Temperature Predictions and Adjustment Factors for Asphalt Pavement

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Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
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LTPP

FOREWORD

Deflection testing is an important tool for pavement evaluation. Critical for the use of this tool is the need to be able to adjust the results of the testing for the effects of the temperature of asphalt. The Seasonal Monitoring Program of the Long Term Pavement Performance program has produced the largest single source of data regarding asphalt temperature and the corresponding deflection response. These data provided an opportunity to develop methods to predict the temperature within the asphalt and to adjust the deflection results for temperature effects.

The contents of this report will be of interest to pavement researchers and to engineers involved in routine deflection testing and analysis.

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Director, Office of Infrastructure
Research and Development

NOTICE

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16. Abstract

This report presents the results of an analysis of the response that deflections and backcalculated asphalt moduli have to the pavement temperature. The study used deflection and temperature data from 40 sites monitored in the Seasonal Monitoring Program of the Long Term Pavement Performance (LTPP) program.

The report presents improved methods of estimating the temperature within an asphalt pavement based on the measurement procedures used for the LTPP program. The data necessary to estimate the temperature within the asphalt included the surface temperature, time of day, depth below the surface, and the average air temperature from the previous day. Backcalculation of the asphalt modulus from the deflection data of the 40 sites was related to pavement temperature, and a method of estimating what the modulus of the asphalt would be at different temperatures is presented. Deflection and deflection basin shape factor response to temperature was also evaluated, resulting in relationships for each of the items evaluated with pavement temperature. Items evaluated include the deflection under the load plate (center sensor), center sensor minus offset sensors, center sensor divided by offset sensors, AREA factor, and the F-1 factor. The relationships were then used to develop procedures for adjusting for the effects of temperature.

17. Key Words
Long Term Pavement Performance, LTPP, Seasonal Monitoring Program, SMP, temperature, temperature adjustment, backcalculated modulus, thermistor, falling-weight deflectometer, FWD.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS/TERMS

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
AREA	deflection basin shape characteristic
BELLS	asphalt temperature prediction equation described in reference 7
BELLS2	modified asphalt temperature prediction equation presented in this report
defl0	deflection sensor at center of FWD load plate
defl8	deflection sensor 203 mm from center of FWD load plate
defl12	deflection sensor 305 mm from center ofFWD load plate
defl18	deflection sensor 457 mm from center ofFWD load plate
defl24	deflection sensor 610 mm from center of FWD load plate
defl36	deflection sensor 914 mm from center of FWD load plate
defl60	deflection sensor 1524 mm from center ofFWD load plate
delta8	d(0)-d(8)
delta12	d(0)-d(12)
delta18	d(0)-d(18)
delta24	d(0)-d(24)
delta36	d(0)-d(36)
delta60	d(0)-d(60)
D.IR	infrared temperature sensor output at factory default calibration settings
F-l	deflection basin shape characteristic
FHWA	Federal Highway Administration
FWD	falling-weight deflectometer
IR	infrared temperature
LTPP	Long Term Pavement Performance
ratio8	r(0)/r(8)
ratio12	r(0)/r(12)
ratio18	r(0)/r(18)
ratio24	r(0)/r(24)
ratio36	r(0)/r(36)
ratio60	r(0)/r(60)
SCR	Surface Condition Rating
SMP	Seasonal Monitoring Program

CHAPTER 1. INTRODUCTION

BACKGROUND

The use of surface deflection measurements on pavements has steadily increased in popularity with highway agencies since the American Association of State Highway Officials (AASHO) Road Test was conducted. Deflection testing is used to evaluate a variety of pavement characteristics, including axle or vehicle load capacity, structural life, and uniformity. Deflection results of all pavements are dependent on seasonal variations that affect the underlying aggregate and subgrade. The results from asphalt pavements are also dependent on the temperature of the asphalt. In order to meaningfully analyze the deflection results, the deflections, or deflection analysis results, must be adjusted to account for the seasonal and temperature effects. Over the years, a number of methods have been developed to measure the asphalt temperature and to adjust the deflection results for the effects of temperature.

Deflection equipment and analysis methodologies have continued to improve over the years, but the study of the effects of temperature on the deflections of asphalt pavements have generally been limited in scope or location. The Seasonal Monitoring Program (SMP)(1) of the Long Term Pavement Performance (LTPP) program(2) provides the most comprehensive temperature and deflection data set ever to be assembled. The LTPP program provides both the need and the opportunity to:

- Develop a means of determining the temperature of the asphalt pavement at depth from surface infrared temperature measurements.

- Develop methods or factors to adjust deflections, or deflection analysis results, for the effects of temperature.

PROJECT SCOPE

The project has two primary objectives that follow the opportunities described above:

- Develop a model that can be used to predict the temperature within an asphalt layer from surface temperature data collected during routine deflection testing.

- Develop relationships between asphalt temperature, pavement deflections, deflection basin shape factors, and backcalculated asphalt modulus. The models are to provide the basis for adjusting the moduli, deflection basin shape factors, and deflections for temperature.

REPORT ORGANIZATION

This report briefly describes the SMP data and the method used to process the data for analysis. The two objectives of the project are covered in separate chapters: Chapter 4 deals with estimating the temperature within an asphalt pavement layer and Chapter 5 deals with the relationship between backcalculated asphalt modulus values and temperature. Chapter 6 discusses the relationships that were developed between deflection basin shape factor responses and temperature. A process for adjusting for the effects of temperature is given for each of the temperature-sensitive responses evaluated.

CHAPTER 2. DATA SOURCE

The LTPP's SMP (SMP) provided the data necessary to accomplish the objectives. Specific program data used included temperature measurements from within the asphalt pavement, falling-weight deflectometer (FWD) deflection data(3), and layer type and thickness data. The initial analysis was with data from 25 LTPP flexible seasonal monitoring sections tested during Round 1 of the SMP, which ran from March 1994 to May of 1995. Upon completion of the analysis and a review of the results, it was decided to use the data from Round 2 of the SMP, which ran from July 1995 to October 1996, for a validation check. As described later, the Round 2 sections were significantly different than the Round 1 sections. The data from Rounds 1 and 2 were combined and subsequently divided into two sets, one for the development of the models and one for validation of the models.

Figure 1 shows the general location of each SMP site. Information regarding each of the SMP sections included in this study is contained in Tables 1 and 2. Table 1 contains a section location description and table 2 lists the section pavement composition.

As shown by the dots in Figure 1, the site locations represent a wide range of geographical and climatic locations, ranging from dry-no freeze to wet-freeze. The sites also provided a reasonably wide range of asphalt thicknesses, ranging from 46 mm to 305 mm.

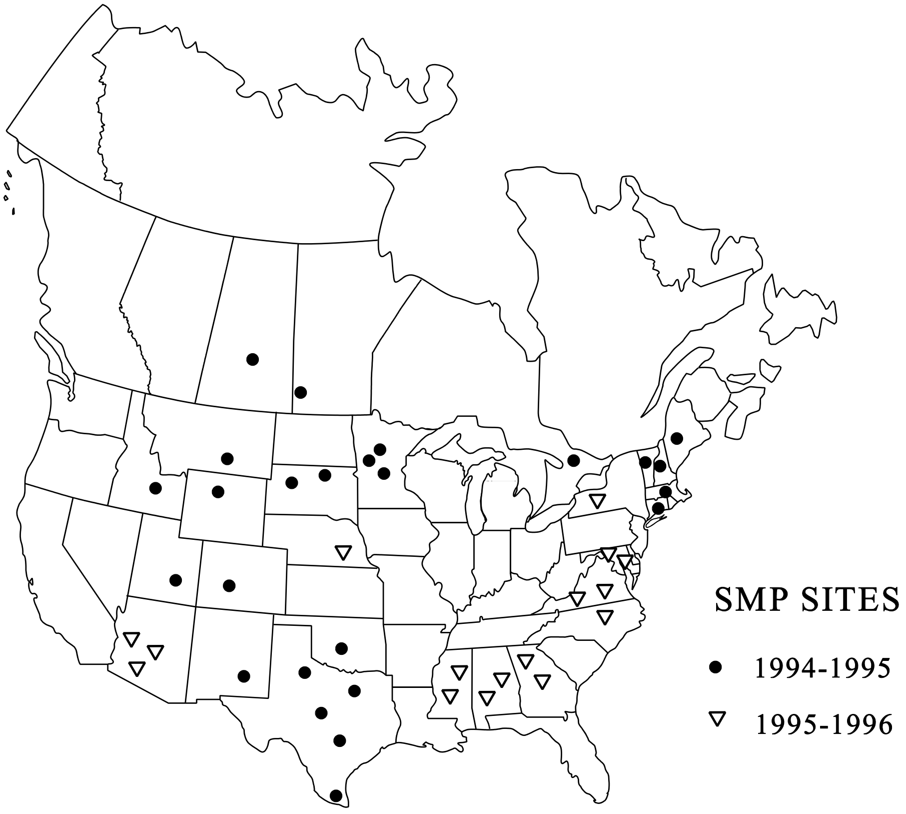

Figure 1. Location of seasonal monitoring sites.

Table 1. Seasonal monitoring study sections.

SMP ID	Round	Section ID	State or Province	Location
01SA	2	010101	Alabama	U.S. 280, 2.9 km W of CR 183
01SB	2	010102	Alabama	U.S. 280, 4.51 km W of CR 183
04SA	2	040113	Arizona	U.S. 93 NB, MP 52.62, Kingman
04SB	2	040114	Arizona	U.S. 93 NB, MP 58.61, Kingman
04SC	2	041024	Arizona	I-40 EB, MP 106.9, approx. 63 km W of U.S. 89
08SA	1	081053	Colorado	U.S. 50 NB, MP 75.3, near Delta
09SA	1	091803	Connecticut	SH 117 NB, MP 3.47, near New London
10SA	2	100102	Delaware	U.S. 113, 2.0 km S of SR 16
13SB	2	131031	Georgia	U.S. 19, 5.64 km N of GA 53
13SC	2	131005	Georgia	SH 247, 1.77 km E of Peach/Houston Co. Line
16SB	1	161010	Idaho	I-15 SB, MP 132 near Idaho Falls
23SA	1	231026	Maine	U.S. 2 WB, near Wilton
24SA	2	241634	Maryland	SH 90, 1.0 km E of US 50
25SA	1	251002	Massachusetts	I-391 WB, MP 1.95, near Springfield
27SA	1	271018	Minnesota	U.S. 10 EB, MP 140, W of Little Falls
27SB	1	271028	Minnesota	U.S. 10 EB, MP 58, E of Detroit Lakes
27SC	1	276251	Minnesota	U.S. 2 WB, MP 113 on Bemidji Bypass
28SA	2	281802	Mississippi	U.S. 84, 2.41 km W of Covington/Jones Co. Line
28SB	2	281016	Mississippi	SH 35, 2.25 km N of Natchez Trail
30SA	1	308129	Montana	U.S. 12 EB, MP 137, near Ryegate
31SA	2	310114	Nebraska	U.S. 81, 10.8 km S of Hebron
33SA	1	331001	New Hampshire	I-393 EB, Concord
35SA	1	351112	New Mexico	U.S. 62 EB, MP 81.3, W of Hobbs
36SB	2	360801	New York	Lake Ontario State Pkwy, Near Hamilton Beach Park
37SE	2	371028	North Carolina	SH 17, 2.6 km S of the Virginia State Line
40SA	1	404165	Oklahoma	U.S. 60 WB, MP 8.4, E of Junction SH 58
46SA	1	460804	South Dakota	SH 1804 EB, 14.5 km NW of Pollock
46SB	1	469187	South Dakota	SH 73 SB, MP 156, 29.0 km S of Faith
48SA	1	481077	Texas	U.S. 287 SB, near Estelline
48SB	1	481068	Texas	SH 19 NB, near Paris
48SE	1	481122	Texas	U.S. 181 NB, near Floresville
48SF	1	481060	Texas	U.S. 77 NB, near Victoria
48SG	1	483739	Texas	U.S. 77 NB, near Raymondville
49SB	1	491001	Utah	U.S. 191 SB, MP 23.74, near Bluff
50SA	1	501002	Vermont	U.S. - 7 NB, near New Haven
51SA	2	510113	Virginia	SR 265, 4.1 km S of SR 695
51SB	2	510114	Virginia	SR 265, 137 m S of SR 695
56SA	1	561007	Wyoming	U.S. 16 EB, MP 60.06, near Cody
83SA	1	831801	Manitoba	PTH 1 WB, 46 km W of Brandon
87SA	1	871622	Ontario	Hwy 11 NB, near Bracebridge
90SA	1	906405	Saskatchewan	PTH 16 EB, E of Plunkett

Table 2. Layer thickness information.

SMP ID	AC (mm)	Base		Sub-Base		Subgrade Type	Comments
		(mm)	Type	(mm)	Type		
01SA	178	203	Cr. Stone	----	----	CL	
01SB	102	305	Cr. Stone	----	----	CL	
04SA	114	191	Agg.	----	----	SW	
04SB	173	305	Agg.	----	----	SW	
04SC	274	160	Agg.	----	----	SW	
08SA	117	114	Cr. Gravel	597	Soil Agg.	CL	
09SA	189	305	Gravel	----	----	ML w/G	
10SA	114	336	Agg.	870	Silty Sand	SC	Section not used
13SB	305	254	Cr. Stone	----	----	MH	
13SC	178	253	Cr. Stone	----	----	SM	
16SB	277	137	Cr. Gravel	----	----	SM	
23SA	147*	447	Gravel	----	----	SM w/G	*L05 is 163 mm AC
24SA	211	246	F. Sand	1117	Sand & Silt	ML	
25SA	193*	102	Cr. Gravel	213	Soil Agg.	SP w/M	*L05 is 163 mm AC
27SA	112	132	Gravel	----	----	SP w/M	
27SB	244	----	----	----	----	SP w/M	
27SC	180	267	Gravel	----	----	SP w/M	
28SA	220	51	Silty Sand	----	----	SC	
28SB	195	525	Granular	----	----	SM	
30SA	76	579	Cr. Gravel	----	----	CL	
31SA	178	305	Agg.	----	----	CL	
33SA	212	490	Gravel	366	Cr. Slag	SP w/M	
35SA	160	152	Soil Agg.	----	----	SP	
36SB	132	238	Agg.	----	----	SC	
37SE	264	136	Silty Sand	----	----	SM	
40SA	64	137	HMAC	----	----	SM	
46SA	178	305	Gravel	----	----	ML	
46SB	140	152	Gravel	76	Gravel w/Silt	CH	
48SA	147*	264	Cr. Stone	----	----	ML	*L05 is 130 mm AC
48SB	254*	152	Cr. Stone	203	Lime-Tr. Soil	CL	*L05 is 276 mm AC
48SE	81	396	Soil Agg.	213	F. Gr.Soil	SP	
48SF	191	312	Cr. Stone	152	Lime-Tr. Soil	SM	
48SG	46	290	Soil Agg.	188	Lime-Tr. Soil	SP	
49SB	140	147	Soil Agg.	----	----	SM	
50SA	211	655	Cr. Gravel	----	----	GP w/M	
51SA	102	203	Agg.	152	Cmt. Tr. Soil	ML	
51SB	178	302	Agg.	150	Cmt. Tr. Soil	ML	
56SA	76	157	Cr. Gravel	----	----	SM	
83SA	114	152	Cr. Gravel	305	Gravel	SM	
87SA	135	168	Cr. Gravel	668	Sand	MH	
90SA	71	279	Cr. Gravel	----	----	SP w/M	

[1] Unified Soil Classification

CHAPTER 3. DATA DEVELOPMENT FOR ANALYSIS

The LTPP program's SMP is the source of all of the data used in this study. The SMP was designed to study the effect that seasonal variations have on pavement performance. Some of the environmental factors include temperature and seasonal effects on pavement deflection response to load. The SMP requires much more intensive monitoring than the rest of the LTPP program. The expectation is that the SMP will be used to establish relationships between pavement performance response measures, such as deflection and profile, and temperature and season, as appropriate. The purpose of the study is to:

- Establish methods of predicting asphalt temperatures from surface temperature measurements.
- Develop a method of adjusting deflection response of asphalt pavements and backcalculated asphalt moduli for the effects of temperature.

The seasonal effects are being evaluated in separate studies.

DATA COLLECTION

Two specific categories of SMP monitoring data from the sites were used;

- Temperature data for the asphalt pavement, both surface and internal, and air temperatures.
- FWD deflection data.

In addition, data describing the section layer type and thicknesses, plus latitude, longitude, and elevation data were obtained.

Temperature Data

Four separate forms of temperature data were obtained for this study:

- Air temperature from SMP instrumentation.
- Asphalt temperature from instrumentation.
- Asphalt temperatures manually recorded during FWD testing.
- Surface temperature recorded by the FWD device.

Air Temperature Instrumentation Data

Each of the SMP sites includes a miniature weather station. The station records air temperature and precipitation on an hourly basis. The air temperatures are recorded once per minute by an on-site data logger. The hourly average is stored in memory at the end of each hour.

Asphalt Temperature Instrumentation Data

The instrumentation includes temperature sensors in the asphalt, as well as in the underlying base and subgrade. The temperature sensors in the asphalt are contained in a 300-mm temperature probe. The probe contains a thermistor at each end and one at the center of the probe as shown in figure 2. The probes were installed in a slot cut in the asphalt; they were positioned so that the ends of the probe were 25 mm from the surface and bottom of the asphalt. The on-site data logger in the weather station reads the temperature from the thermistors once a minute. The readings are stored internally and at the end of every hour, the average temperature for each probe is stored in the data logger memory. This method of monitoring and recording the average hourly asphalt temperature results in a temperature that, for this study, was associated with the half-hour. This method of data recording became statistically important in the analysis as discussed later.

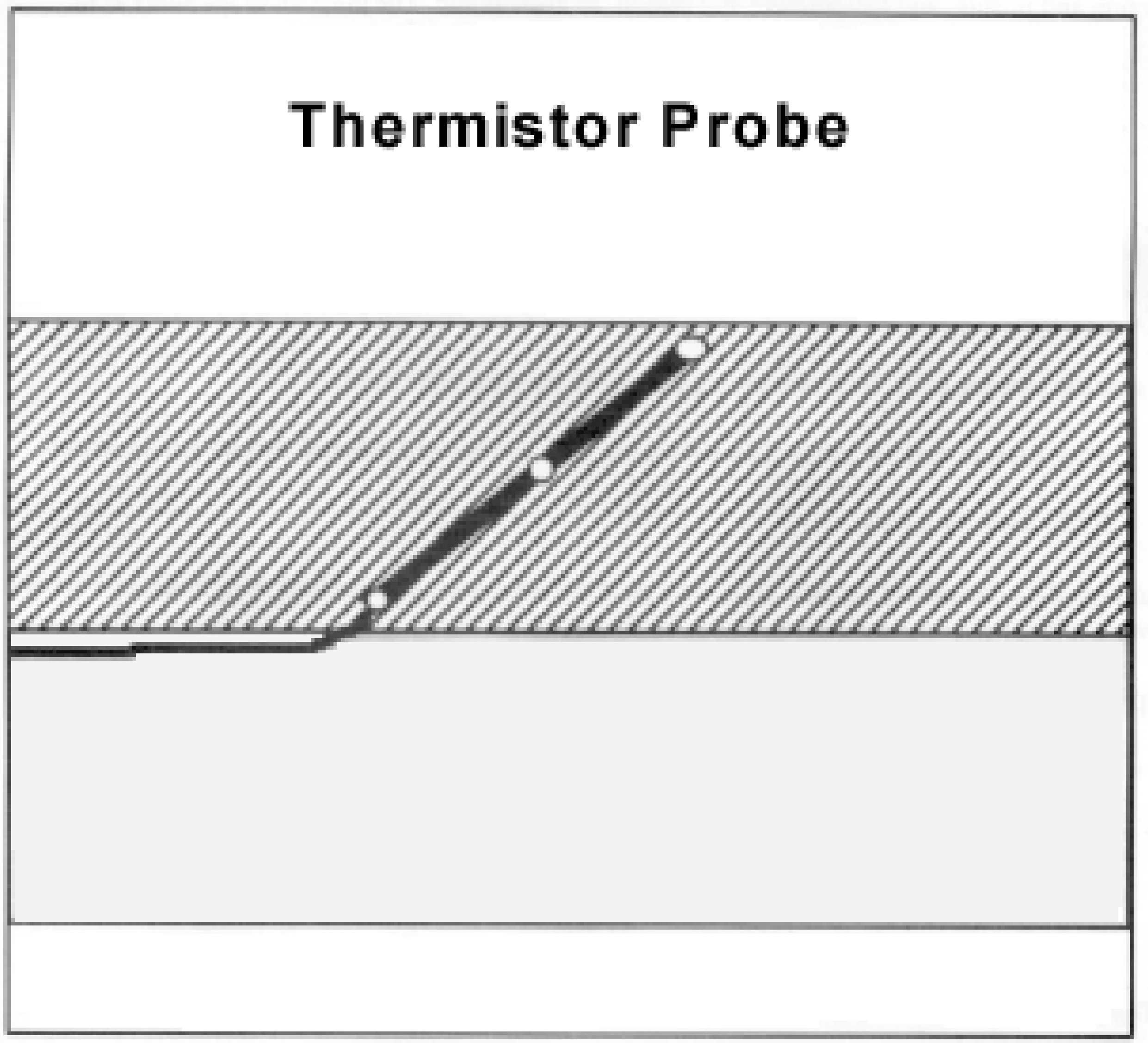

Figure 2. Thermistor probe in the asphalt.

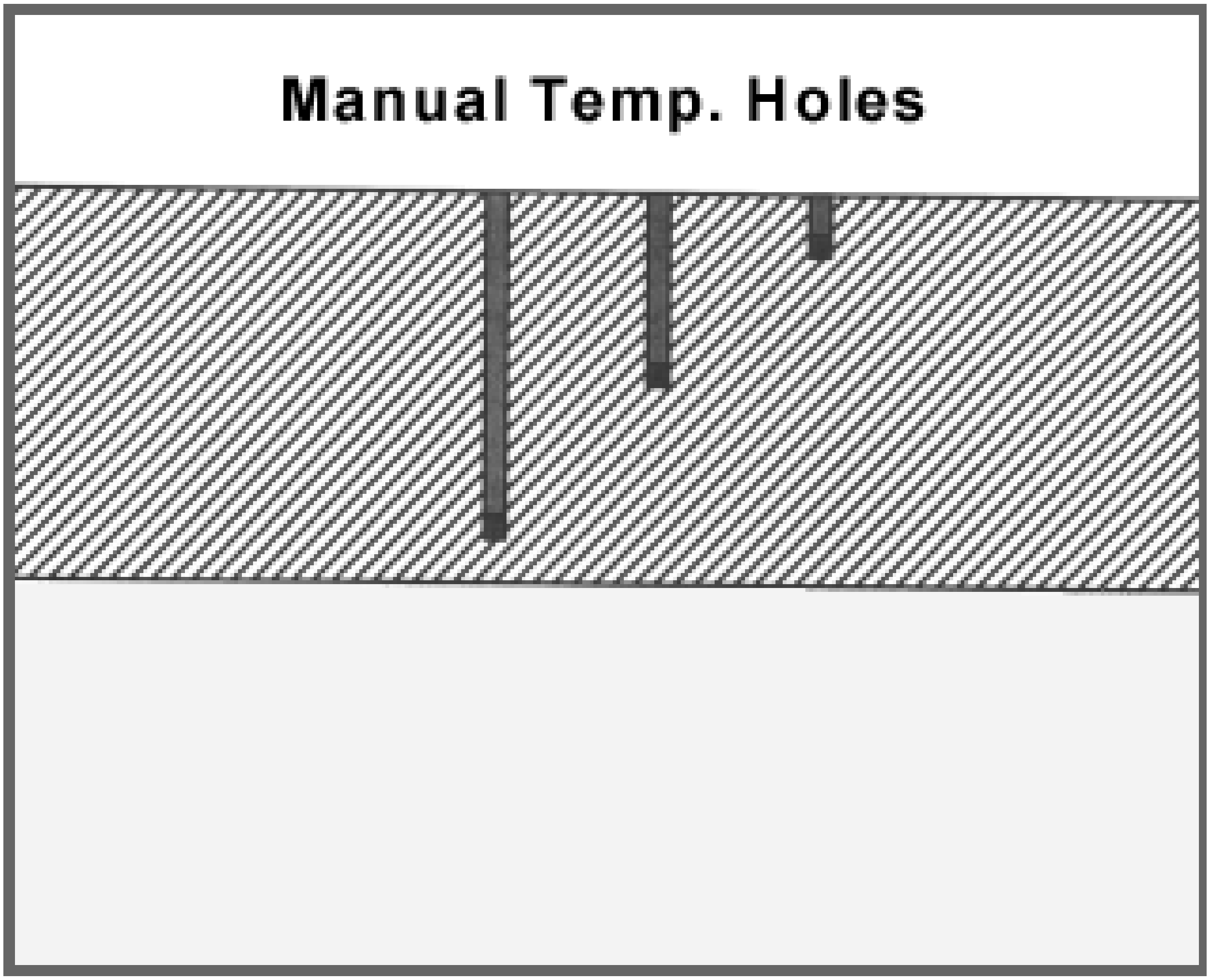

Figure 3. Manual temperature measurement holes.

Data collected in the North Central Region (NCR) for the LTPP program was collected initially to develop a process to assemble the data into a suitable format for analysis. A small filter program was developed to extract data from the environmental monitoring instrumentation files to develop flat files of the hourly temperatures of the three thermistors in the asphalt at each seasonal site.

Manually Recorded Temperatures

During deflection testing, the asphalt temperature was manually measured at approximate half-hour intervals at holes drilled to about 25 mm from the surface, mid-depth, and 25 mm from the bottom of the asphalt as shown in figure 3. A small amount of mineral oil or glycol (about 12-mm deep) is placed at the bottom of each hole for heat transfer. A tip-sensitive probe, attached to a hand-held device that displays the temperature to the nearest tenth degree Fahrenheit, is placed in the liquid at the bottom of the hole. The time, temperature, and depth is manually recorded for each set of manual readings. These data are referred to as the manual temperatures in this report.

The association of the manual temperature measurement with a specific time resulted in a better statistical relationship with the surface temperatures as described later in this report.

Surface Temperature

For each deflection test, an infrared sensor mounted on the FWD measured the surface temperature of the asphalt. The surface temperature readings were recorded in the deflection data file. It should be noted that the test locations are about 7.6 meters apart, but the FWD and tow vehicle is about 10 meters long. Thus, the tow vehicle shades two test locations at the same time — the location tested and next test location. The typical time test at each location is about 3 minutes. Since the temperature is recorded at the end of the test cycle, the pavement surface has been in shade for about 6 min. before the infrared temperature measurement is made.

Time of Temperature Measurements

The times for the surface temperature measurements and manual temperature measurements are specifically recorded at the time of measurement. The time of the instrumentation temperature is the time that the data are recorded into the data logger. Because the data logger measures the temperature every minute and records the average temperature for the hour, the temperature is not associated with any specific time. Since the temperature recorded represents the average temperatures for the previous hour, for this study, the instrumentation temperatures were assigned to be the temperature of the pavement at the half-hour.

Temperature Depth Data

The temperatures measured within the asphalt, by thermistors or manually, have a specific depth associated with each measurement. The depth data is used in an interpolation process to estimate the temperature at the mid-depth and third-depth locations.

Thermistor Depths

The depth of each thermistor below the surface of the asphalt was recorded at the time of installation. These depths are considered to remain constant over the course of this study. If a pavement was overlaid during the study, the depths need to be adjusted.

Temperature Hole Depths

The temperature hole depths were measured at each monitoring cycle. The hole depths were not constant over the duration; they occasionally changed if the holes were cleaned or were redrilled. Details regarding the temperature measurement process are in the FWD operators field manual(3).

DATA PROCESSING FOR ANALYSIS

The data processing for analysis included a number of specific steps to associate an asphalt temperature within the pavement with the surface temperature measured by the FWD. Since the surface temperature measurements did not occur at the same time as the in-depth measurements, interpolation methods were used to estimate the manual and thermistor temperatures at the times of the surface temperature measurements. Also, since the depths associated with the temperatures measured within the pavements varied, interpolation methods were used to estimate the temperatures at the third- and the half-depth positions.

Thermistor Data

The thermistor data was obtained in its raw field file format from the on-site data logger files. One file was generated each time the section was visited for monitoring which was approximately once per month. These files contain a variety of records, of which only specific record containing the time, the air temperature, precipitation, and thermistor temperature data for the top five thermistors were of interest. A QuickBASIC[1] program was written that would extract the data from the field (onsite) files and write the instrumentation data of interest into one comma-delimited flat file for each section. The times in the field files that covered the beginning and ending of daylight savings time were adjusted based on information provided by each region. Each region handled daylight savings time in a different way, so even with the time-change adjustment, there may be a few data records that have incorrect times. This is important since the surface temperature data were only obtained during the warming time of the day and an hour difference may result in temperature change of several degrees.

Manual Temperatures

Manual temperatures for the SMP sections were extracted by each of the regions from the Regional Information Management System (RIMS) and furnished in an ASCII flat file format. The flat file contained the date, time, depth, and temperature of each manual temperature measurement. No additional intermediate processing of the manual temperature data was necessary.

Surface Temperatures

The surface temperatures measured during FWD testing was the primary independent variable used in the asphalt temperatures analysis predictions. These temperatures were extracted from the FWD files and placed into a single flat file for each site that included the section identification, date, time, station, lane, surface temperature (called the infrared (IR) temperature), and normalized 40.5 kN (9,000-lbf) deflections.

Creating the Data Analysis Files

A QuickBASIC program was written that would first read the IR data file to get the date and time of the IR temperature. The program would than search the thermistor data file for the daily high and low air temperature for each of the 5 days preceding the day of testing, the previous night's low temperature, and all of the thermistor data for the day of testing. The thermistor data for each sensor was then fitted to a cubic spline routine(4) to interpolate the thermistor temperatures to the time of the IR temperature readings. Once the thermistor temperatures were interpolated for time, a second interpolation was used to interpolate the thermistor temperatures to third-depth and mid-depth temperatures using a second-order polynomial.(5) The resulting time- and depth-interpolated thermistor data was written to a flat file. Interpolated manual data were written to the same file; however, the manual data was treated differently. The manual data were first interpolated for the third-depth and mid-depth using the polynomial interpolation; the cubic spline procedure was then used to interpolate third-depth and mid-depth temperatures for each FWD test time. The reason for proceeding with depth first and time second was that the depth of measurement sometimes changed during the day if the hole was re-drilled or cleaned. If

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[1] QuickBASIC is a trade mark of Microsoft.

the time of the FWD test occurred before or after the time the manual temperatures were measured, no extrapolation was made and a missing data filler was written to the file instead. Therefore, the resulting flat file consisted of:

- Site ID.
- Date and time.
- IR and air temperatures measured by the FWD.
- Last night's low air temperature.
- Daily high and low temperatures for each of the preceding 5 days.
- Time-interpolated individual thermistor data.
- Corresponding thermistor depths.
- Time- and depth-interpolated thermistor temperatures for third and mid-depth.
- Depth- and time-interpolated manual temperatures.
- Sky cover recorded during the manual temperature measurement that was the closest, timewise, to the IR test time.

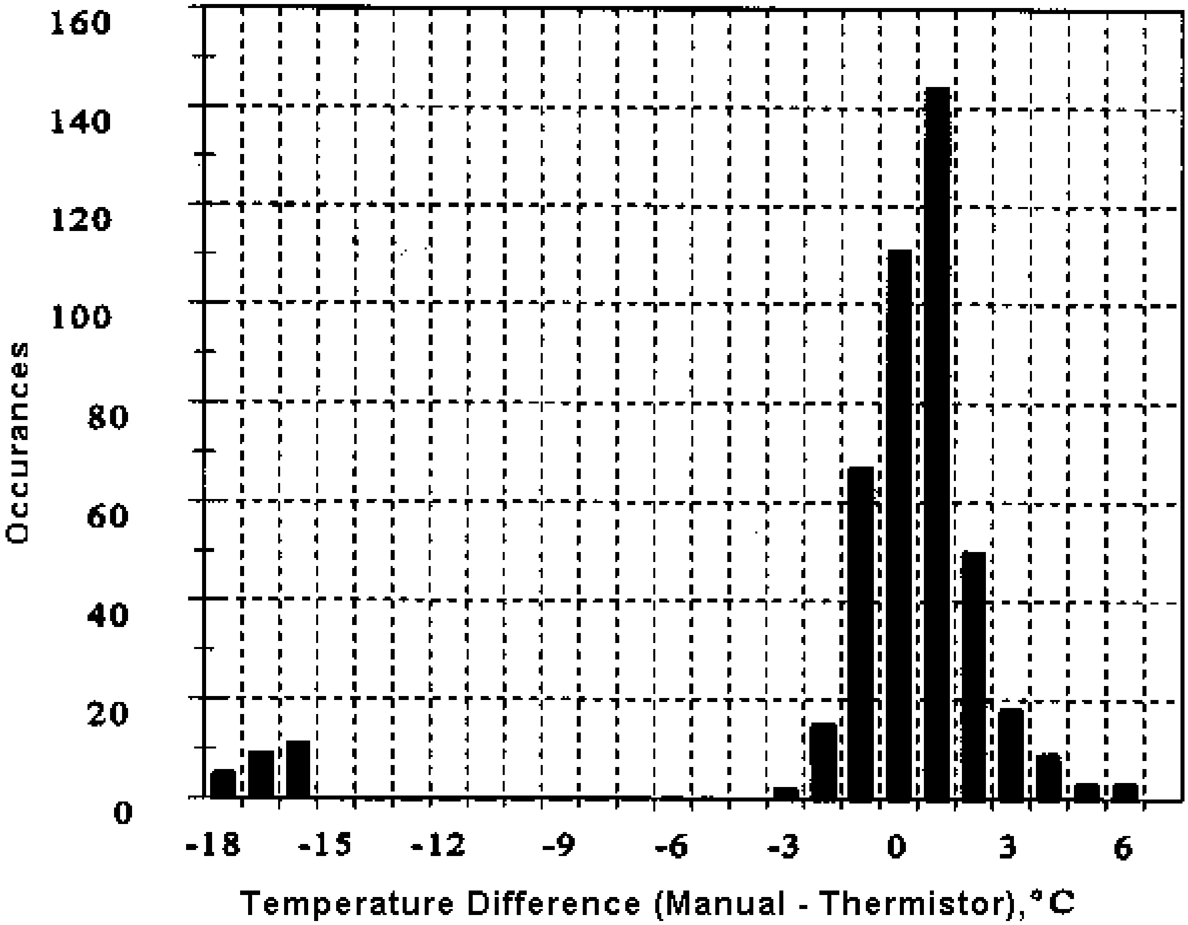

Figure 4. Comparison of mid-depth temperatures for Site 25A.

Comparison of Resulting Temperatures

The above filtering and interpolations required numerous calculations. Since the thermistor and manual interpolations underwent separate calculation processes, a comparison of the third-depth and mid-depth thermistor and manual temperatures were made. In addition, the third-depth manual temperatures were compared with the IR temperatures as an independent check.

Manual Versus Thermistor Comparisons

The thermistor and manual comparisons identified three forms of discrepancies — those caused by programming and processing errors, those caused by errors made when the manual data was recorded in the field or entered into RIMS, and discrepancies that could not be explained with the information available. Fortunately, after the programming errors were corrected, the remaining discrepancies made up only a small amount of the overall data set. The final data set used to develop the models for predicting temperatures within the asphalt had good agreement between the thermistor and manual mid-depth temperatures. A linear regression correlation between the manual and thermistor values had a standard error of estimate of 1.27°C, an intercept of 0.37°C, and a slope of 0.977.

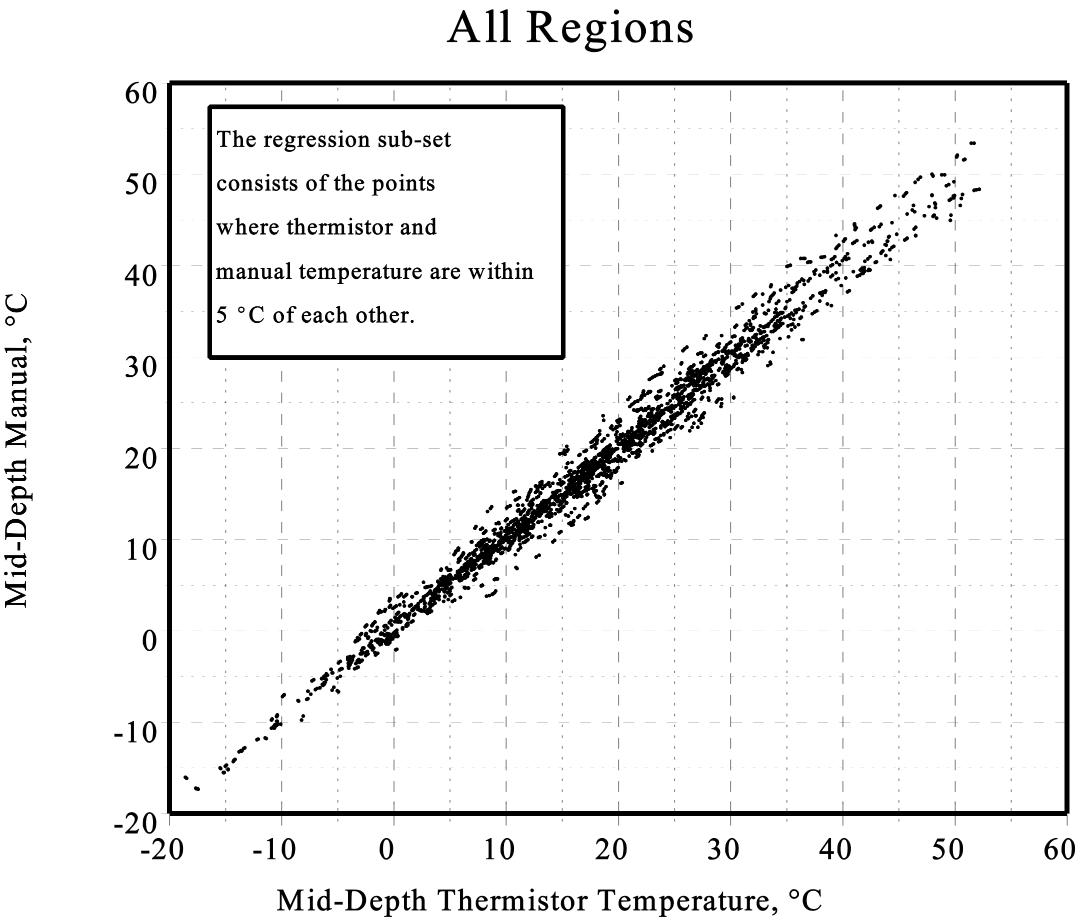

Figure 5. Comparison of the thermistor temperature and manual temperature data.

During the development of the final data set used for developing the prediction models with the Round 1 data, only IR data from within 10 m of the instrumentation were used, and only the records where the absolute value of the difference between the mid-depth thermistor and manual temperatures was less than 5° C. The 5° C value was selected as a reasonable value to use based on the distribution of differences to cull out problem data records. Figure 4, developed from site 25SA, show the frequency distribution of the difference between the manual and thermistor temperatures at mid-depth. The plot shows a bi-modal shape with a grouping at about -15 to -18° C, which was considered to be data errors or misreadings. Without checking all 25 sections, the value of 5 was selected as a query screening criteria for all of the temperature data.

Stability of the Manual Temperatures

Figure 5 shows the comparison of the mid-depth manual temperatures and thermistor temperatures representing a data set with the manual and thermistor mid-points are within 5° C of each other as described above. The 5° C criteria only eliminated about 5 percent of the data. From a regression standpoint, the biggest impact of removing the records with more than 5° C difference between the manual and thermistor temperatures was the improvement of the correlation coefficient and standard error of estimate; the constant and x coefficients remain about the same, implying that the data errors did not contain a significant bias.

Figure 5 also shows that the temperatures agree quite well at the lower temperatures and spread out as the temperature increases. This is more evident when evaluating the plots of manual and thermistor data at a site on a specific day. The thermistors seem to stay more consistent. The thermistor data is actually an average of the last 60 readings taken at 1-min. intervals, so any of the short-term fluctuations are averaged out of the thermistor data. The averaging process filters the short-term temperature variations out of the data before it is recorded.

The regression results for the mid-depth manual and thermistor temperatures are shown below in figure 6. This shows encouraging results with an intercept (constant) that is less than 1 and a slope that is less than 2 percent off of unity. The regression line crosses the line of equality at about 29 °C.

M.mid=Const.+Slope*T.mid	
Regression Output:	
Constant	0.37
Std. Error of Y Estimate	1.27
R-Squared	0.989
No. Of Observations	3658
Degrees of Freedom	3656
X Coefficient(s)	0.977

Figure 6. Regression coefficients for manual and thermistor data.

Surface Versus Manual Third-Depth Comparisons

The comparison of the IR data to the third-depth temperatures revealed a problem of a different nature. It was discovered that there were distinct differences in IR measurements, depending on the FWD used. This problem was traced to the IR calibration process. As a final result, only data from the Raytec brand of sensor, adjusted to restore the IR readings to the default manufacturer calibration factors, were used to develop the temperature prediction models.

Infrared Sensor Calibrations

The initial attempt at developing a pavement temperature prediction model was with all of the data from the Round 1 sites. During this process, it was discovered that there were characteristic differences between FWD units. To evaluate the extent of this difference, a simple regression of the IR temperatures to manually measured temperatures, interpolated to the third-depth, was made for each individual unit. The results of the regressions are shown in table 3. (Unit 060W is Unit 060 with a Williams sensor, and 060R is with a Raytec sensor.) All the units show reasonably good correlation coefficients, but there was significant differences in the slopes and constants.

There could be a variety of reasons for the differences if the comparisons were made on a site-by-site basis. Factors such as the surface color of the pavement and depth to the third-depth would be expected to result in different slopes and constants. However, these results are from a number of sites so it is unlikely that the differences in the constants and slopes were site dependent.

Table 3. Regression comparison of infrared sensors.

Simple Linear Regression: M.third = Const. + Slope * IR						
Region	**FWD SN**	**Const.**	**Slope**	**Std. Err.**	**R^2**	**No.**
North Atlantic	058 (a)	2.43	0.6307	2.93	0.861	191
	129 (b)	1.01	0.8474	2.31	0.938	874
N.Central	060W (c)	4.24	0.8141	4.14	0.929	43
	060R (d)	3.95	0.7579	3.17	0.934	886
South	059 (e)	-1.65	0.9301	2.60	0.952	258
	132 (f)	1.52	1.1350	2.20	0.974	293
West	061 (g)	0.90	0.7925	2.14	0.870	192
	131 (h)	1.23	1.0932	2.79	0.964	318
Average		1.70	0.8751	2.79	0.928	
Standard Dev.		1.88	0.1703	0.66	0.041	

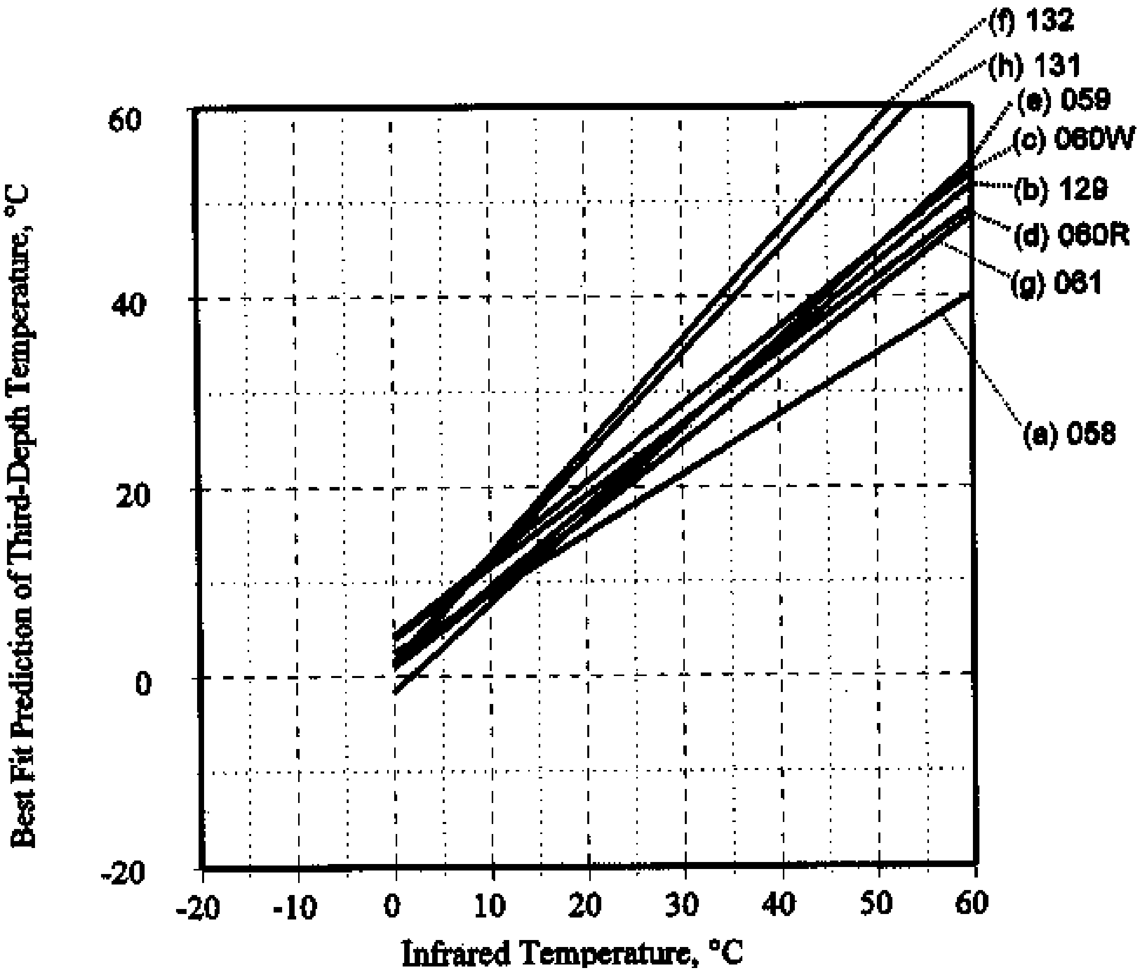

Figure 7. Infrared sensor performance by FWD serial number.

Figure 7 shows of each of the regression lines keyed to the letters in the left column of table 3. The graph shows that five of the units are grouped reasonably close together, and at high temperatures, Units 131 (h) and 132 (f) are reading high and Unit 58 (a) is reading low. Of the units that are grouped together, Unit 59 (e) has a higher slope. It is apparent that a combination of data from all of the infrared sensors may not be a good predictor of the internal temperatures of the pavement. If the data used in the analysis was to be restricted to the four units with similar coefficients — Units 058, 060R, 060W, and 061 — the result would be a much smaller data set, but still representing a wide geographical area, but not all of the units.

Figure 8 is a more detailed plot the differences between the two units in the Southern Region. The data points show that the relationship between the IR temperature measurements and the manually measured temperatures, interpolated to the third-depth, have similar scatter, but significantly different slopes and intercepts. This shows that the sensors are equally stable, but indicates that they may not have been calibrated to the same temperatures. (Calibration of the IR sensors was done by calibrating the sensor output to the temperature of an ice bath and to a container of hot water.)

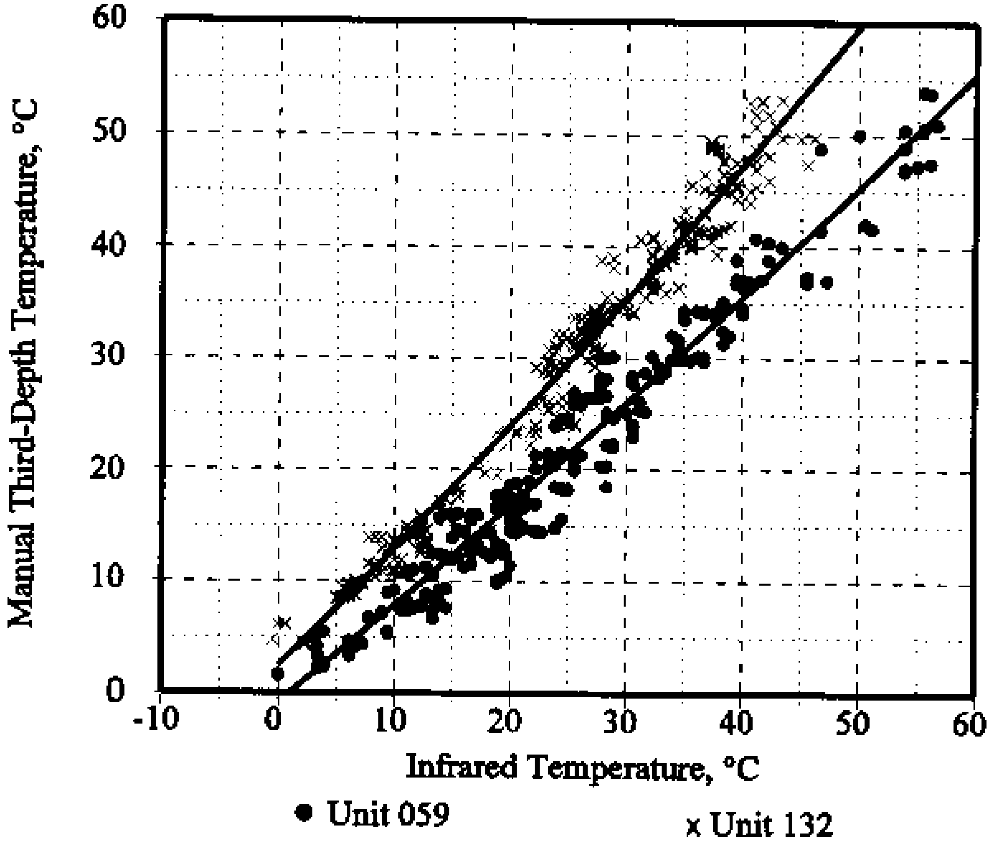

Figure 8. Comparison of two infrared sensors used on the same sites.

Investigating the possibility of a calibration problem, Dynatest noticed that the header files of several of the FWDs they had worked on still had default IR sensor calibrations factors. Looking into the calibration factors revealed that some of the units had the calibration numbers changed from time to time and some had the default calibration values. Units 059 and 132, however, had both been calibrated. Because of the inconsistencies with calibration, the calibration factors in the header of each FWD file was recorded and used to adjust the IR readings back to what they would have been for default calibration values. The default IR data (D.IR) was again regressed against the third-depth manual temperatures.

Removal of the calibration factors improved the fit considerably. However, the results of the regression analysis of IR temperatures versus third-depth temperatures are not as good as we expected they could be, even after removing the effects of the field calibrations. Since the calibration factors were removed, there was an expectation that the default IR temperatures contain an undetermined amount of bias from one device to the other. To check for possible evidence of bias, the default IR temperatures from each FWD unit was correlated to the interpolated manual third-depth temperatures and the results were compared as shown in table 4.

Table 4. Comparison of infrared sensor default output.

Comparison of IR sensors by correlating the default IR to the interpolated manual temperature at third-depth.							
FWD by IR Sensor	**Regression Coefficients $T_{1/3}$ = Constant + x Coef. * IR**						
	Constant	**Std. Error of Y Estimate**	**R-Squared**	**No. of Observations**	**Degrees of Freedom**	**x Coefficient**	**Std. Error of Coefficient**
058	-0.41458	1.77483	0.94942	189	187	0.76953	0.01299
059	-0.69662	2.87543	0.93959	343	341	0.90952	0.01249
060W	6.93162	2.24609	0.96227	621	619	0.77404	0.00616
060R	1.75579	2.09092	0.95475	499	497	0.88203	0.00861
061	3.75686	3.77776	0.82738	407	405	0.67594	0.01534
129	2.07866	2.58846	0.93056	893	891	0.82774	0.00757
131	1.91422	2.72482	0.96992	390	388	0.88756	0.00794
132	2.53508	2.03758	0.97845	373	371	0.89156	0.00687
ALL UNITS	3.29893	3.38347	0.93098	3734	3732	0.81298	0.00362

Table 4 shows the differences that still existed in the data set for developing temperature prediction models. The serial number of the FWD identifies the specific IR sensor manufacturer. All of the older units have Williamson sensors except unit 060R which has a Raytec sensor. Of the sensors used in the above units, the default IR results of three units do not conform with the group: Unit 058 and Unit 061 both tend to read higher pavement surface temperatures at the upper range as indicated by the low x coefficient; unit 060W reads lower pavement surface temperatures as indicated by the high constant as shown in figure 9.

Unfortunately, Unit 060W is the sensor the BELLS(6) equation was based on as reported at the fourth International Conference on the Bearing Capacity of Roads and Airfields. Therefore, the BELLS equation overpredicts the asphalt temperatures in the low temperature range and underpredicts in the high temperature range. It is also apparent that the results from Unit 060W was suspect based on the work done by Dr. Richard Kim at North Carolina State University(7).

Further evaluations found the Raytec factory calibrations to be reasonably good, leading to the process of doing periodic field checks with an independent sensor to confirm the sensor was working properly. On that basis, the development of a temperature prediction model was based on the IR readings from the Raytec sensors, adjusted to the factory calibration settings.

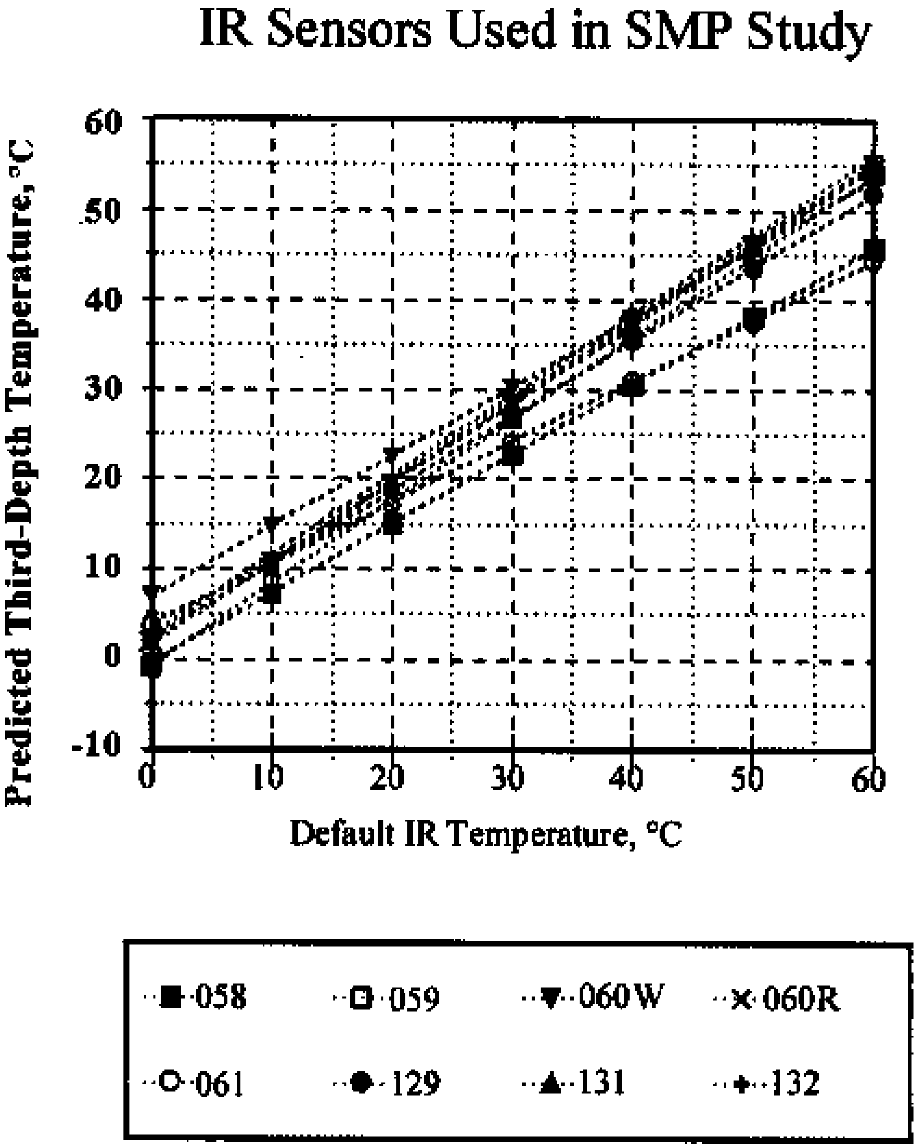

Figure 9. Machine difference in the default infrared temperature output.

CHAPTER 4. TEMPERATURE PREDICTION MODELS

There are two objectives for the development of methods to predict temperature within an asphalt pavement.

- Develop new coefficients for the BELLS temperature prediction model. The equation was developed to predict temperature within asphalt pavements at the third-depth. Independent variables used in the equation include surface temperature, time of test, the previous 5-day average air temperature, and the depth to the third-point.

- Determine if improvements could be made in the BELLS model and whether previous 5-day average air temperature, which is difficult to obtain, could be replaced by a more easily obtained air temperature.

PREDICTION MODELS

BELLS Model

A regression analysis was run to develop a new set of BELLS model coefficients using the Round 1 Raytec data. Remarkably, the R-squared and standard error of estimate were very close to that of the original BELLS model, particularly when considering that the data now represented 25 sites rather than 9, and that the temperature at both the mid-depth and third-depth are included in the same data set. The R-squared using 0.975 and the standard error of estimate is 1.91°C, which is close to the original model R-squared of 0.97 and standard error of estimate of 1.8°C. However, the new coefficients were very different. A malfunctioning IR sensor was used to collect much of the data used to develop the original BELLS model, as discussed above, and was thought to be the reason for the difference in the coefficients.

The new coefficients for the BELLS equation are:

$$T_d = 2.8 + 0.894 * IR + \{\log(d) - 1.5\}\{-0.540 * IR + 0.770 * (5\text{-day}) + 3.763 * \sin(hr - 18\} + \{\sin(hr - 14)\}\{0.474 + 0.031 * IR\} \qquad \textbf{(1)}$$

where:

T_d = Pavement temperature at depth d, °C
IR = Infrared surface temperature, °C
log = Base 10 logarithm
d = Depth at which mat temperature is to be predicted, mm
5-day = Previous mean 5-day air temperature, °C
sin = Sine function on a 24-hr clock system, with 2π radians equal to one 24-hour cycle
hr = Time of day in 24-hr system

Note: To use the time-hour function correctly, divide the number of hours (after subtracting the appropriate shift of 14 or 18) by 24, multiply by 2π, and apply the sine function in radians.

A reason for such a large change in the coefficients is the IR sensors used to measure this data are more accurate over the range of data collected, and the model, therefore, is less dependent on the 5-day air temperature.

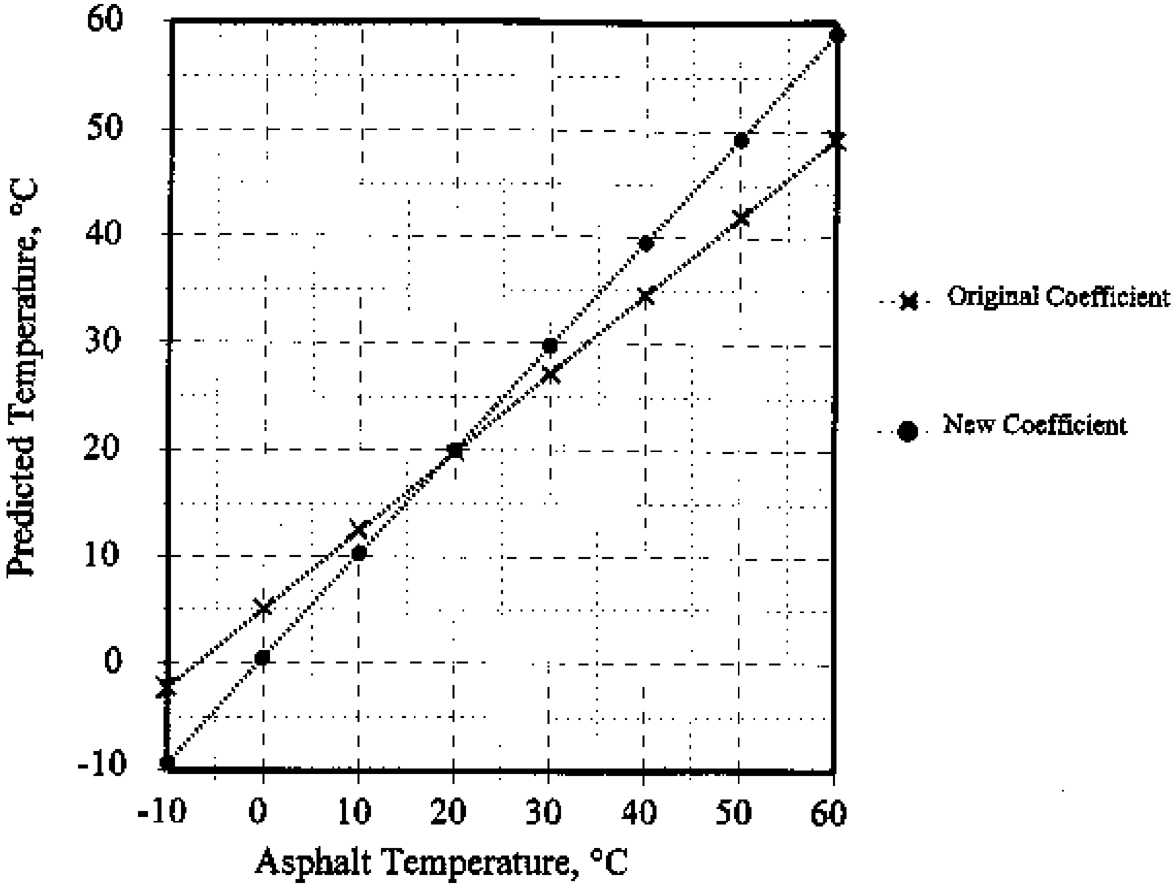

Figure 10. Comparison of the BELLS model original and new coefficients.

Figure 10 shows the prediction trend of the original BELLS coefficients compared to the updated coefficients. It shows that the original coefficients resulted in an overprediction of temperature when it was cold, the same at about 20 °C, and under prediction of temperatures when it was hot.

Development of BELLS2

The 5-day air temperature has proven to be difficult to obtain for routine testing; the previous day's air temperature is more easily obtained by the FWD operator. Sources, such as local radio or newspapers, can provide a recent temperature history. For LTPP data analysis, the 5-day air temperature can be obtained from the climatic database that is associated with LTPP; however, agencies performing routine testing have no easy source for such information.