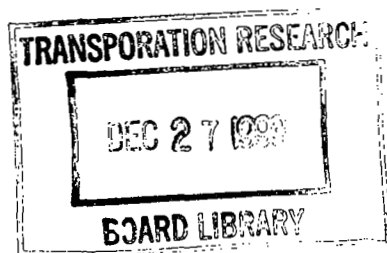SHRP-P-654

SHRP Procedure for Temperature Correction of Maximum Deflections

shrp

Strategic Highway Research Program
National Research Council

Strategic Highway Research Program Executive Committee

SHRP-P-654

SHRP Procedure for Temperature Correction of Maximum Deflections

PCS/Law Engineering

Strategic Highway Research Program
National Research Council
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Abstract

Nondestructive deflection testing using falling weight deflectometers (FWDs) is one element of the monitoring effort currently underway by the Strategic Highway Research Program (SHRP) for the Long-Term Pavement Performance (LTPP) study. Because accurate data are key to the success of the LTPP study, SHRP has implemented a number of measures to ensure the quality of the deflection data. They include equipment comparison and calibration, standardized field testing procedure and field data checks, and quality assurance software.

In turn, the quality assurance software includes a program called FWDCHECK which has been developed to analyze deflection data for, among other things, overall reasonableness from a structural capacity viewpoint. In the case of asphaltic concrete pavements, this structural capacity analysis follows the AASHTO direct structural number procedure. Since asphaltic concrete materials are temperature dependent in nature, measured deflections and hence the structural capacity of the pavement vary with temperature. Thus, a procedure to correct measured maximum deflections to a standard temperature is required so that the comparison of predicted versus expected structural capacities is a valid one. This report documents the temperature correction procedure developed for and used in the FWDCHECK program.

INTRODUCTION

SHRP's Long-Term Pavement Performance (LTPP) study involves extensive monitoring of numerous pavement sections located throughout North America. One aspect of the LTPP data collection is deflection testing, which provides information on structural capacity and material properties. Because accurate data is key to the success of the LTPP study, SHRP has implemented a number of measures to ensure the quality of deflection data. They include: equipment comparison and calibration, standardized field testing procedures and field data checks, and quality assurance software. For the final stage in the quality assurance process, a computer program called FWDCHECK has been developed to analyze deflection data for test section homogeneity, the degree to which test pit data is representative of the section, the presence of data outliers within the section, and overall reasonableness from a structural capacity viewpoint (1).

The last set of deflection data checks in FWDCHECK -- overall reasonableness from a structural capacity viewpoint -- involve the computation of pavement structural capacity and the comparison of the results to what one might expect based on known layer thicknesses and material properties. In the case of flexible (asphalt concrete or AC) pavements, this structural capacity analysis follows the AASHTO direct structural number procedure. The outer deflection basin data are used to estimate the subgrade modulus and this parameter, along with the maximum deflection, is used to directly estimate the effective structural number (SN) of the pavement system.

Because of the temperature-dependent nature of the asphalt concrete modulus, however, measured deflections and hence the structural capacity (or SN value) of the pavement will also vary with temperature. Thus, a procedure to correct the measured maximum deflection to a standard temperature is required so that the comparison of predicted versus expected SN values is a valid one. Also, since the AASHTO structural number or SN value is computed at a standard temperature of 68 F, maximum deflection measured in the field must be corrected to this standard temperature. This report documents the temperature correction procedure developed for and used in the FWDCHECK program.

FWDCHECK TEMPERATURE CORRECTION PROCEDURE

The maximum deflection temperature correction procedure incorporated in the FWDCHECK program is based upon the following relation:

$$Dr = \frac{\delta o_s}{\delta o_f}$$

where Dr = temperature correction factor, δo_s = maximum surface deflection at standard temperature of 68°F, and δo_f = maximum surface deflection measured in the field (i.e., at test temperature).

The loading, structural and temperature factors affecting the maximum measured deflection, δo_j, are illustrated in Figure 1. They include:

1. Loading Factors - applied load (P), radius of circular load plate (a_c), and plate contact pressure (p_c).
2. Structural Factors - number of layers (n), layer thicknesses (h_i), layer elastic moduli (E_i), and layer Poisson's ratios (u_i).
3. Temperature Factors - temperature of the asphalt concrete surface layer (T_f); (Note: mid-depth temperature is used in the FWDCHECK program analysis).

The loading factors P, a_c, and p_c are always known for a given deflection basin test (stored in the deflection data file). Layer thicknesses (h_i) are also known from coring and test pit information collected at both ends of the pavement section; they are assumed to remain constant throughout the section. The mid-depth temperature of the AC surface layer (T_f) can be estimated for each deflection basin based on temperature readings taken throughout the test day, at both ends of the pavement section and at various depths; Figure 2 shows a typical trend of mid-depth temperature versus time of testing. The only unknown factors are the layer elastic moduli (E_i) and Poisson's ratios (u_i).

The loading, structural and temperature factors used in the determination of the temperature correction factor are illustrated in Figure 3. Figure 3a represents the actual conditions at the time of testing, T_f, while Figure 3b represents the conditions at the standard temperature of 68°F. The major difference between the two sets of conditions is the mid-depth surface temperature, which in turn affects the elastic modulus of the AC surface layer, E_i, and hence the maximum deflection, δ_o. The loading factors and layer thicknesses are the same as those measured in the field. Because layer moduli and Poisson's ratios are generally unknown, the following assumptions have been made:

*   All layers are homogeneous and linearly elastic (even though non-linearity is built into the FWDCHECK analysis).
*   All layers have a Poisson's ratio of 0.5.
*   With the exception of the AC surface and subgrade layers, the elastic modulus of all other layers is a constant value defined according to material type; see Table 1.

The subgrade elastic modulus is determined from the composite moduli predicted as a function of geophone location (i.e., radial distance). More specifically, it is assumed that the subgrade modulus is equal to the minimum value in the composite modulus-radial distance relationship. Composite moduli are calculated at each radial distance using the measured deflection basin data as input into Boussinesq's one-layer deflection equation (2):

$$E_c = \frac{2*(1 - \mu_{sg}^2)*p_c*a_c}{\delta}; \quad \text{if } r \le 0.25a_c \tag{1a}$$

or

(a)
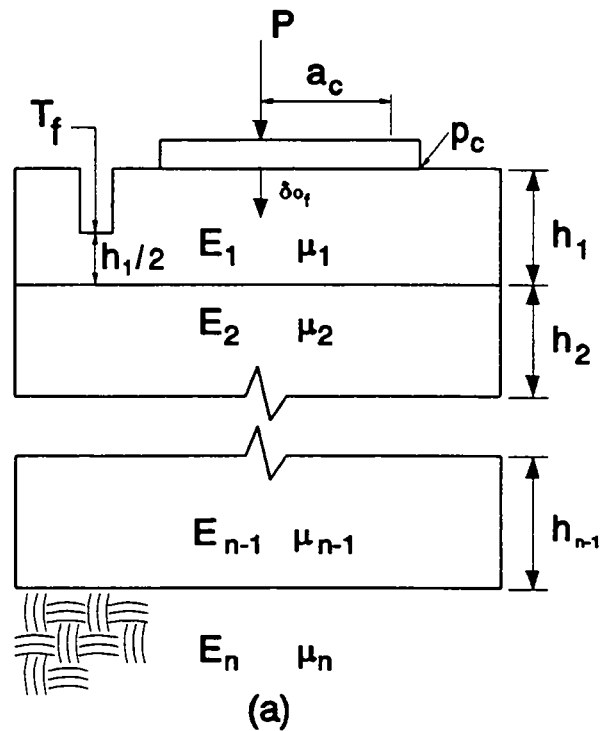
FIELD CONDITIONS AT
TEMPERATURE = T_f

Figure 1 - Actual Testing Conditions and Pavement Structure

3
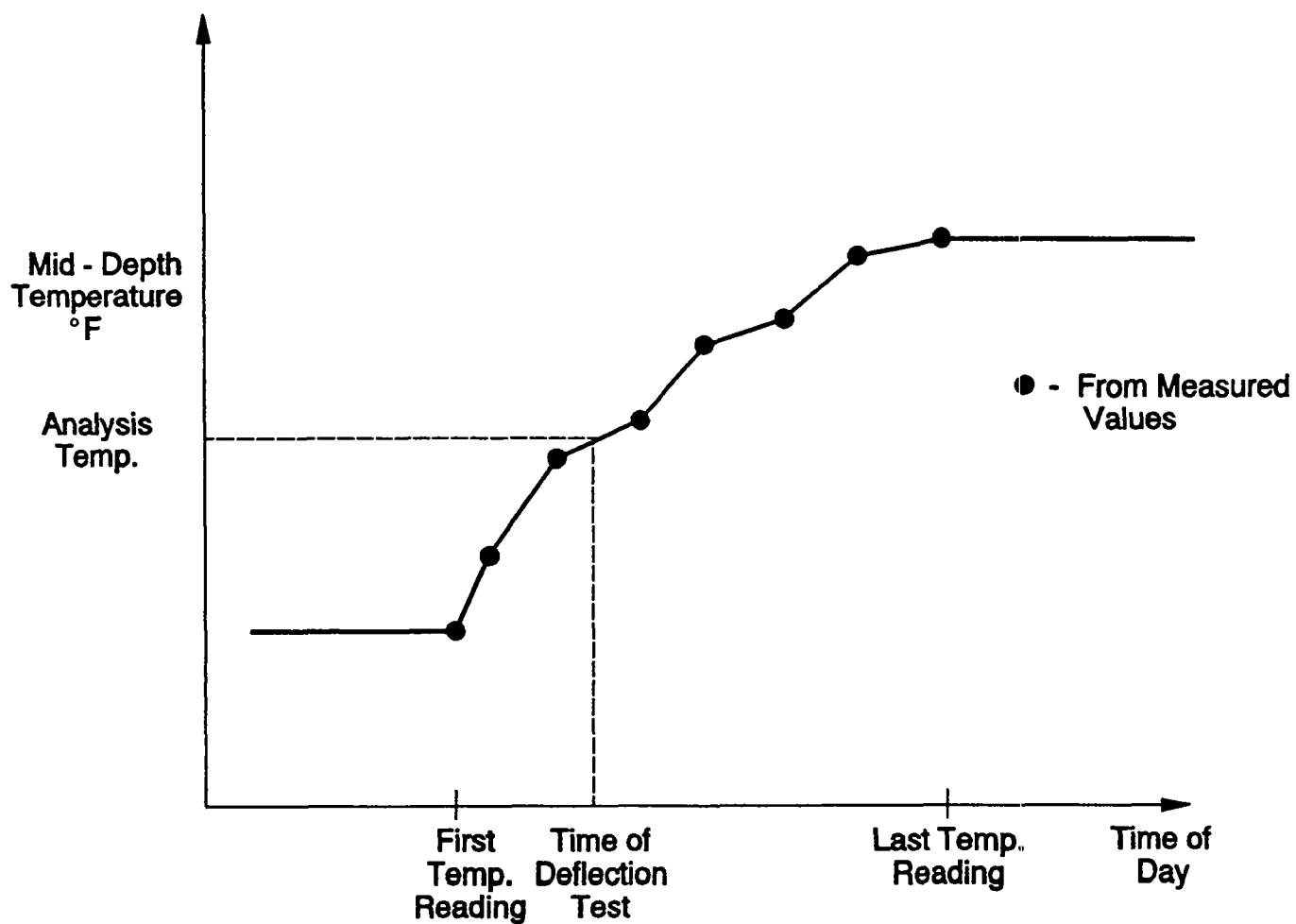
Note: Temperature data is interpolated in order to provide for the best estimate at the time of testing

Figure 2 - Hypothetical Trend of Field Temperatures

4
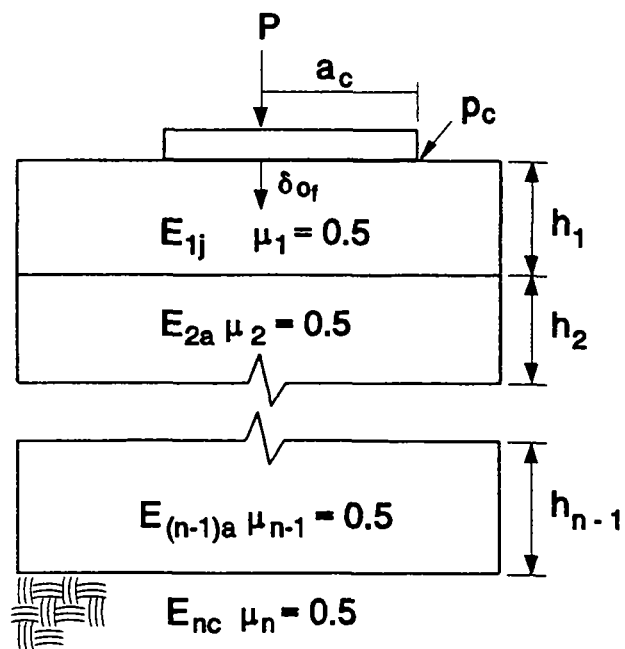
(a)

**CONDITIONS USED IN MODEL
AT TEMPERATURE = T_f**
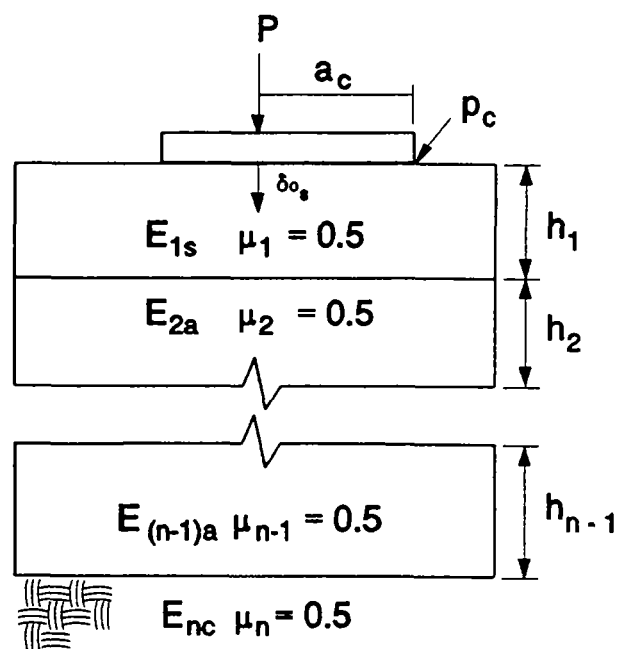
(b)

**CONDITIONS USED IN MODEL
AT TEMPERATURE = 68°F**

Figure 3 - Testing Conditions and Pavement Structure Used in Correction Procedure

Table 1 - Layer Elastic Modulus as a Function of Material Type

Material Type	Material Code	Elastic Modulus (ksi)
Uncrushed Gravel	302	20.0
Crushed Stone	303	45.0
Crushed Gravel	304	30.0
Crushed Slag	305	50.0
Sand	306	10.0
Fine Soil-Agg. Mixture	307	15.0
Coarse Soil-Agg. Mixture	308	20.0
Sand Asphalt	320	200.0
Asphalt Treated Mixture	321	300.0
Cement Aggregate Mixture	331	750.0
Econocrete	332	1,500.0
Cement Treated Soil	334	100.0
Lean Concrete	336	1,500.0
Sand-Shell Mixture	337	75.0
Limerock, Caliche	338	200.0
Lime Treated Soil	339	75.0
Soil Cement	340	200.0
Pozzolanic-Agg. Mixture	341	500.0
Cracked & Seated PCC	730	1,000.0
Portland Cement Concrete	700	5,000.0

$$E_c = \frac{(1 - \mu_{sg}^2) * p_c * a_c^2}{\delta * r} * C; \quad \text{if } r > 0.25a_c \tag{1b}$$

where:

E_c	= composite modulus;
r	= radial distance;
p_c	= contact pressure applied by NDT device;
a_c	= radius of contact of NDT device;
μ_{sg}	= Poisson's Ratio of the subgrade (= 0.5);
δ	= measured deflection at given radial distance; and
C	= deflection constant equal to the lower of [1.1log(r/a_c) + 1.15] and [0.5*μ_{sg} + 0.875].

The elastic modulus of the asphalt concrete layer, both at field and standard temperatures, is determined by means of the following dynamic modulus predictive equation developed by the Asphalt Institute:

$$\log_{10} E^* = 0.553833 + 0.028829(p_{200})f^{-0.17033} - 0.03476V_a + 0.070377\eta_{70;\,10^\wedge 6}$$
$$+ 0.000005\left[t_p^{(1.3\,\cdot\,0.49825\log f)}p_{ac}^{0.5}\right] - 0.00189\left[t_p^{1.3\,\cdot\,0.49825\log f}p_{ac}^{0.5} * f^{-1.1}\right] + 0.931757f^{-0.02774} \tag{2}$$

where:

E^*	= AC modulus (10^5 psi);
p_{200}	= percent weight passing the No. 200 sieve (%);
f	= test frequency of load wave (cps or Hz);
V_a	= percent air voids in mix (%);
$\eta_{70;10^\wedge 6}$	= AC Viscosity at 70°F (10^6 poises);
t_p	= AC temperature (°F); and
p_{AC}	= percent asphalt content by weight of mix (%).

To simplify the temperature correction analysis, the following typical asphalt concrete properties were assumed:

p_{200}	=	5.0%
f	=	20Hz
V_a	=	4.0%
$\eta_{70;\,10^\wedge 6}$	=	1.5 x 10^6 poise
p_{ac}	=	5.0%

Thus, the AC modulus predictive equation (Eq. 1) is reduced to:

$$\log_{10} E = 6.464 - 0.000145t_p^{1.94824} \tag{3}$$

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Having established the various loading, structural and temperature factors, the maximum deflection response of the pavement (i.e., directly under the load plate) is predicted for both the assumed field and standard temperature conditions. To accomplish this, a closed form solution was developed based on equivalent layer theory and Boussinesq's one-layer deflection equations. The derivation of this solution is presented below.

The maximum surface deflection is equal to the sum of the compressions of each pavement layer plus the deflection at the interface of the bottom of layer (n-1) and the top of the subgrade, as shown in Figure 4. The compression of each layer is determined by subtracting the interface deflections which occur just above and below the pavement layer. This difference represents the cumulative strain that is contributed by the pavement layer. The remainder of the surface deflection results from strains developed in the underlying layers.

The compression of each pavement layer can be determined in this manner with the exception of the subgrade. If the subgrade is assumed to have an infinite thickness, no compression will occur, therefore 100 percent of the interface deflection at the top of the subgrade contributes to the total surface deflection. Thus, the final equation for the total surface deflection is as follows:

$$\delta_o' = \left(\delta_{1T}' - \delta_{1B}'\right) + \sum_{i=2}^{n-1} \left(\delta_{iT}' - \delta_{iB}'\right) + \delta_{nT}'$$

where:

δ_o' = total surface deflection;

δ_{1T}' = deflection at top of layer 1;

δ_{1T}' = interface deflection at bottom of layer 1;

δ_{iT}' = interface deflections at the top of layer i;

δ_{iB}' = interface deflections at the bottom of layer i; and

δ_{nT}' = interface deflection at the top of subgrade.

Interface deflections are determined using Boussinesq's one-layer deflection equation. When using these equations, multiple layers are transformed into a single, homogeneous material layer. Specifically, when determining the compression of layer i, all layers above it are transformed into an equivalent material having the same characteristics as layer i (i.e., same E_i and u_i). The thicknesses of these transformed layers are such that the stiffness of each layer remains the same (i.e., as before the transformation).

The stiffness of any given pavement layer, S, is defined by:

$$S = \frac{E_j h_j^3}{12 \left(1 - \mu_j^2\right)} \tag{4}$$

where E_j, h_j and u_j are the elastic modulus, thickness and Poisson's ratio of layer j, respectively. Thus, if a layer characterized by these properties is transformed into an
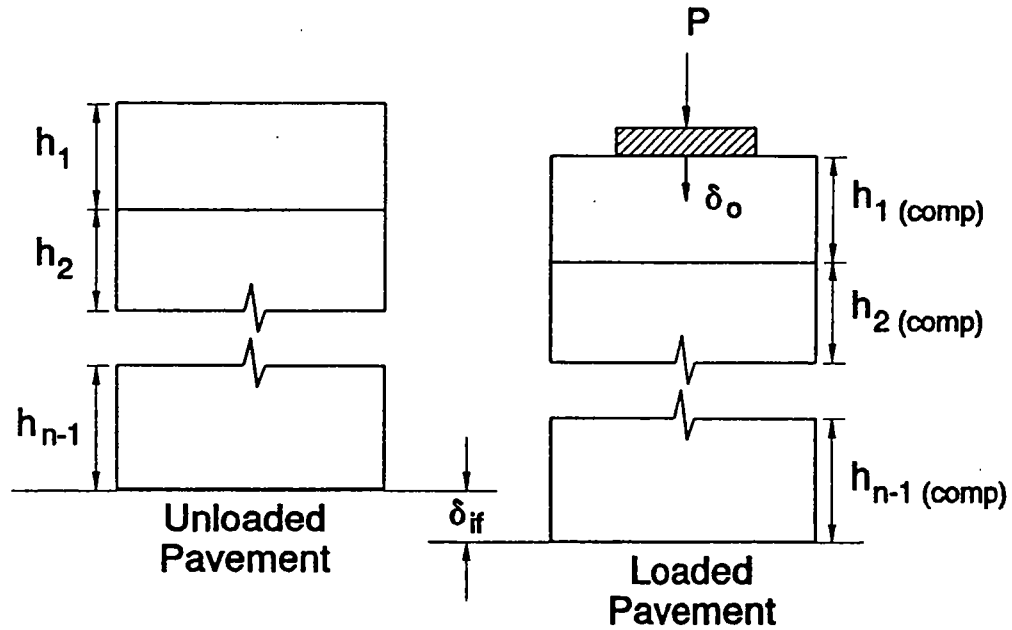
$$\delta c_1 = h_1 - h_1'$$

$$\delta c_2 = h_2 - h_2'$$

$$\delta c_{n-1} = h_{n-1} - h_{n-1}'$$

$$\delta_{if} = \delta_{if}$$

$$\delta_0 = \delta c_1 + \delta c_2 + \dots + \delta_{n-1} + \delta_{if}$$

Note: $h_{i(comp)}'$ as shown in the above illustration refers to the compressed layer thickness after the pavement is loaded.

Figure 4 - Components of Maximum Surface Deflection

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equivalent material (having E_i, h_i and u_i) but the stiffness remains the same, the following relationship must hold true:

$$\frac{E_j\,h_j^3}{12\left(1 - \mu_j^2\right)} = \frac{E_i\,h_i^3}{12\left(1 - \mu_i^2\right)}$$

Or, rearranging the transformed thickness equation, h_i' can be solved as follows:

$$h_i' = h_j \sqrt[3]{\frac{E_j\left(1 - \mu_i^2\right)}{E_i\left(1 - \mu_j^2\right)}} \tag{5}$$

Furthermore, if the Poisson's ratio of all layers is assumed to be $\mu_i = \mu_j = 0.5$, then the transformed thickness equation is reduced to:

$$h_i' = h_j \sqrt[3]{\frac{E_j}{E_i}} \tag{6}$$

To compensate for errors inherent in this approximate procedure, an adjustment factor, α, is typically incorporated into the thickness transformation equation:

$$h_i' = \alpha h_j \sqrt[3]{\frac{E_j}{E_i}}$$

where:

$$\alpha = 1 - \frac{\log\left(\frac{E_j}{E_i}\right)}{7.5 h_j^{0.2}}$$

The α function used in the FWDCHECK temperature correction procedure was determined by comparing (and analyzing) deflection results generated from hundreds of Chevron runs with those generated using the transformed section approach discussed next. The results typically ranged from $\alpha = 0.8$ to 0.9.

In the case of a one-layer pavement system, the maximum deflection directly under the center of the load plate can be estimated from the following Boussinesq equation:

$$\delta_{r\,=\,0,\,z\geq0} = \frac{p_c\,a_c^2\left(1 - \mu^2\right)}{E} F_b \tag{7}$$

where:
   z   = depth from surface;
   r   = radial distance from load; and
   F_b = Boussinesq one-layer deflection factor, which in turn is defined by:

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$$F_b = \left(\sqrt{1 + \left(\frac{h}{a_c}\right)^2} - \left(\frac{h}{a_c}\right) \right) \left(1 + \frac{\left(\frac{h}{a_c}\right)}{2(1 - \mu)\sqrt{1 + \left(\frac{h}{a_c}\right)^2}} \right) \tag{8}$$

If the Poisson's ratio for this one-layer system is assumed to be $\mu = 0.5$, then the above equation is reduced to:

$$\delta_{r=0, z \geq 0} = \frac{0.75 p_c a_c^2}{E} \frac{1}{\sqrt{1 + \left(\frac{h}{a_c}\right)^2}} \tag{9}$$

However, since pavement structures generally consist of multiple layers, the concepts of layer thickness transformations and interface deflections must be incorporated into the Boussinesq one-layer deflection equation. The maximum surface deflection is determined as follows:

1. The first layer (i.e., AC surface) of the pavement structure does not require transformation because no layers lie above it. Therefore, the interface deflections at the top and bottom of the layer ($\delta_T{}'$ and $\delta_{1B}{}'$) are defined by:

$$\delta_{1T}{}' = \frac{0.75 p_c a_c^2}{E_1}$$

and

$$\delta_{1B}{}' = \frac{0.75 p_c a_c^2}{E_1} \left(\frac{1}{\sqrt{1 + \left(\frac{h_1}{a_c}\right)^2}} \right) = \frac{0.75 p_c a_c^2}{E_1} F_{b1B}$$

where E_1, h_1 and u_1 are the elastic modulus, thickness and Poisson's ratio of the AC surface layer.

2. To determine the interface deflections for each of the remaining pavement layers above the subgrade, all layers above the one in question (i.e., layer i) are transformed into an equivalent, single material characterized by E_i and u_i. This process is shown below:

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$$h_i' = \sum_{j=1}^{i-1} h_j \sqrt[3]{\frac{E_j}{E_i}}$$

$$\delta_{iT}' = \frac{0.75 p_c a_c^2}{E_i} \left(\frac{1}{\sqrt{1 + \left(\frac{h_i'}{a_c}\right)^2}} \right) = \frac{0.75 p_c a_c^2}{E_1} F_{biT}$$

and

$$\delta_{iB}' = \frac{0.75 p_c a_c^2}{E_i} \left(\frac{1}{\sqrt{1 + \left(\frac{h_i' + h_i}{a_c}\right)^2}} \right) = \frac{0.75 p_c a_c^2}{E_1} F_{biB}$$

where E_j, h_j and u_j are the elastic modulus, thickness and Poisson's ratio of layer j.

3. The interface deflection at the top of the subgrade, δ_{nT}, is determined as follows:

$$h_n' = \sum_{j=1}^{n-1} h_j \sqrt[3]{\frac{E_j}{E_n}}$$

$$\delta_{nT}' = \frac{0.75 p_c a_c^2}{E_n} \left(\frac{1}{\sqrt{1 + \left(\frac{h_n'}{a_c}\right)^2}} \right) = \frac{0.75 p_c a_c^2}{E_n} F_{bnT}$$

4. As indicated earlier, the maximum surface deflection is equal to the sum of the compression in each layer plus the interface deflection at the top of subgrade:

$$\delta_o = \left(\delta_{1T}' - \delta_{1B}'\right) + \sum_{i=2}^{n-1} \left(\delta_{iT}' - \delta_{iB}'\right) + \delta_{nT}$$

Substituting the interface equations (presented in Steps No. 1 through 3 above) into the maximum surface deflection equation yields:

$$\delta_o = 0.75 p_c a_c^2 \left[\frac{1}{E_1}(1 - F_{b1B}) + \sum_{i-2}^{n-1} \frac{1}{E_i}(F_{biT} - F_{biB}) + \frac{1}{E_n} F_{bnT} \right] \tag{10}$$

This last equation is used in the FWDCHECK temperature correction procedure to estimate both the maximum surface deflection at field temperature, δo_f, and the maximum surface deflection at the standard temperature of 68°F, δo_s. The only difference in these two calculations is the elastic modulus assigned to the AC surface layer -- E_{1f} (at field temperature) and E_{1s} (at 68°F). In turn, the temperature correction factor, Dr, is determined from δo_f and δo_s as follows:

$$Dr = \frac{\delta o_s}{\delta o_f} = \frac{\frac{1}{E_{1s}}(1 - F_{b1B}) + \sum_{i-2}^{n-1} \frac{1}{E_i}(F_{biT} - F_{biB}) + \frac{1}{E_n} F_{bnT}}{\frac{1}{E_{1f}}(1 - F_{b1B}) + \sum_{i-2}^{n-1} \frac{1}{E_i}(F_{biT} - F_{biB}) + \frac{1}{E_n} F_{bnT}} \tag{12}$$

This factor is only used to temperature correct maximum deflections, after the subgrade modulus has been established.
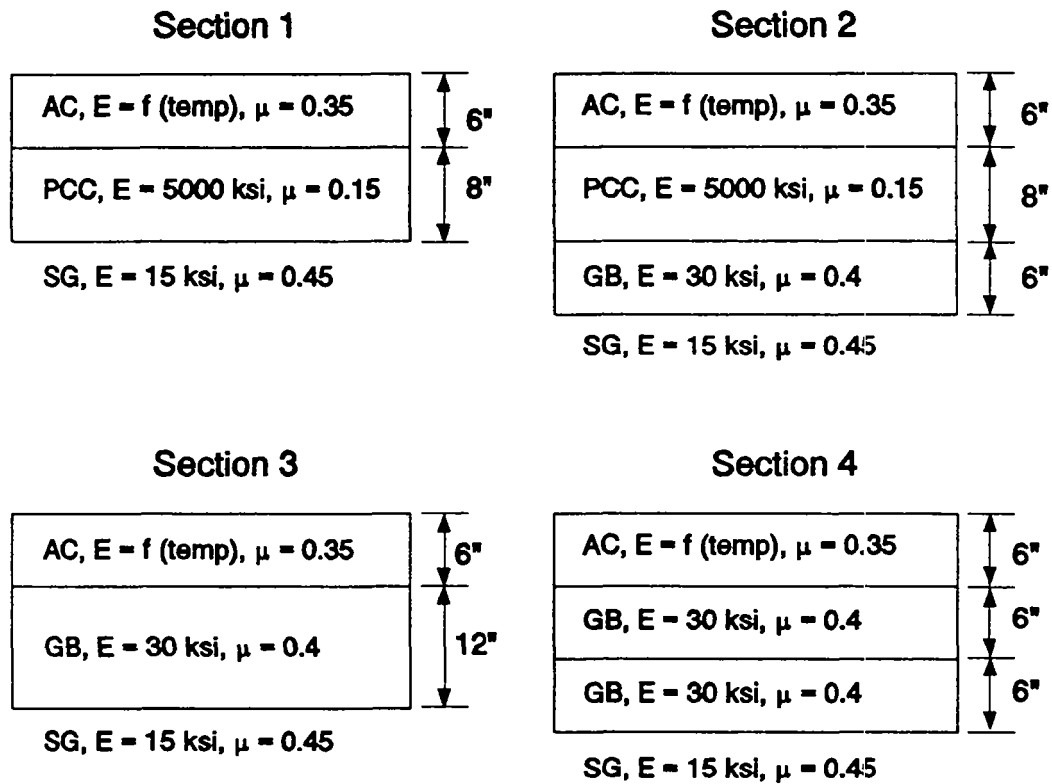
SENSITIVITY ANALYSIS

In order to assess the influence of the various factors used to determine the temperature correction factor, Dr, a sensitive analysis was undertaken. These factors included:

1. Asphalt Concrete thickness (when used as a surface layer)
2. Layer moduli (other than surface layer)
3. Layer Poisson's ratio

Deflection temperature correction factors were first determined for the four hypothetical structures shown in Figure 5, which include two and three layer flexible structures and two and three layer composite structures. The influence of each parameter on the temperature correction factor was determined by varying the values shown in Figure 5 to those shown in Table 2.

The analysis results are summarized in Figure 6. As can be observed, changes in the thickness of the asphalt concrete layer and the elastic modulus of the subgrade have the greatest effect on the temperature correction factor, Dr. The impact of these two factors upon Dr is further illustrated in Figures 7 and 8, which show the change in Dr due to changes in either AC layer thickness or subgrade modulus and temperature. The remaining factors, E_i and μ_i, had little to no effect on Dr (up to 7% change in Dr, see Figure 6).

It should be noted that when determining the temperature correction factor, the asphalt concrete modulus is predicted from the Asphalt Institute dynamic modulus equation and the subgrade modulus is calculated from the outer geophone deflection readings. Therefore,

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Section 1

AC, E = f (temp), μ = 0.35	6"
PCC, E = 5000 ksi, μ = 0.15	8"

SG, E = 15 ksi, μ = 0.45

Section 2

AC, E = f (temp), μ = 0.35	6"
PCC, E = 5000 ksi, μ = 0.15	8"
GB, E = 30 ksi, μ = 0.4	6"

SG, E = 15 ksi, μ = 0.45

Section 3

AC, E = f (temp), μ = 0.35	6"
GB, E = 30 ksi, μ = 0.4	12"

SG, E = 15 ksi, μ = 0.45

Section 4

AC, E = f (temp), μ = 0.35	6"
GB, E = 30 ksi, μ = 0.4	6"
GB, E = 30 ksi, μ = 0.4	6"

SG, E = 15 ksi, μ = 0.45

AC = Asphalt Concrete
GB = Granular Base
PCC = Portland Cement Concrete
SG = Subgrade

Figure 5 - Hypothetical Pavement Sections

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Table 2 - Values Used in Sensitivity Analysis

Parameter	Section 1			Section 2			Section 3			Section 4		
	Min	Max	Inc	Min	Max	Inc	Min	Max	Inc	Min	Max	Inc
Temperature, °F	0	120	10	0	120	10	0	120	10	0	120	10
AC Thickness, inches	2	12	2	2	12	2	2	12	2	2	12	2
Base Course Elastic Modulus, ksi	1000	10000	1000	1000	10000	1000	10	100	10	10	100	10
Subbase Course Elastic Modulus, ksi	N/A	N/A	N/A	10	100	10	N/A	N/A	N/A	10	100	10
Subgrade Course Elastic Modulus, ksi	5	50	5	5	50	5	5	50	5	5	50	5
Surface Course Poisson's Ratio	0.3	0.5	0.05	0.3	0.5	0.05	0.3	0.5	0.05	0.3	0.5	0.05
Base Course Poisson's Ratio	0.1	0.5	0.05	0.1	0.5	0.05	0.3	0.5	0.05	0.3	0.5	0.05
Subbase Course Poisson's Ratio	N/A	N/A	N/A	0.3	0.5	0.05	N/A	N/A	N/A	0.3	0.5	0.05
Subgrade Course Poisson's Ratio	0.3	0.5	0.05	0.3	0.5	0.05	0.3	0.5	0.05	0.0	0.5	0.05

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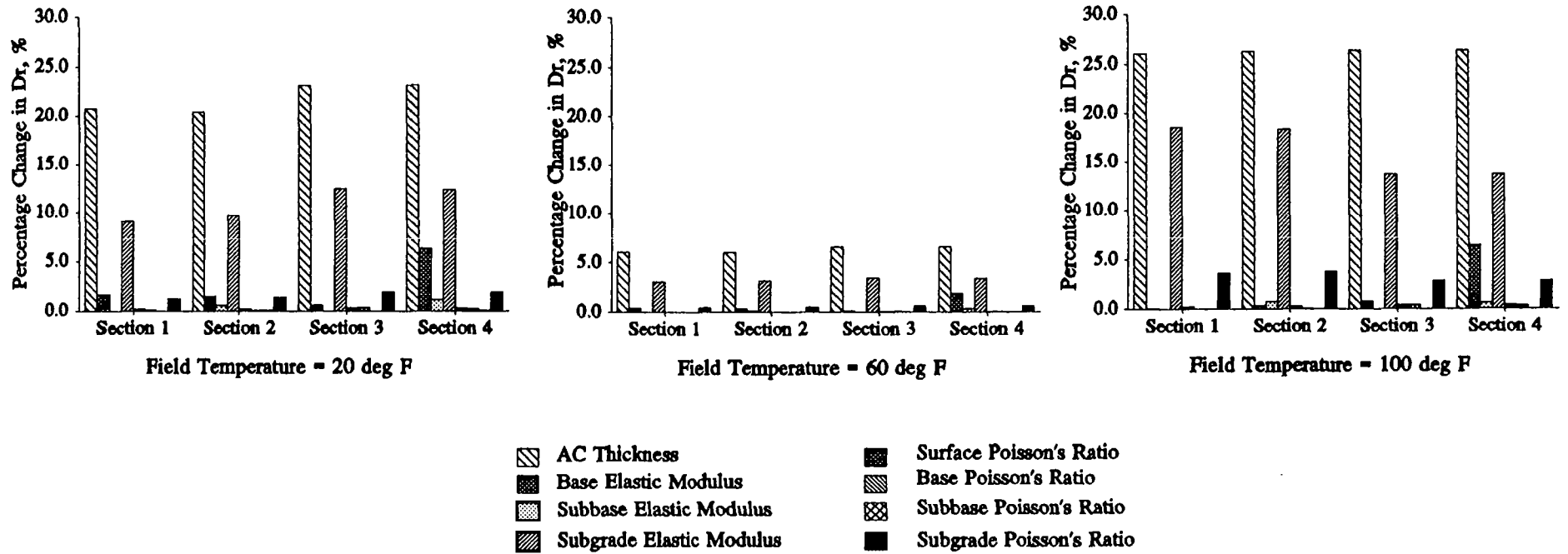
Figure 6 - Summary of Sensitivity Analyses (Temperature = 20, 60, and 100°F)
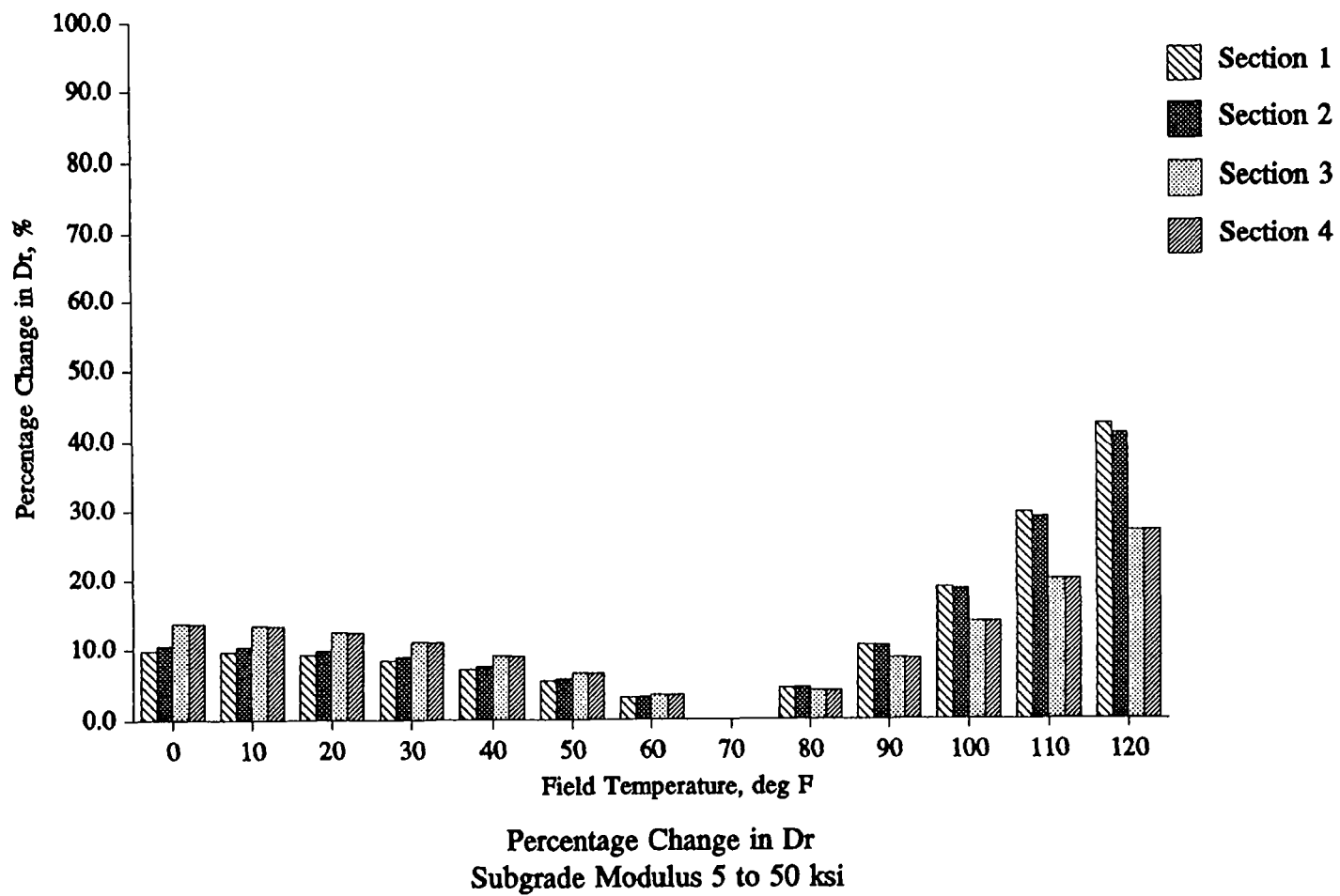
Figure 7 - Effect of Subgrade Modulus on Temperature Correction

Percentage Change in Dr (h = 2″ to 12″)
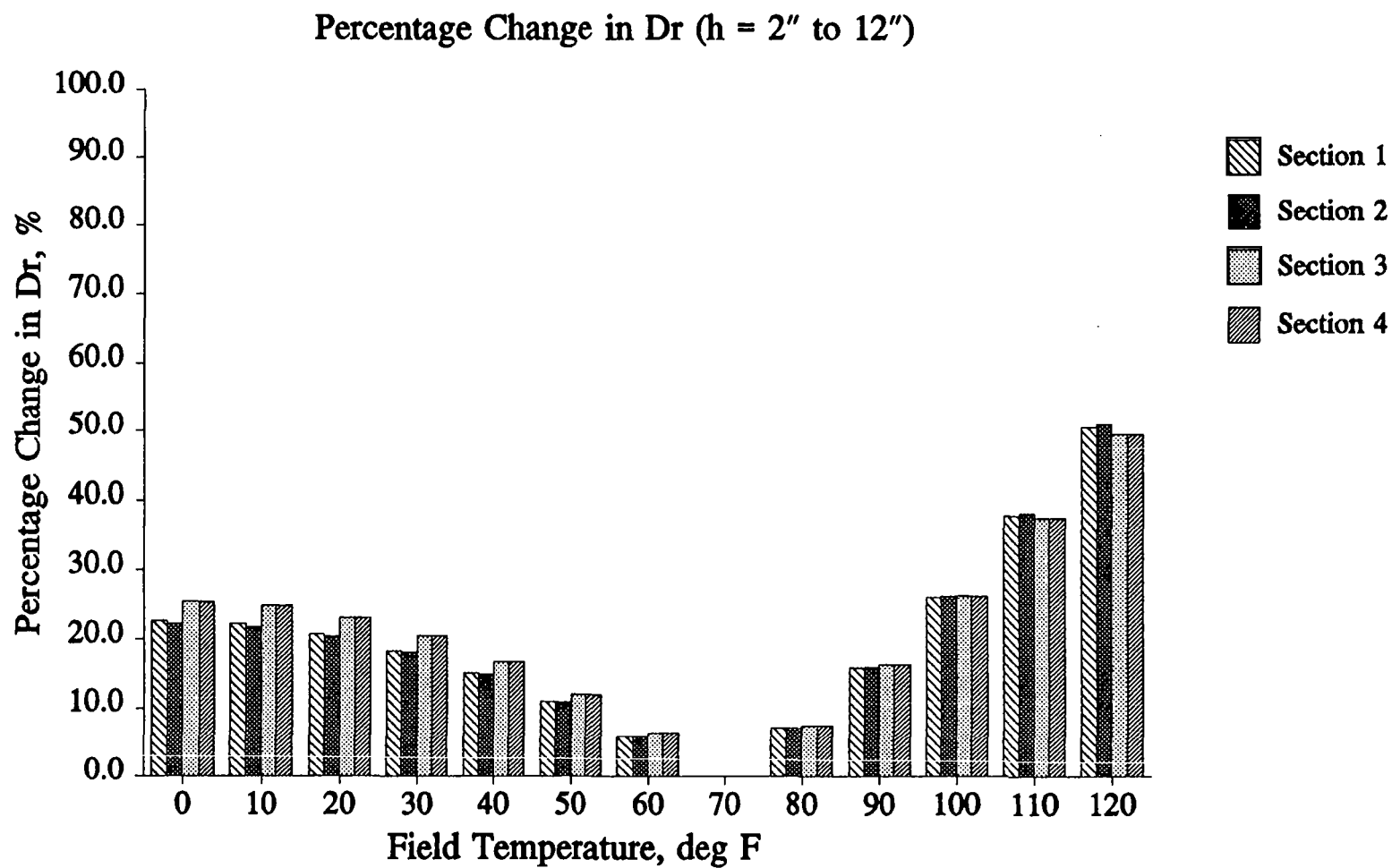
Figure 8 - Effect of AC Thickness on Temperature Correction

changes in Dr are accurate when due to changes in AC thickness and subgrade modulus. Alternatively, the parameters that are assumed in the procedure -- E_2 through E_{n-1} and μ_i through μ_n -- have little effect on the resulting temperature correction factor.

Typical temperature correction curves have been developed for flexible pavements with weak subgrade support, flexible pavements with strong subgrade support, composite pavements with weak subgrade support and composite pavements with strong subgrade support based on analysis results. These curves are shown in Figures 9 and 10. In them, a weak subgrade soil is defined as having an elastic modulus of 10 ksi or less, while a strong subgrade soil is defined as having a modulus greater than 20 ksi. Prior to implementation, however, it is recommended that temperature correction curves be developed for a wider range of anticipated subgrade modulus values.

SUMMARY

A temperature correction procedure has been developed and implemented in the FWDCHECK software to correct measured maximum surface deflections to a standard temperature. Documentation of the procedure is included in the text of this report. A summary of some of the features of the procedure are listed below:

- The procedure is based on a multi-layer analysis so that the properties of each layer within the pavement structure are considered.

- Only the change in the compression of the AC surface layer due to temperature changes is considered in the procedure.

- The multi-layer procedure considers the incompressibility of PCC layers much better than the original two-layer procedure.

- Values assumed in the procedure -- E_i and μ_i for base and subbase layers -- have very little to no effect on the resulting temperature correction factor.

- Predictions of the AC modulus as a function of temperature are based on the Asphalt Institute procedures (3).

- The procedure can be made more accurate if properties of the AC mix are known.

- The estimate of the subgrade modulus, which has an effect on Dr, is based on actual deflection measurements (outer geophone readings).

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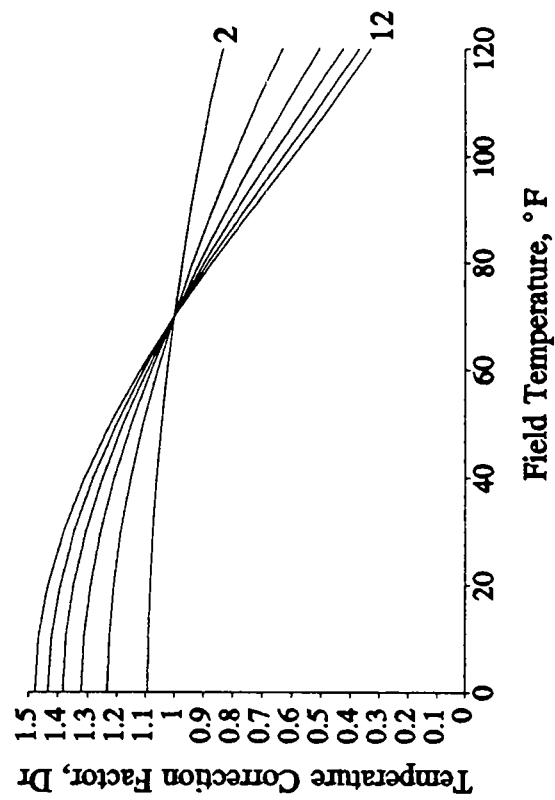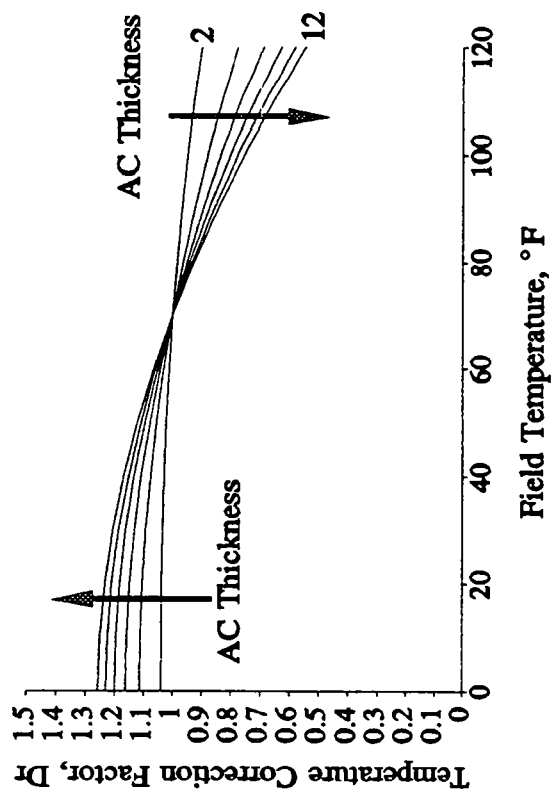
Figure 9 - Temperature Correction Factor Charts for Flexible Pavements
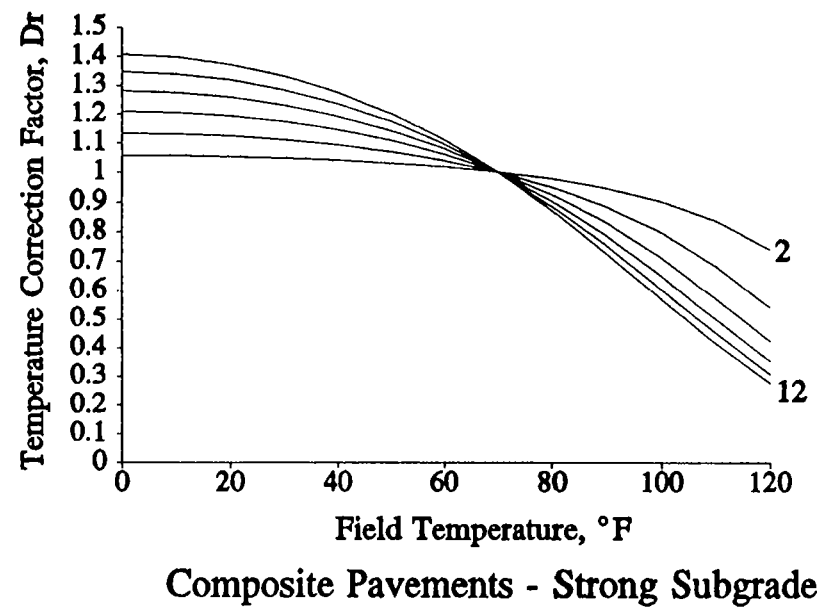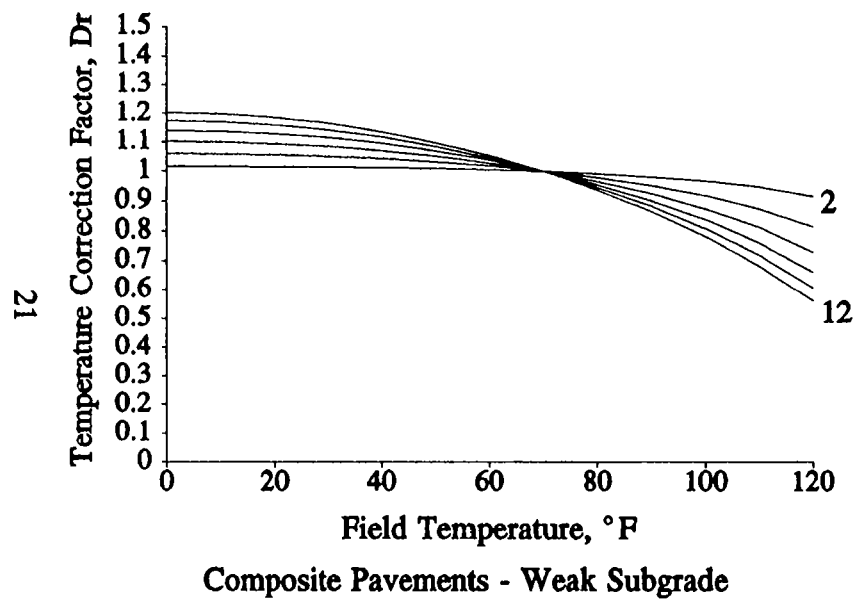
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Figure 10 - Temperature Correction Factor Charts for Composite Pavements

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