Prediction of Effective Asphalt Layer Temperature

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The most widely used method for evaluating deflection measurements for overlay design analysis is the 1993 *AASHTO Guide for Design of Pavement Structures*. Researchers and numerous users of the AASHTO overlay design procedure have challenged the accuracy of the AASHTO temperature correction procedure for deflections. In another paper presented at the 1995 TRB Annual Meeting a new temperature correction procedure was presented, and that procedure resulted in significant improvements over the AASHTO procedure. That procedure requires the middepth temperature of asphalt layers as input for the effective temperature of the layers. A new prediction method for an asphalt concrete middepth temperature on the basis of a data base approach is described. The major improvements over the AASHTO method are (a) air temperatures for the previous 5 days are not needed, which allows simpler and quicker deflection analyses in the North Carolina Department of Transportation (NCDOT), and (b) different temperature-depth gradients between the heating (morning) and the cooling (afternoon) cycles are taken into account. The comparison of the measured and predicted temperature demonstrated an acceptable degree of accuracy of this model for routine deflection analyses by state highway agencies. In addition to presenting the NCDOT temperature prediction procedure, an alternative temperature prediction model, known as BELLS equation, is also studied. Comparison of the measured pavement temperatures and the predicted values obtained by the BELLS equation showed underprediction of the one-third-depth temperatures at temperatures higher than 32°C (90°F).

The use of nondestructive deflection testing has become one of the primary means of determining the in situ structural capacities of existing pavements. Use of deflection measurements in flexible pavement design and analysis requires the adjustment of deflections to a reference temperature. The 1993 *AASHTO Guide for Design of Pavement Structures* (*1*) presents the temperature correction procedure for falling weight deflectometer (FWD) deflections. This procedure, however, has been reported to be inaccurate and impractical because of the use of the average air temperature for previous 5 days to predict pavement depth temperatures.

A research study sponsored by the North Carolina Department of Transportation (NCDOT) was recently performed by North Carolina State University. In that study a new temperature correction procedure for deflections was developed for flexible pavements in North Carolina. The procedure has been described by Kim and colleagues (this Record). One of the critical parameters to be determined by the procedure is the middepth temperature of asphalt layers, which represents the effective temperature of the layers. In this paper a data base approach to predicting the middepth temperature of asphalt concrete (AC) is presented.

Similar research in dealing with temperature correction and temperature prediction was recently reported by Baltzer and Jansen (*2*) and Stubstad et al. (*3*). The major conclusion of their research was that the effective AC temperature is better represented by the one-third-depth temperature instead of the middepth temperature. By using the measured pavement depth temperatures from the Strategic Highway Research Program's Long-Term Pavement Performance Program data base, an equation, referred to as the BELLS equation, was developed as a means of predicting the one-third-depth temperature. The temperature data collected from the NCDOT study were used in checking the accuracy of the BELLS equation for predicting the one-third-depth temperature for North Carolina pavements.

MEASUREMENT OF PAVEMENT TEMPERATURES

Four pavement test sections in the Piedmont area of North Carolina were selected for use in performing FWD testing and temperature measurements. These sections are referred to as Section 17, US-70, Section 13, and Section 20. The thicknesses of the asphalt layers in these pavements are 89, 140, 191, and 229 mm (3.5, 5.5, 7.5, and 9 in.), respectively. These sections were instrumented with thermocouples at various depths of the asphalt layers. Each section was subjected to FWD testing and temperature measurements at four different seasons for a duration of 1 year. During each of the site visits the measurements were made on an hourly basis for 1 full day for each section. Details on the structural designs, instrumentation, and testing plans for these sections can be found in the paper by Kim et al. (this Record).

PREDICTION OF PAVEMENT TEMPERATURE: NCDOT PROCEDURE

The NCDOT temperature correction procedure presented by Kim et al. in this Record requires the determination of middepth temperature of the AC layer as the effective temperature. Because of the routine use and speed of FWD testing, it is desirable to predict the middepth temperature of the AC layer from readily available information without performing destructive tests. To develop a simple and accurate prediction model for the middepth temperature of the AC layer, a detailed study was carried out, using the measured data, on the change of temperature as a function of the AC layer thickness, depth in pavements, time of day, season, and so forth.

By a nondestructive technique the only two temperature parameters that can be measured are the air and pavement surface temperatures. Therefore, the temperature prediction procedure that relates

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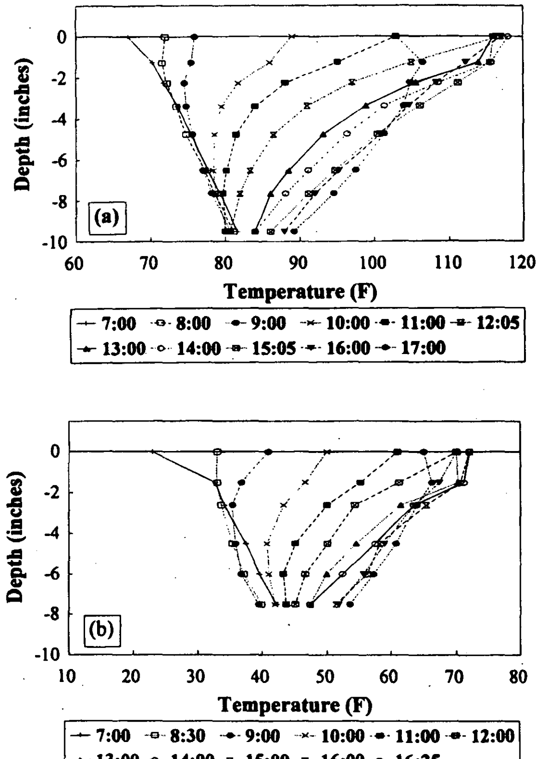

FIGURE 1 Temperature change as a function of pavement depth and time of measurement: (*a*) Section 20 in September; (*b*) Section 13 in February [1 in. = 25.4 mm; °C = (°F − 32)/1.8].

air or surface temperature to the middepth temperature is preferred for practical reasons. From the measured data a graph of pavement depth versus temperature can be plotted (Figure 1). Note in Figure 1 that surface temperatures move considerably, whereas temperatures at lower depths maintain greater consistency, resulting in cone shapes of pavement depth-versus-temperature graphs. Figure 2 displays the changes in various temperatures as a function of time of day by using the 24-hr data obtained from US-70 section [AC layer thickness of 140 mm (5.5 in.)] in May 1993. The surface temperature peaks at about 2 p.m., whereas the highest middepth and bottom temperatures occur at times somewhat delayed from that time. This delay in the peak temperature causes the change in the slope of the temperature pavement depth curves shown in Figure 1 before and after 2 p.m. The conclusion of this observation is that the slope of the temperature gradient varies with time, and neglecting it could result in significant errors in the predicted middepth temperatures. Therefore, a detailed study was carried out, using the measured temperature data, to develop a relationship between the slope of the temperature gradient and the time of day.

To investigate this relationship the temperature gradients for a particular time of day of a particular season were first grouped together, regardless of the thickness of the AC layer. Some examples are shown in Figure 3. Figures 3(*a*) and 3(*b*) contain the seasonal temperature data for four asphalt layer thicknesses. It can be observed from these figures that in most cases the temperature gradients of the four different AC layer thicknesses have similar curves. That is, the thinner pavements have the same temperature gradient shape as the thicker pavements, although the temperature gradients of the thinner pavements stop at shallower depths. This observation is very important in simplifying the temperature prediction procedure by eliminating the effect of AC layer thickness on the temperature gradient. This finding also suggests that the heat transfer mechanism in asphalt layers is the top–down process, meaning that the temperature gradients are more sensitive and more dependent on the surface temperatures than the base temperatures.

Further investigation of the effect of seasonal variation on the temperature gradient shape was done. In general, it was found that the difference in the surface temperatures between two seasons was greater than the difference in temperatures at the bottom of the AC layer between two seasons. This behavior suggested a possibility of parallel gradients for different seasons if the data were plotted on a logarithmic scale. The temperature gradients of all four sections for four seasons are presented in Figure 4 on a logarithmic scale. Since the surface temperature with a depth equal to zero could not be plotted on a log-log scale, this temperature was plotted at a depth equal to 0.1 in.

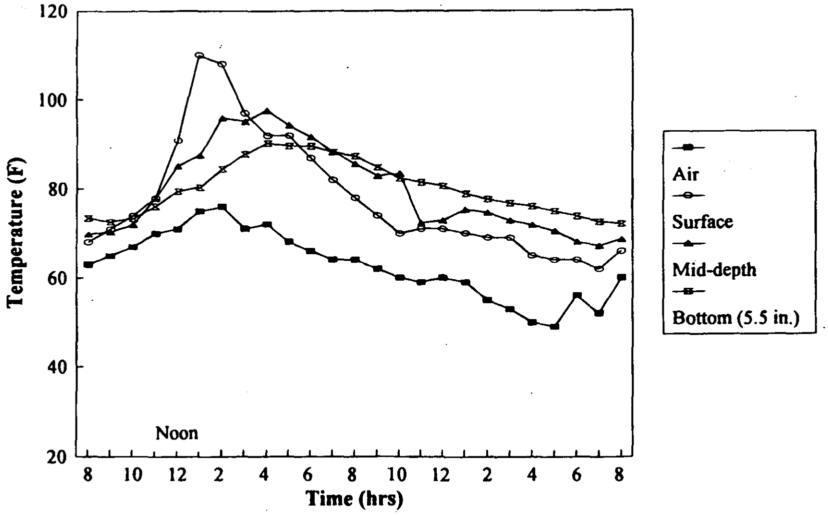

FIGURE 2 Change in temperatures during a 24-hr period measured for the US-70 Section in May 1993 [1 in. = 25.4 mm; °C = (°F − 32)/1.8]

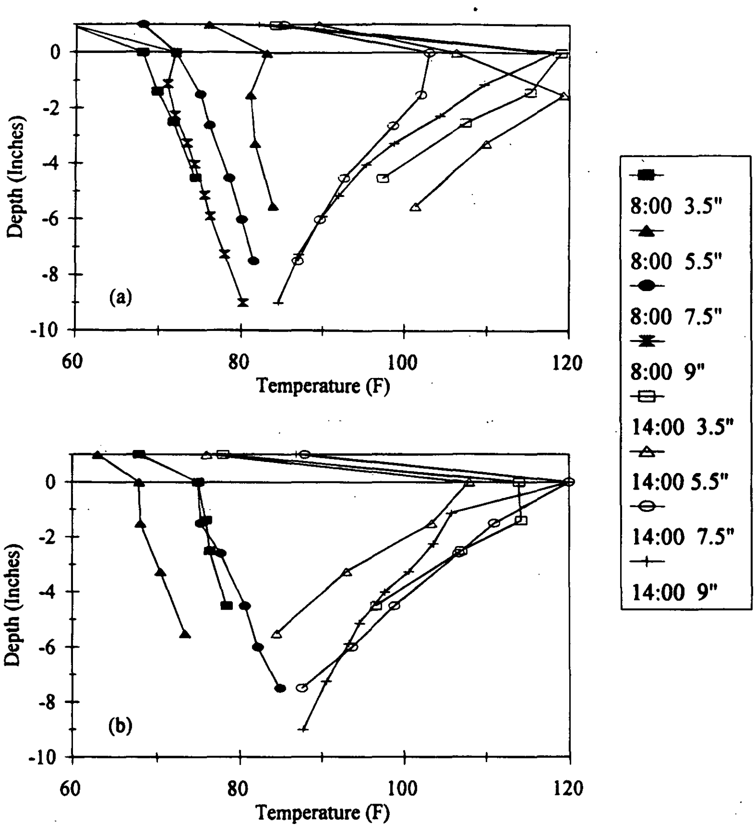

FIGURE 3 Temperature gradients for all four test sections at 8 a.m. and 2 p.m.: *(a)* September; *(b)* May [1 in. = 25.4 mm; °C = (°F − 32)/1.8].

Two important observations can be made from Figure 4. First, the temperature gradients on a logarithmic scale were composed of two straight lines, one above a depth of 38 mm (1.5 in.) depth and the other below a depth 38 mm. The significance of the 38 mm is due only to the fact that in most sections this was the depth where the shallowest thermocouple was installed. In fact, in Section 20, where the first sensor was installed at a depth of 25 mm (1 in.), depth a break in the linearity of the temperature gradient was found at a depth of 25 mm. Since the majority of the sections had first sensors at 38 mm, this depth was selected as the breakpoint for further analyses.

The second point to be made from Figure 4 is that the logarithmic temperature gradient lines are mostly parallel to each other regardless of season and time of day. This observation has a significant meaning in modeling the temperature gradient. Provided that a reference temperature gradient equation is determined for a particular time of day, one can measure the surface temperature at that time and predict the middepth temperature by shifting the reference curve to the surface temperature.

The relationship between the gradients can be proven to be parallel if the gradients are superposed when the individual gradients are all shifted along the temperature axis to one reference temperature. Since the only pavement temperature that can be measured nondestructively is the surface temperature, all of the temperature gradients at a particular time were first shifted to a reference surface temperature (Figure 5). The degree to which the gradients are superposed was not as precise as that required by the procedure. This discrepancy was due to the change in the slope of temperature gradients at 38 mm. Therefore, another shift was made to the reference 38-mm-depth temperature as shown in Figure 6. It can be seen from Figure 6 that the difference in gradients after the shift can be minimized by shifting the gradients to a reference 38-mm-depth temperature instead of a reference surface temperature. The degree to which the gradients are superposed is better, especially at depths greater than 38 mm. Use of the reference 38-mm-depth temperature also helps to minimize the effect of radiation or sunlight on the surface temperature.

Once all of the gradients were shifted to the reference 38-mm-depth temperature, as shown in Figure 6, a regression equation was derived to represent the temperature gradient shape below a depth of 38 mm for each working hour of the day (i.e., from 8 a.m. to 5 p.m.). The general form of the temperature gradient equation is

$$T_d = A \times d^B$$

where

T_d = pavement temperature at depth d,
d = pavement depth, and
A, B = regression constants.

Since the regression analyses were performed on the temperatures at depths below 38 mm from the surface, selection of the reference 38-mm-depth temperature was needed to represent an average 38-mm-depth temperature for the entire year at that particular hour of day. Regression constants and the reference 38-mm-depth temperature for each hour of the day are given in Table 1.

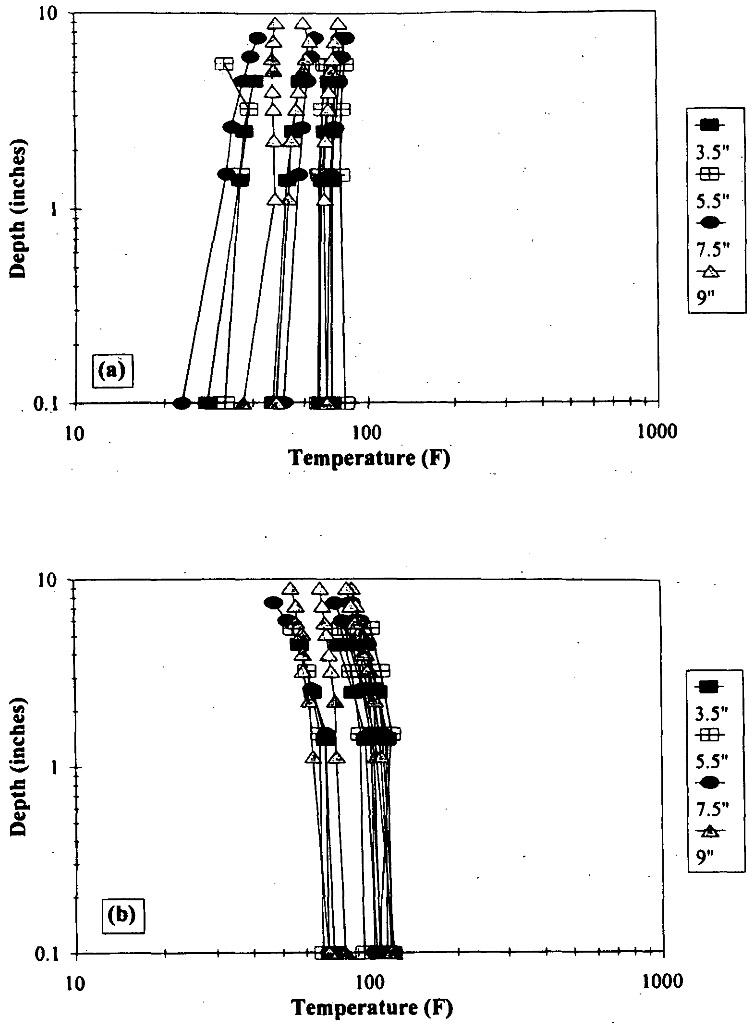

FIGURE 4 Temperature gradients for all four sections plotted on a log-log scale: (*a*) 8 a.m.; and (*b*) 2 p.m. [1 in. = 25.4 mm; °C = (°F − 32)/1.8].

Although the use of the 38-mm-depth temperature enhanced the accuracy of predicting the middepth temperature, it cannot be measured by nondestructive methods. Therefore, surface temperatures corresponding to the reference 38-mm-depth temperatures had to be determined. A reference surface temperature was selected for each hour of the day by identifying the average surface temperature when the pavement had a 38-mm-depth temperature close to the selected 38-mm-depth reference temperature given in Table 1. The reference surface temperatures for every hour of the day are also given in Table 1.

By using a measured surface temperature and the reference surface temperature, a shift factor can be developed. The shift factor is the ratio of the measured surface temperature to the reference surface temperature for a particular time. The shift factor provides a relationship between the reference gradient equation and the actual temperature gradient. By using the parallel nature of the gradients at a particular time of day, the shift factor for surface temperatures would also be a shift factor for the middepth temperature. The middepth of the asphalt layer can be substituted into the regression equation for a particular time to calculate a reference middepth temperature. The calculated middepth temperature can then be multiplied by the shift factor to obtain a final middepth temperature. An example of determining the middepth temperature by the NCDOT procedure is given below.

EXAMPLE OF MIDDEPTH TEMPERATURE PREDICTION

FWD tests were conducted at about 2 p.m. on a flexible pavement with a total AC thickness of 191 mm (7.5 in.). The measured surface temperature at the time of FWD testing was 18°C (65°F). The middepth temperature can be predicted in the following steps.

1. The general form of the temperature gradient equation is

$$T_d = A \times d^B$$

where

T_d = pavement temperature at middepth,
d = middepth, and
A, B = regression constants in Table 1.

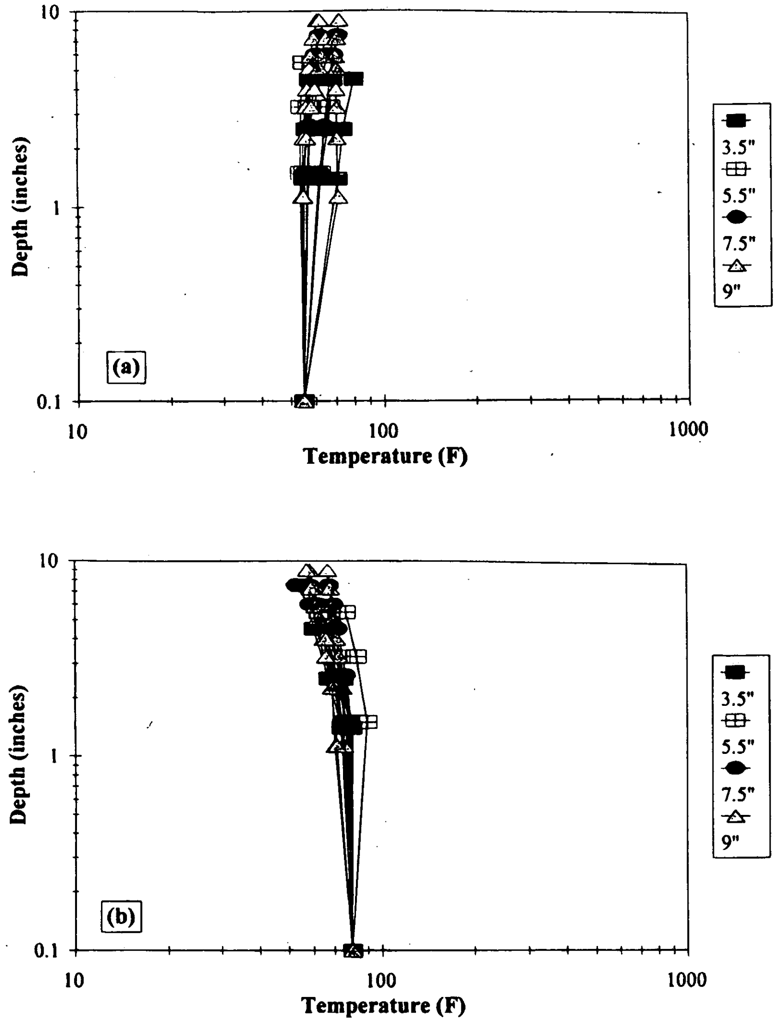

FIGURE 5 Temperature gradients shifted to a reference surface temperature: (*a*) 8 a.m.; (*b*) 2 p.m. [1 in. = 25.4 mm; °C = (°F − 32)/1.8].

In this example *d* is equal to 95 mm (3.75 in.) and *A* and *B* are 93.85 and −0.1173, respectively. Thus, the middepth temperature in the reference temperature gradient is 26.9°C (80.4°F).

2. Determine a shift factor by dividing the measured surface temperature (in °F) by the reference surface temperature for the time of FWD testing in Table 1. The shift factor adjusts the calculated reference middepth temperature in Step 1 to the actual middepth temperature corresponding to the input surface temperature.

Shift factor = 65/95 = 0.684

3. Multiply the calculated middepth temperature (in °F) from Step 1 by the shift factor from Step 2 to predict the actual middepth temperature.

Actual middepth temperature = 80.4 × 0.684 = 55°F

This procedure was applied to all of the measured data, and the accuracy of this method is demonstrated in Figure 7 by comparing the predicted middepth temperatures with the measured values. Actual application of this prediction method to the temperature correction procedure is presented in the paper by Kim et al. (this Record).

VALIDATION OF BELLS EQUATION

The widespread knowledge of the incorrect AASHTO procedure and the importance of temperature correction in using FWD deflections in pavement analysis have spawned various researchers to develop their own temperature correction procedures. Recently, Baltzer and Jansen (*2*) presented the temperature correction factors for backcalculated AC moduli and suggested that the effective AC temperature is the temperature at the one-third depth of the asphalt layer. The philosophy behind using the one-third-depth temperature instead of middepth or other depth temperatures is based on the relationships between the elastic modulus of AC and temperature. Their research showed that the variation in elastic modulus was less when it was plotted against the one-third-depth temperature. The reason for the smaller variation is that the heating and cooling of the asphalt at the one-third depth progressed at the same rate. The elastic modulus was of the same magnitude for a given temperature, independently of

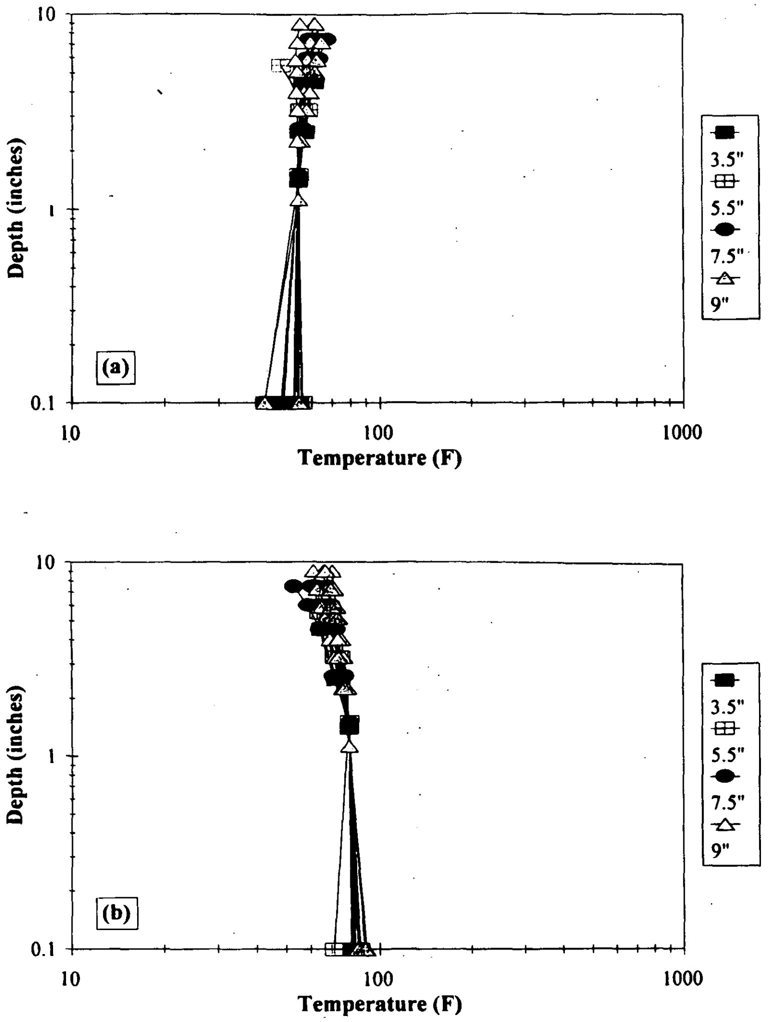

FIGURE 6 Temperature gradients shifted to a reference 38-mm (1.5-in.)-depth temperature: (*a*) 8 a.m.; (*b*) 2 p.m. [1 in. = 25.4 mm; °C = (°F − 32)/1.8].

TABLE 1 Regression Constants and Reference Temperatures for Each Hour of Day [°C = (°F − 32)/1.8]

Time of Day	A	B	Reference 38 mm Temperature (F)	Reference Surface Temp. (F)
8:00	53.79	0.0530	55	55
9:00	58.78	0.0225	60	60
10:00	65.42	-0.0283	65	70
11:00	76.83	-0.0914	75	79
12:00	83.75	-0.1433	80	86
13:00	88.61	-0.1246	85	95
14:00	93.85	-0.1173	90	95
15:00	89.27	-0.1151	85	85
16:00	83.65	-0.0926	80	80
17:00	78.20	-0.0768	75	76

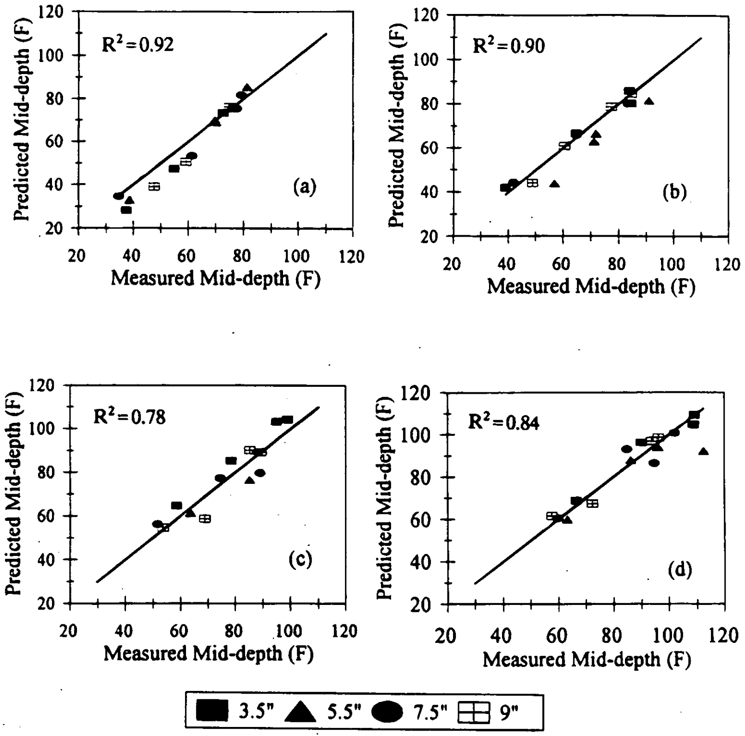

FIGURE 7 **Comparison of predicted and measured middepth temperatures: (*a*) 8 a.m.; (*b*) 10 a.m.; (*c*) 12 noon; and (*d*) 2 p.m. [1 in. = 25.4 mm; °C = (°F − 32)/1.8].**

whether the asphalt layer was heating or cooling. For depths other than the one-third depth, the magnitude of the elastic modulus was different for a given temperature, depending on whether the asphalt layer was in a heating or a cooling cycle. In support of Baltzer and Jansen's work, Stubstad et al. (*3*) presented the BELLS equation for the prediction of the one-third-depth temperature.

In order to validate the one-third-depth theory, maximum deflection data from the NCDOT data base were plotted against measured one-third-depth and middepth temperatures for all four pavements (see Figures 8 and 9 for examples). If the one-third-depth research claim were valid, the one-third-depth temperature would show smaller differences in the deflection values between the heating cycle in the morning and the cooling cycle in the late afternoon at the same one-third-depth temperature. Figures 8 and 9 show no improvement by using the one-third-depth temperature instead of using the middepth temperature.

The validity of the BELLS one-third-depth prediction equation was also studied. Measured values from the NCDOT data base were applied to the BELLS equation, and predicted versus measured temperatures are plotted in Figure 10. The BELLS equation resulted in a relatively small variation; however, the slope of the relationship that the BELLS equation displays is incorrect. The BELLS equation consistently underpredicts values at high temperatures and overpredicts values at low temperatures. The fact that the BELLS equation was developed on the basis of data collected mostly from northern states may present a possible reason for its poorer predictions at higher temperatures. Another possible source of this discrepancy is that the BELLS equation was developed by using the AC surface temperature measured with an infrared sensor mounted on the FWD, which could have measured the surface temperatures in the shade.

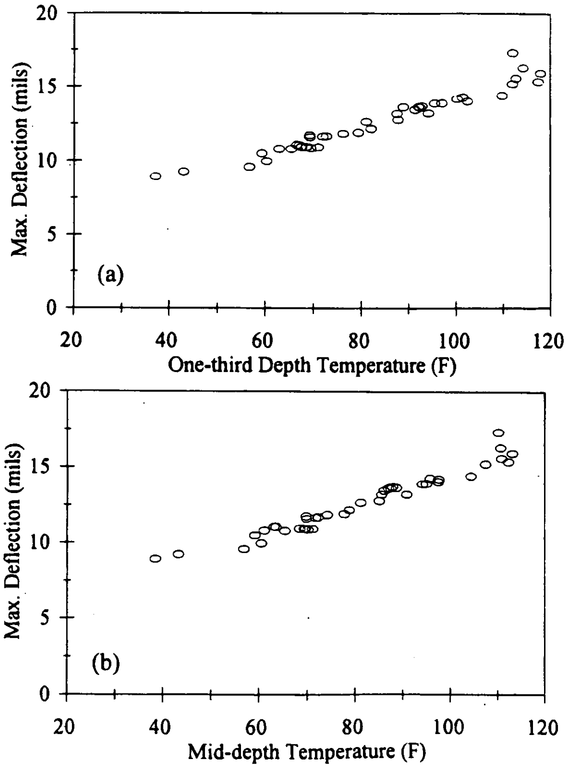

FIGURE 8 **Maximum deflection versus effective AC temperature for US-70 section (140-mm-thick AC): (*a*) one-third depth; (*b*) middepth [1 mil = 0.0254 mm; °C = (°F − 32)/1.8].**

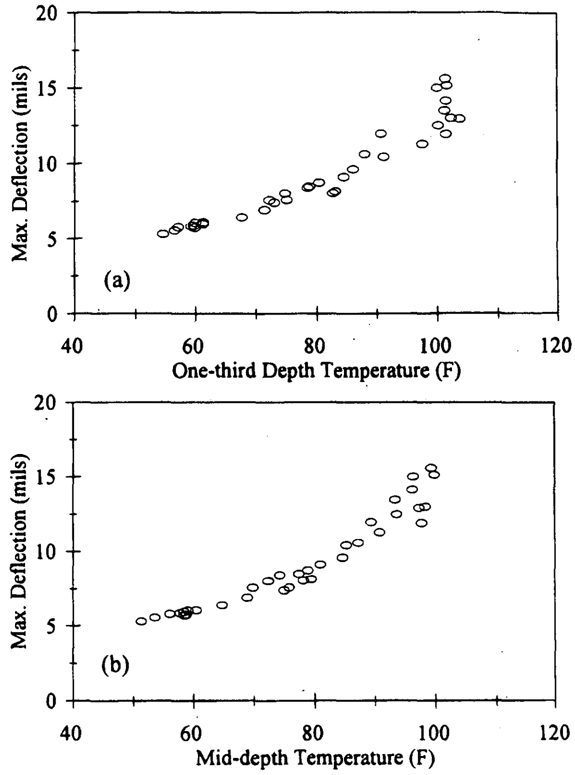

FIGURE 9 Maximum deflection versus effective AC temperature for Section 20 (229-mm-thick AC): (*a*) one-third depth; (*b*) middepth [1 mil = 0.0254 mm; °C = (°F − 32)/1.8].

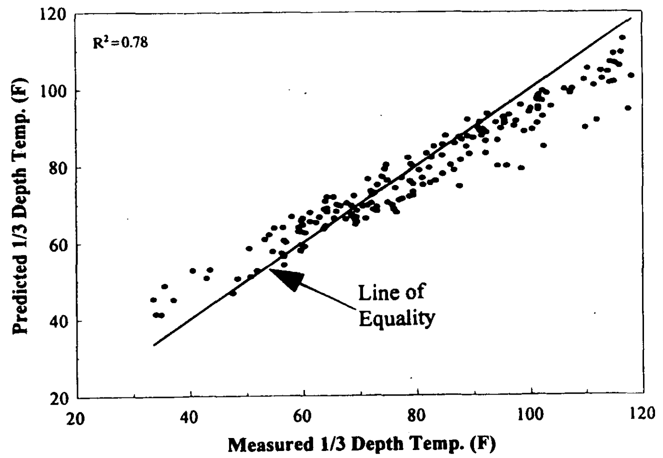

FIGURE 10 Validation of the BELLS equation using temperatures measured from pavements in North Carolina [°C = (°F − 32)/1.8].

Currently, the statewide calibration of the NCDOT procedure is conducted at North Carolina State University by testing a larger number of pavements widely spread throughout the state of North Carolina. This research will provide the necessary data to improve the temperature prediction model presented here.

CONCLUSIONS

Development of the NCDOT temperature correction procedure described in the paper by Kim et al. (this Record) produced a method that greatly improved the accuracy of the temperature-deflection correction. To supplement the NCDOT method, a temperature prediction model that predicts the middepth temperature of the AC layer was also developed. The key concept of the prediction model was the inclusion of temperature gradients along the depth as a function of the time of day. This data base approach of temperature prediction produced satisfactory results without requiring any material properties and air temperatures during the 5 days before FWD testing.

An alternate temperature prediction model, known as the BELLS one-third-depth equation, was studied by using the measured data from the North Carolina pavements. The prediction obtained by the BELLS equation showed relatively small variation, but at higher temperatures it underpredicted the measured one-third-depth AC temperature. Also, within the data base studied in this research, the AC one-third-depth temperature did not demonstrate any improvement in corrected deflection-versus-temperature relationship over the AC middepth temperature.

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