of the AC layer at the time of FWD testing.

A similar equation for temperature correction of AC moduli was recently reported by Baltzer and Jansen (*6*), except their power coefficient is 0.010 in English units. The slight difference between these two coefficients may be due to pavement location-specific factors as well as the type of backcalculation program used in the analysis.

NEW TEMPERATURE CORRECTION PROCEDURE FOR FWD DEFLECTIONS

In this section the temperature correction procedure developed in the present study is summarized. This procedure was developed with the purpose of creating a method that could be implemented in a computer program with easily obtainable input data. Input data for the method consist of

1. Surface temperature measured at the time of FWD testing by an infrared thermometer.
2. Thickness of the AC layer.
3. Time of day. The actual time of day that the individual FWD drop was performed should be recorded and then rounded off to the nearest hour for computer input.
4. Location of FWD test (wheelpath or lane center).
5. Measured FWD deflections and the load level of FWD drop.

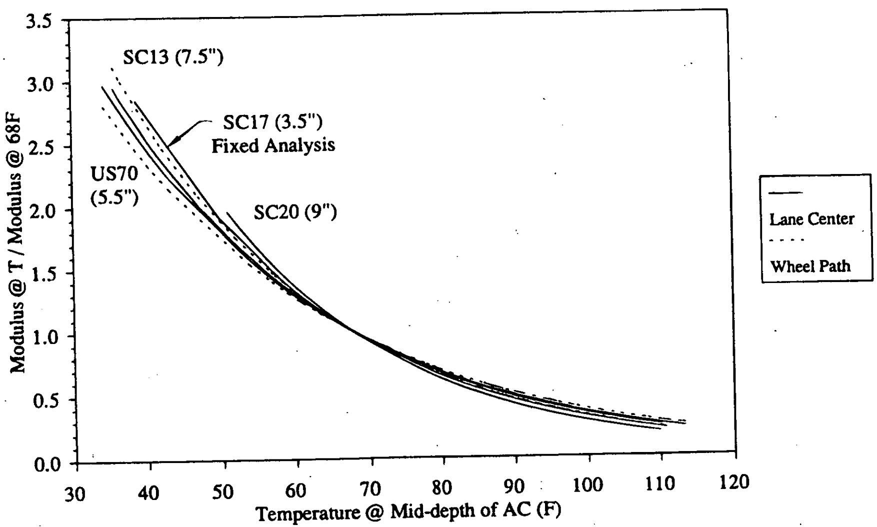

FIGURE 8 Temperature correction factors for backcalculated AC moduli.

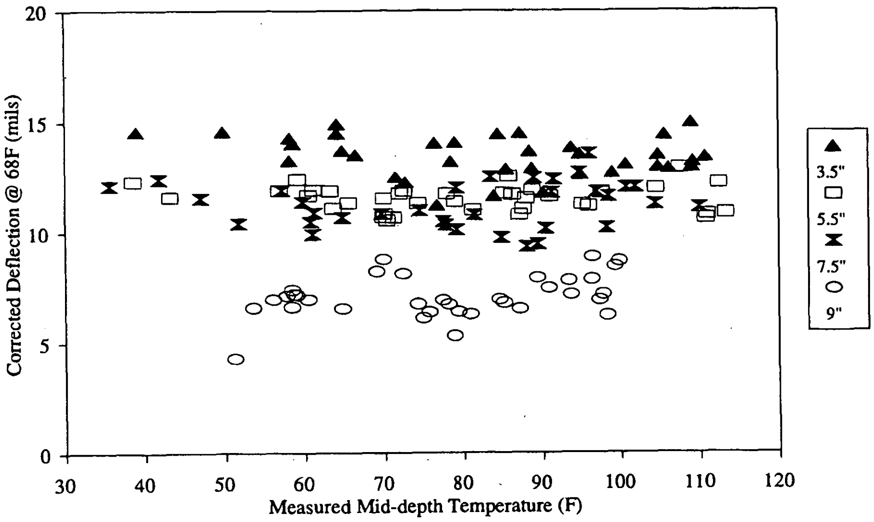

FIGURE 9 Corrected deflections using the predicted middepth temperature versus measured middepth temperature.

The reference temperature and the FWD load level were set to 20°C (68°F) and 4082 kg (9,000 lb), respectively. In the following the temperature correction procedure is described stepwise.

1. Calculate the middepth of the AC layer from the thickness of the AC layer.
2. Predict the AC middepth temperature by using the pavement surface temperature and the time of day. Details on the prediction method for the AC middepth temperature are discussed elsewhere (*5*).
3. Use the predicted middepth temperature to calculate the adjusted deflection by using Equation 1.

VALIDATION OF NCDOT PROCEDURE

To test the accuracy of the entire procedure the deflection and surface temperature data measured in the project were first used. The stepwise procedure described earlier was applied to the measured surface temperature for the known time of day to predict the middepth temperature. The predicted middepth temperature was input to the temperature correction charts to determine the corrected deflection for 20°C (68°F). The results were plotted against the measured middepth temperature (Figure 9). Compared with Figure 5(*b*), which displays the same data except that the deflections were corrected by using the measured middepth temperatures, a larger variation is observed in Figure 9. This is due to errors involved in predicting the middepth temperature from the surface temperature. In general the results show relatively constant corrected defection values at changing middepth temperatures.

The validation results in Figure 9 are somewhat expected because the same data have been used both in developing the temperature correction factors and in the validation study. Therefore, the North Carolina Department of Transportation (NCDOT) procedure must be validated with data that were not included in the development of the correction factors. Additional data were obtained from Sections 1, 2, and 3 of the Siler City test road, the AC layer thicknesses of which were 89, 51, and 140 mm (3.5, 2.0, and 5.5 in.), respectively. The data included a yearly range of FWD deflections for each section and corresponding surface temperatures. The NCDOT correction procedure was applied to the data, and the results were plotted in Figure 10. Again, the procedure provided a constant value of corrected deflections except the four points in Section 3 at the high temperature range in Figure 10(*c*). These FWD drops were performed on the same day in May 1991, which was the first set of data available for this section. Some errors may have been caused by using an inconsistent method of surface temperature collection on this day

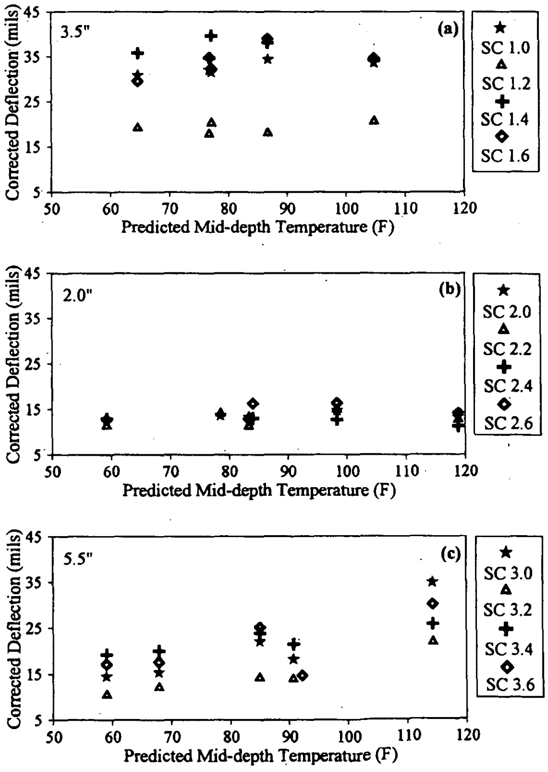

FIGURE 10 Validation of NCDOT procedure with data from Siler City: (*a*) Section 1; (*b*) Section 2; (*c*) Section 3.

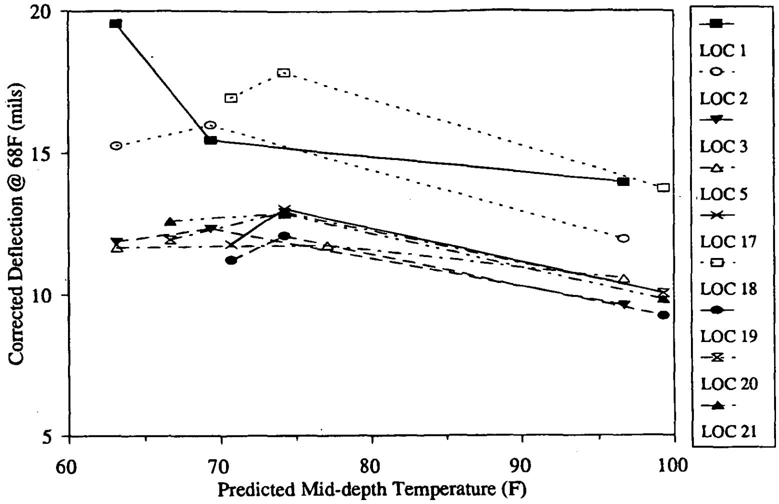

FIGURE 11 Validation of NCDOT procedure with data from Black Mountain.

compared with the methods used on the following trips, such as holding the thermocouple onto the pavement versus using an infrared thermometer. In developing the NCDOT procedure an infrared thermometer was used to measure the surface temperature throughout the entire study. It was found during the study that the measurements made with the thermocouple were different from the ones made with an infrared thermometer and that the thermocouple results would be more inconsistent because they were dependent on how the thermocouples were attached or held to the pavement.

To further add credibility to the NCDOT procedure, this method was applied to FWD data from Black Mountain, North Carolina. The results are displayed in Figure 11. The results again demonstrate the horizontal relationship between the corrected deflections and the middepth temperatures that the correct procedure should provide. Results for certain locations or sections were better than those for other locations; however, this was found to be a result of the fact that some sections were highly distressed and the meaningful temperature correction of deflections is not achievable. Overall, the results were positive, but the small variations could have resulted from climatic differences between the Black Mountain area (western area) and the Piedmont area, the pavements of which were used to develop the NCDOT procedure. Although the study has significantly improved the accuracy and reliability of the deflection-temperature correction procedure, some weaknesses remain mainly because the data were obtained from a limited number of pavements in fairly good condition and in the central area of North Carolina. The coefficients and basic relationships used in the recommended procedure could be sensitive to local climatic conditions and states of pavement damage. Calibration or generalization of the recommended procedure for different climatic regions in North Carolina and for different states of pavement damage is needed to take full advantage of the results of the study.

CONCLUSIONS

The measured deflection and pavement temperature data collected in the present study demonstrate the problems related to using the AASHTO mean temperature as the effective temperature of the AC layer. These inaccurate results were obtained because the difference in temperature-depth gradients in the heating versus cooling cycles could not be considered. In addition, the temperature adjustment factors from the AASHTO procedure overcorrected the deflections at higher temperatures, resulting in an increase in the corrected deflections as the mean temperature of the pavement increases.

The North Carolina temperature correction procedure based on the temperature at the middepth of the AC layer was found to greatly improve the accuracy of the temperature-deflection correction. The temperature correction procedure for deflections was validated with data collected from four other pavement sections. Future research efforts should be concentrated on accurately predicting the middepth temperature from the air or surface temperature and improving the accuracy of the proposed procedure for pavements in other climatic regions of North Carolina and for pavements with different damage states.

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