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16. Abstract
SUPERPAVE binders are selected based on the lowest and highest pavement temperatures expected at a job. The original SUPERPAVE specifications were developed with limited data for validating the low-temperature algorithm for pavement temperatures. The lowest air temperature was assumed for the lowest pavement temperature. In areas with extremely low temperatures, this conservative approach has led to the selection of more restrictive binder grades than may be necessary. These binder grades usually require that modifiers be added to the asphalt, which increases the cost of the project.

The initial round (Loop-1) of the Long Term Pavement Performance study's Seasonal Monitoring Program (LTPP-SMP) - the collection of pavement and air temperatures at 30 test sites throughout North America - was completed in 1995. The availability of these data makes it possible to evaluate and refine existing pavement temperature algorithms.

Two new temperature data bases that combine the SMP data with weather station data from the original SUPERPAVE binder specifications were developed under this study. These data bases are used as tools throughout the study to further refine the existing low- and high-temperature models.

This report proposes revisions to the Strategic Highway Research Program (SHRP) Performance Grading System for asphalt binder selection. Revised models for determining the low- and high-temperature component of SUPERPAVE performance-based binders are presented and compared with existing models and resulting performance grades.

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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		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
NOTE: Volumes greater than 1000 l shall be shown in m³.				
		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/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	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		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		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/m²	candela/m²	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/in²

* 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)

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1. OBJECTIVE

The objective of this study is to: (1) develop a data base of pavement temperatures using the Long Term Pavement Performance study's Seasonal Monitoring Program (LTPP-SMP) data; and (2) develop low and high pavement temperature models for the purpose of improving the Strategic Highway Research Program's (SHRP) asphalt binder selection procedure used in SUPERPAVE.

2. INTRODUCTION

The SUPERPAVE binder selection procedure is based on the lowest and highest temperatures expected at a job. Two models are used to estimate low and high pavement temperatures from air temperature. The estimated pavement temperatures are then used to determine the low- and high-temperature asphalt performance grades for any location within the United States and Canada.

The SHRP binder selection procedure calculates the high pavement temperature from the highest 7-day average air temperature during the year. A theoretical model is used to estimate the high pavement temperature from the high air temperature and geographical location. This model was developed based on the results of heat-transfer modeling and regression analysis.

The SHRP binder selection procedure calculates the low pavement temperature from the lowest air temperature during the year. It assumes that the design low pavement temperature is equal to the lowest air temperature. Canadian SHRP (C-SHRP), on the other hand, uses a model to estimate the low pavement temperature at a depth below the surface of the asphalt concrete (AC) layer from the low air temperature.[2]

The initial round (Loop-1) of LTPP-SMP – collection of pavement and air temperatures at 30 test sites throughout North America – was completed in 1995. These data are now available and are used throughout this study to evaluate existing pavement temperature models and to develop improved models for SUPERPAVE binder selection. Figure 1 shows the location of LTPP-SMP sites that are part of the General Pavement Studies (GPS) experiment.

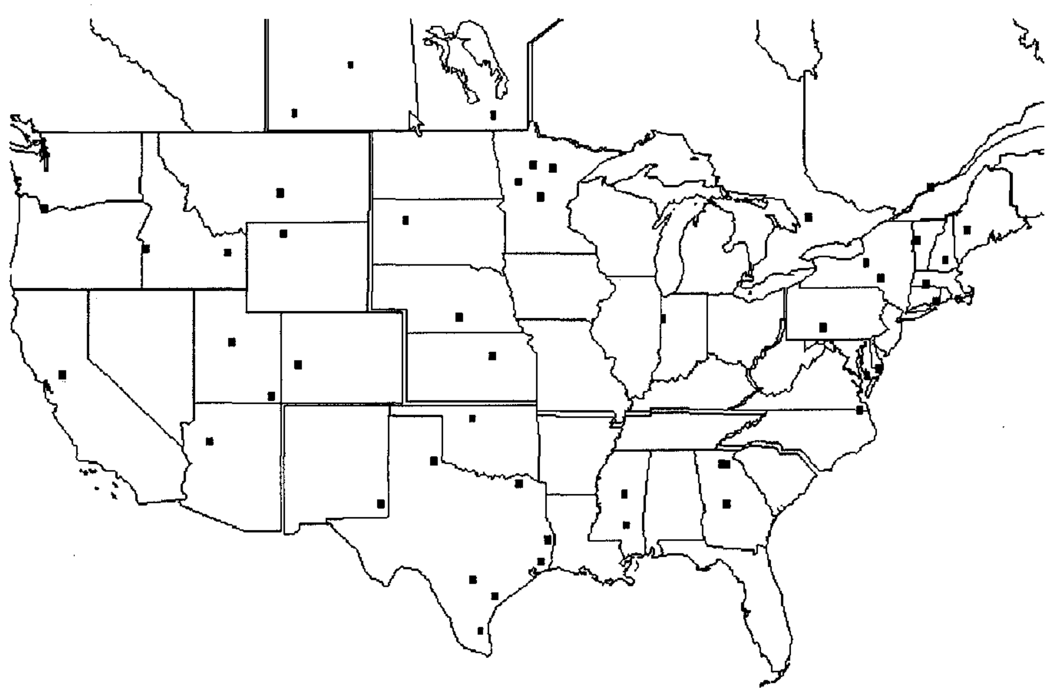

Figure 1 - Location of LTPP-SMP Sites (GPS Only) Within the United States and Canada.

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SMP low and high air and pavement temperature data were compiled and summarized into two data bases that include daily low- and high-temperature data for different pavement depths. These data bases were used to develop the LTPP Seasonal AC Pavement Temperature Models. Figure 2 shows daily low air and pavement temperatures for cold months for an SMP section in Minnesota.

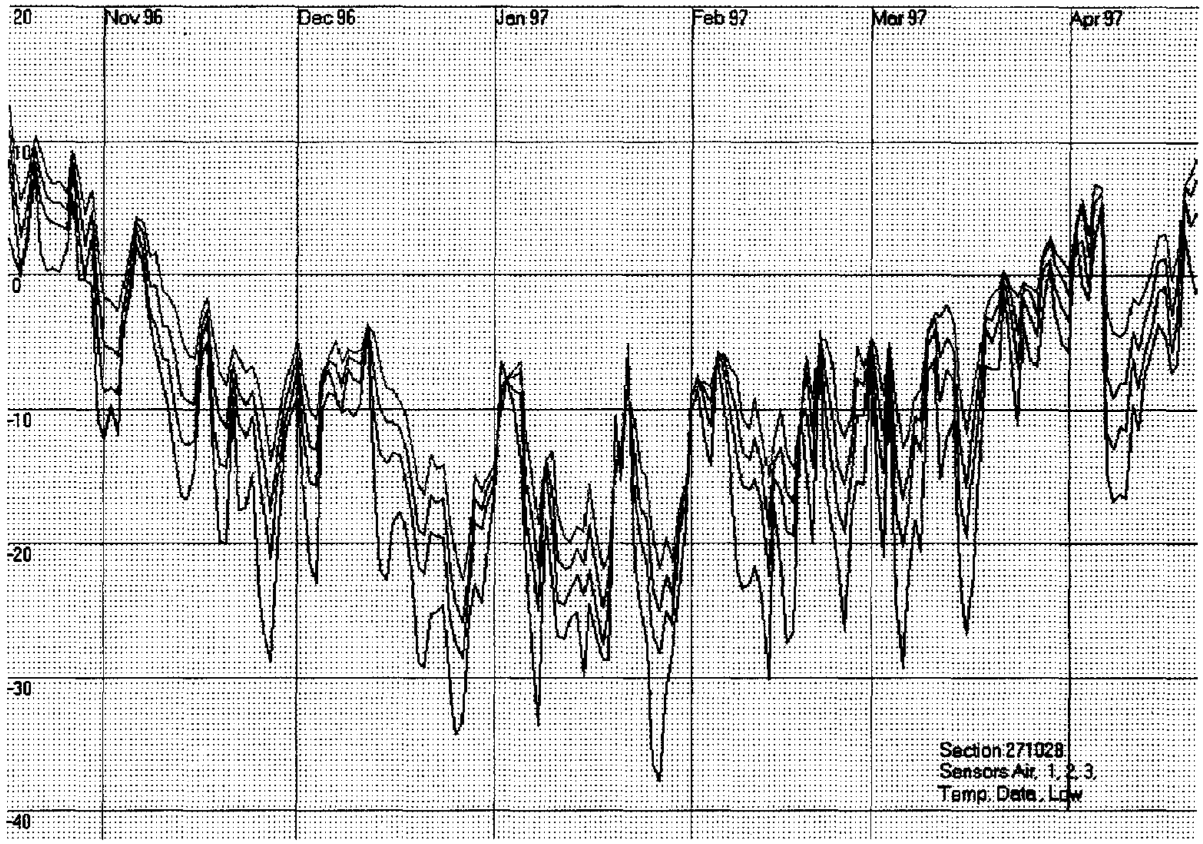

Figure 2 - Daily Low Air and Pavement Temperatures at Three Different Depths for the Cold Months.

The SMP data were also used in a range of data and model comparisons throughout the study. These comparisons were performed to validate the LTPP model, quantify differences with existing SHRP models, and compare performance grades determined from the models. For performance grade comparisons, data (average low and high air temperatures from 7,801 weather stations throughout the United States and Canada) from the SHRPBIND program were also used.[3]

3. SEASONAL MONITORING PROGRAM (SMP)

The LTPP-SMP was intended to provide:

- The means to link the pavement response data obtained at random points in time to critical design conditions.
- The means to validate models for relationships between environmental conditions and in situ properties of pavement materials.
- New knowledge of the magnitude and impact of the changes involved.[1]

3.1. SMP Temperature Probes

The TP101 thermistor probe from Measurement Research Corporation was used to measure temperature through the pavement. The degree of accuracy of the thermistors is ±0.1 °C.

Two different types of temperature probes were used for SMP Loop-1. One probe consisted of three thermistor sensors in a 330-mm-long metal rod; the other probe consisted of a string of 15 thermistors encased in a clear rod 25 mm in diameter and 1.83 m long. The metal rod was installed in the pavement so that measurements at approximately 25 mm deep, mid-depth, and 25 mm from the bottom of the layer could be made. The clear rod was installed below the surface layer into the subgrade. Figure 3 includes an illustration of SMP instrumentation installation. For more information on the instrumentation, see reference 1.

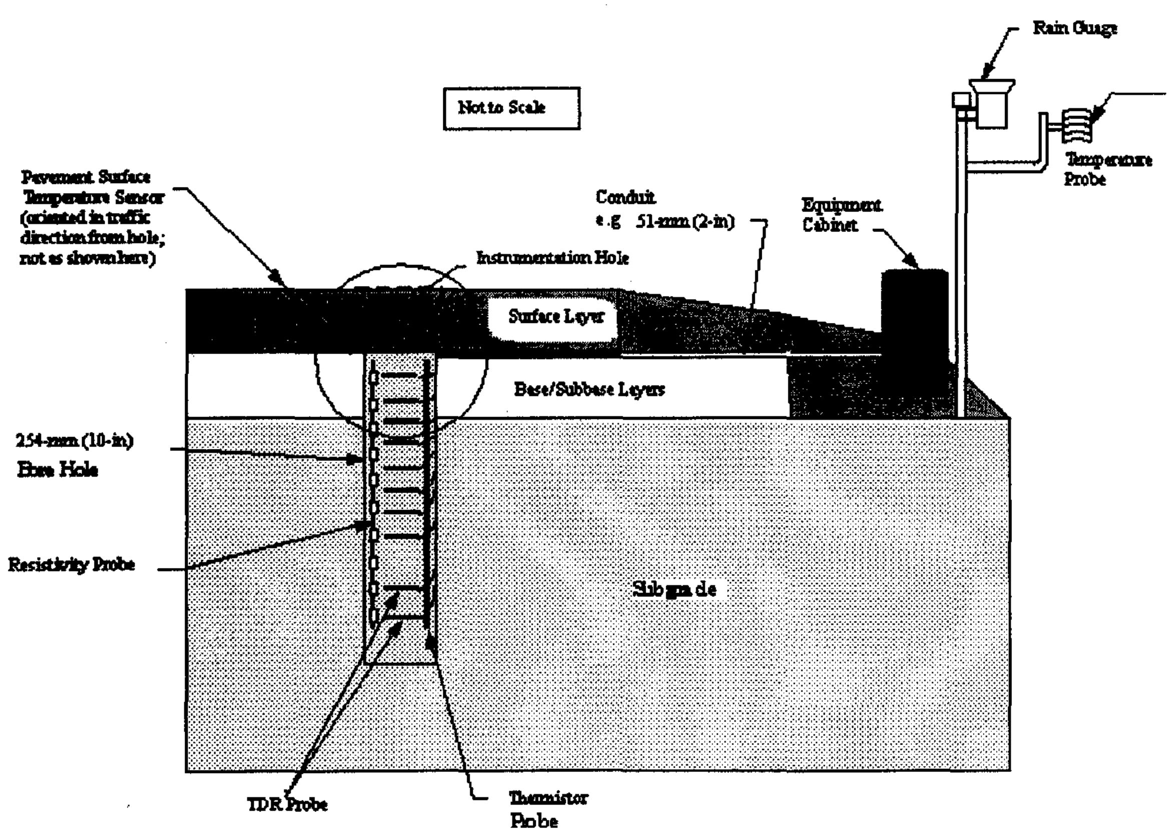

Figure 3 - Illustration of SMP Instrumentation Installation.

3.2. *SMP Onsite Data Files*

A Campbell Scientific CR10 Datalogger/Controller was used to collect environmental data from instrumentation installed at SMP sites. The ONSITE (ONS) program module of the Datalogger is used for continuous data collection at these sites. These data are summarized and stored in files with "ONS" extension.

Each ONS data file (figure 4) contains the daily low and high air and pavement temperatures, as well as average hourly air and pavement temperatures. Each data file contains several different record types that store data in a separate line as follows:

Record 1: Minimum and maximum daily air temperatures and their times.
Record 4: Minimum and maximum pavement temperatures for all (18) sensors.
Record 5: Average hourly air temperature.
Record 6: Average hourly pavement temperatures for the top five sensors.

Only data from record 1 (minimum and maximum daily air temperatures) and record 4 (minimum and maximum daily pavement temperatures at three different depths in the pavement surface layer) are used in this study.

```
5,1994,138,2200,12.15,9.98,0
6,1994,138,2200,13.99,15.89,16.78,16.56,16.34
5,1994,138,2300,12.15,9.71,0
6,1994,138,2300,13.79,15.3,16.36,16.34,16.3
1,1994,138,2400,12.16,12.17,1138,12.14,2256,10.8,14.47,1520,6.12,447,1,4067
2,1994,138,2400,16.33,15.77,15.59,15.37,15.43,15.33,15.46,15.47,15.45,15.3,15.05,
14.57,14.22,13.7,13,12.57,12.08,11.76
3,1994,138,2400,24.03,1310,19.81,1353,17.65,1642,16.76,1919,16.39,2112,15.93,2217,
15.85,1,15.9,4,15.82,1,15.6,1,15.29,127,14.72,536,14.32,429,13.79,508,13.07,2212,
12.64,2159,12.17,2003,11.85,2031
4,1994,138,2400,10.71,438,12.26,555,13.54,742,13.97,859,14.54,948,14.75,1032,15.06,
1158,15.18,1448,15.21,1703,15.07,2355,14.87,2255,14.44,2358,14.15,1833,13.63,1049,
12.92,1111,12.49,1007,11.99,1027,11.67,1115
```

Figure 4 - Sample Seasonal Monitoring Onsite (ONS) File.

4. SMP TEMPERATURE DATA

The LTPP-SMP data were collected from LTPP Regional Coordinating Office Contractors for the months of November 1993 through June 1995 from 25 SMP sites (from a total of 30 sites in SMP Loop-1). These data were summarized and stored in 526 ONS files. Each ONS file contains approximately 1 month of data. The number of files received from each region by section and year is shown in table 1. The section identification, geographic location, elevation, and surface layer thickness for 24 SMP sections were extracted from the LTPP Information Management System data base and are listed in table 2. Section 46SA was not included in the analysis because surface layer thickness data were not available at the time.

Table 1 - Number of ONS Files Used in the Study by Region, Section, and Year.

		Year			
REGION	Section	1993	1994	1995	Total
North Atlantic	09SA	4	13	9	26
	23SA	3	14	7	24
	25SA	3	13	9	25
	33SA	2	13	8	23
	50SA	3	14	8	25
	87SA	2	14	10	26
North Central	27SA	3	14	9	26
	27SB	3	12	9	24
	27SC	3	14	8	25
	46SA	.	5	7	12
	46SB	.	6	8	14
	83SA	2	13	7	22
	90SA	2	14	8	24
Southern	35SA	.	6	5	11
	40SA	.	8	5	13
	48SA	1	12	6	19
	48SB	1	12	5	18
	48SE	2	11	6	19
	48SF	1	12	4	17
	48SG	.	12	6	18
Western	08SA	3	12	7	22
	16SB	3	13	7	23
	30SA	3	13	7	23
	49SB	3	14	6	23
	56SA	3	13	8	24
ALL		50	297	179	526

Table 2 - SMP AC Site Identification, Geographic Location, and Surface Thickness.

Seasonal ID	SHRP ID	State	LTPP Region	Elevation, meter	Latitude, degree	Longitude, degree	Thickness, mm
08SA	81053	CO	4	1567	38.701	108.032	117
09SA	91803	CT	1	50	41.395	72.028	183
16SB	161010	ID	4	1455	43.682	112.117	272
23SA	231026	ME	1	148	44.573	70.294	137
25SA	251002	MA	1	27	42.139	72.615	198
27SA	271018	MN	2	341	45.995	94.469	112
27SB	271028	MN	2	422	46.683	95.667	244
27SC	276251	MN	2	416	47.433	94.85	180
30SA	308129	MT	4	1353	46.309	109.126	81
33SA	331001	NH	1	77	43.222	71.513	239
35SA	351112	NM	3	1146	32.638	103.525	160
40SA	404165	OK	3	402	36.383	98.233	206
46SB	469187	SD	2	719	45	102.15	140
48SA	481077	TX	3	559	34.533	100.433	130
48SB	481068	TX	3	136	33.505	95.59	277
48SE	481122	TX	3	139	29.233	98.25	86
48SF	481060	TX	3	24	28.5	97.05	191
48SG	483739	TX	3	11	26.983	97.8	46
49SB	491001	UT	4	1336	37.278	109.585	140
50SA	501002	VT	1	86	44.12	73.179	216
56SA	561007	WY	4	1586	44.501	108.923	71
83SA	831801	MB	2	427	49.833	100.5	112
87SA	871622	ON	1	301	45.142	79.258	142
90SA	906405	SK	2	544	51.908	105.325	300

4.1. Daily Temperature Data Bases

To reduce the size of the data, the daily temperature data from all 526 ONS files were collected into a single summary file. The minimum and maximum daily air and pavement temperatures were extracted from record 1, while the minimum and maximum daily pavement temperatures for the top three sensors were extracted from record 4. A sample of the summary file is shown in figure 5 and data elements are explained in figure 6.

Sec	Yr	Day	Tair	Tpav1	Tpav2	Tpav3
09A	94	121	18.0	19.6	19.2	18.4
09A	94	122	16.3	18.2	18.9	18.4
09A	94	123	16.4	17.3	18.3	18.3
09A	94	124	15.1	16.1	17.7	18.1
09A	94	125	12.9	14.9	17.0	17.8

Figure 5 - Sample Daily Data Base.

SEC	Seasonal section ID
YR	Year data was collected
DAY	Day of the year data was collected
TAIR	Air temperature, °C
TPAV1	Pavement temperature at 1" below the surface
TPAV2	Pavement temperature at mid-depth of AC layer
TPAV3	Pavement temperature at 1" over bottom of layer

Figure 6 - Data Elements in the Daily Data Base.

Other data such as geographic location, pavement thickness, and weather data from the closest weather station to the section were extracted from two other sources – SHRPBIND and LTPP Data Sampler computer programs – and added to the summary data file. These data are listed and annotated in figure 7 and figure 8.

SHRPID	GPS section identification corresponding to the seasonal section
LAT	Latitude of the section, degrees
LON	Longitude of the section, degrees
ELEV	Elevation of the section, meters
THICK	Thickness of the top AC layer, mm

Figure 7 - LTPP Data Sampler Data Elements.

Low-Temperature Data Base	
STATION	Closest weather station to the section
LOWEST	Lowest temperature ever recorded
LOWMEAN	Mean of the yearly low temperature
LOWSTD	Low-temperature standard deviation
High-Temperature Data Base	
STATION	Closest weather station to the section
HIGHEST	Highest 7-day average temperature ever recorded
HIMEAN	Mean of the yearly 7-day average high temperature
HIGHSTD	High-temperature standard deviation

Figure 8 - SHRPBIND Data Elements.

This information was further refined and divided into two temperature data bases – one for low temperature and another for high temperature. The low-temperature data base contains minimum daily air and pavement temperatures for the months of November through March. The high-temperature data base contains maximum daily air and pavement temperatures for May through September.

The daily low- and high-temperature data bases were included in files "LOWTEMP.DAT" and "HIGHTEMP.DAT" in ASCII (text) form. The worksheet versions of the two data bases are in Microsoft Excel format and were named "LOWTEMP.XLS" and HIGHTEMP.XLS." The data elements in each data base are explained in text files "LOWTEMP.TXT" and "HIGHTEMP.TXT." These data bases are available from the LTPP study on a single floppy disk entitled "SAPT Data Base."

4.2. Monthly Temperature Data Bases

Monthly low- and high-temperature data bases were developed from the summary daily data bases. The low monthly temperature data base includes the low monthly air and pavement temperatures for the cold months (November through March). The high monthly temperature data base includes the high monthly air and pavement temperatures for the warm months (May through September). These data bases provide a reasonable quantity and range of data for developing pavement temperature models. A sample of a monthly temperature data base is shown in figure 9. As illustrated in figure 9, the data bases include latitude (LAT), AC depth (THICK), air temperature (TAIR), and pavement temperature (TPAV) at a certain depth (H, mm).

SEC	SHRPID	ST	LAT	ELEV	THICK	YEAR	MONTH	DAY	H	TAIR	TPAV
09SA	91803	CT	41.395	50	183	93	Dec	363	25.40	-15.00	-10.68
09SA	91803	CT	41.395	50	183	93	Dec	363	91.44	-15.00	-7.13
09SA	91803	CT	41.395	50	183	93	Dec	363	157.48	-15.00	-3.76
09SA	91803	CT	41.395	50	183	94	Jan	27	25.40	-20.90	-13.74
09SA	91803	CT	41.395	50	183	94	Jan	27	91.44	-20.90	-9.29
09SA	91803	CT	41.395	50	183	94	Jan	27	157.48	-20.90	-5.79
09SA	91803	CT	41.395	50	183	94	Feb	41	25.40	-14.76	-10.99
09SA	91803	CT	41.395	50	183	94	Feb	41	91.44	-14.76	-7.99
09SA	91803	CT	41.395	50	183	94	Feb	41	157.48	-14.76	-5.27
09SA	91803	CT	41.395	50	183	94	Mar	61	25.40	-11.60	-7.15
09SA	91803	CT	41.395	50	183	94	Mar	61	91.44	-11.60	-4.14

Figure 9 - Sample Monthly Data Base.

5. COMPARING THE SMP DATA WITH EXISTING PAVEMENT TEMPERATURE MODELS

SMP data in the low and high monthly temperature data bases were compared with the existing SHRP and C-SHRP models to validate the models and to propose improvements to them.

To quantify the difference between SMP data and SHRP and C-SHRP estimates of pavement temperatures, several comparisons were made between the data and the models. The difference between measured air and pavement temperatures at a depth of 25 mm was used for comparisons. The actual SMP measured difference was compared to the calculated differences used in the SHRP and C-SHRP pavement temperature models.

5.1. Comparing the SHRP Low-Temperature Model With SMP Data

SHRP considers the low air temperature as the design low pavement temperature. An equation was developed by SHRP for the change in temperature with depth (equation 1). C-SHRP, on the other hand, uses an equation developed by Robertson mostly from the Canadian data (equation 2).[2]

$$T(d) = T(air) + 0.051\, d - 0.000063\, d^2 \qquad (1)$$

Where:
- T(d)= Pavement temperature at a depth, °C.
- T(air)= Air temperature, °C.
- d= Depth, mm.

Equation 1 - SHRP Low Pavement Temperature Model With Depth.

$$T_{pav} = 0.859\, T_{air} + (0.002 - 0.0007\, T_{air})\, H + 0.17 \qquad (2)$$

Where
- T_{pav}= Low AC pavement temperature, °C.
- T_{air}= Low air temperature, °C.
- H= Depth, mm.

Equation 2 - C-SHRP Low Pavement Temperature Model With Depth.[2]

Figure 10 shows the measured SMP low-temperature data at a depth of 25 mm in the low monthly data base vs. the low air temperature; the SHRP estimate of the low pavement temperature at the surface (equality line); the SHRP pavement temperature at 25 mm of depth (using equation 1); and the C-SHRP estimate (using equation 2).

It reveals a significant difference between the SHRP estimate and SMP data, especially for the lower air temperatures. The C-SHRP estimates are closer to the data, but are still conservative. The SHRP estimates are up to 12 degrees higher than the SMP data, while C-SHRP estimates are about 7 to 8 degrees higher.

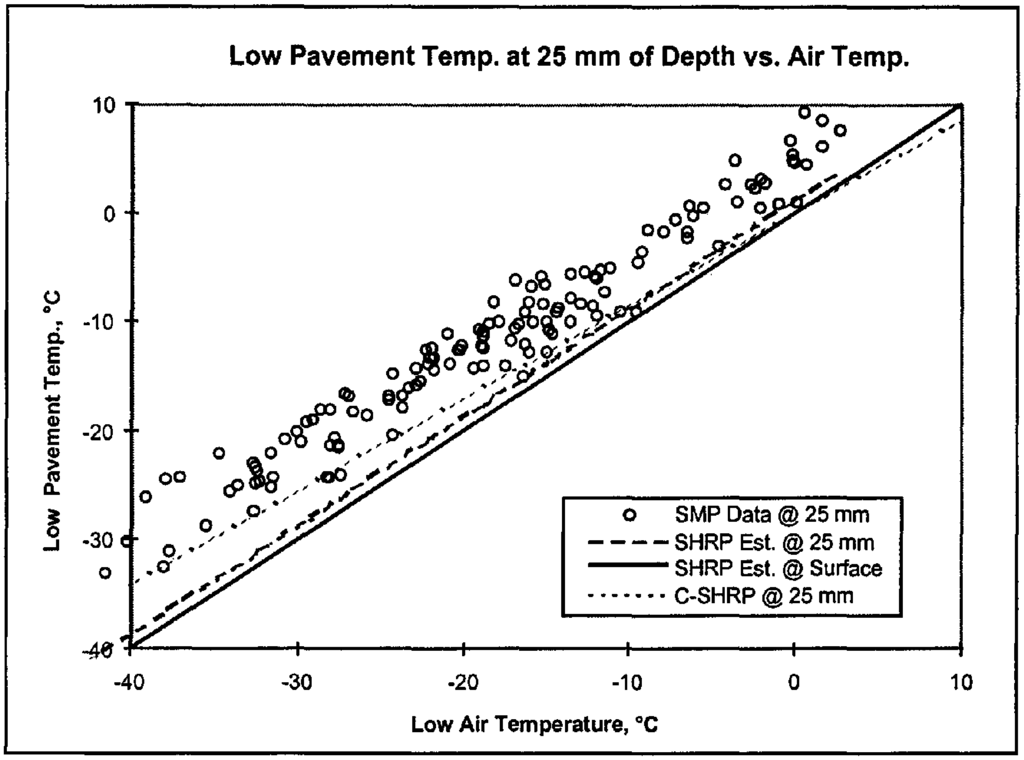

Figure 10 - SMP Low Pavement Temperature at 25 mm of Depth vs. Low Air Temperature.

Table 3 shows the average temperature difference between air and pavement temperatures at a depth of 25 mm in the SMP low monthly temperature data base for different ranges of air temperatures and latitudes. Table 4 shows the average difference when the low pavement temperature was calculated using the C-SHRP equation (equation 2).

Table 3 - Average Difference Between SMP Low Air Temperature and Pavement Temperature at a Depth of 25 mm for Different Latitude and Air Temperature Ranges.

	Air Temperature								
Lat	<-35	-40 to -35	-35 to -30	-30 to -25	-25 to -20	-20 to -15	-15 to -10	-10 to -5	>-5
<30	.	.	.	.	.	.	.	6	5.9
30-35	.	.	.	.	.	10.1	.	5.9	4.2
35-40	.	.	.	.	.	7.7	6.5	6.5	2.8
40-45	.	13	10.8	10.4	7.9	6.2	5.6	2.9	.
>45	9.4	8.2	8.2	6.9	7.9	5.3	2.9	.	.

Table 4 - Average Difference Between SMP Low Air Temperature and C-SHRP Estimated Temperature at a Depth of 25 mm for Different Latitude and Air Temperature Ranges.

	Air Temperature								
Lat	<-35	-40 to -35	-35 to -30	-30 to -25	-25 to -20	-20 to -15	-15 to -10	-10 to -5	>-5
<30	.	.	.	.	.	.	.	1	0.2
30-35	.	.	.	.	.	2.5	.	1.2	0.3
35-40	.	.	.	.	.	2.5	2.1	1.3	0.4
40-45	.	5.6	4.7	4.2	3.4	2.6	2	1.5	.
>45	6	5.5	4.8	4.1	3.4	2.6	1.9	.	.

Table 3 shows that SHRP estimates of low pavement temperature at the surface of the AC layer may be as much as 13 degrees lower than SMP field measures at a depth of 25 mm. Table 3 also shows that within a temperature range, the average difference increases as latitude decreases and the difference also increases as the temperature decreases. Comparing the data in table 3 with the data in table 4 shows that the SMP temperature difference at a depth of 25 mm is significantly higher than the C-SHRP calculated difference for the same depth. Since the latitude effect is not considered in the C-SHRP model, the temperature difference between air and pavement remains the same for different latitudes.

5.2. Comparing the SHRP High-Temperature Model With SMP Data

The SHRP high-temperature model was developed from the results of theoretical heat-transfer modeling.[3] Several sites throughout the United States were considered, and for each site, pavement temperatures were calculated from air temperature, latitude, solar absorption, and wind speed. A regression model was then developed from the data. The SHRP high pavement temperature model for surface AC is shown in equation 3 and the model with depth in equation 4. A combined model for a depth of 20 mm is shown in equation 5.

$$T(surf) = T(air) - 0.00618\ Lat^2 + 0.2289\ Lat + 24.4 \qquad (3)$$

Where: T(surf)= High AC pavement temperature at the surface, °C.
T(air)= High air temperature, °C.
Lat= Latitude of the section, degrees.

Equation 3 - SHRP High Pavement Temperature Model for the Surface.

$$T(d) = T(surf)\,(1 - 0.063\,d + 0.007\,d^2 - 0.0004\,d^3) \quad (4)$$

Where: T(d)= High AC pavement temperature at a depth, °F.
T(surf)= High AC pavement temperature at the surface, °F.
d= Pavement depth, in.

Equation 4 - SHRP High Pavement Temperature Model With Depth.

$$T_{pav} = (\,T_{air} - 0.00618\,Lat^2 + 0.2289\,Lat + 42.4)\,0.9545 - 17.78 \quad (5)$$

Where: T_{pav}= High AC pavement temperature at 20 mm below the surface, °C.
T_{air}= High air temperature, °C.
Lat= Latitude of the section, degrees.

Equation 5 - SHRP High Pavement Temperature Model for a Depth of 20 mm.

Actual SMP high pavement temperature data at a depth of 25 mm vs. SHRP estimates of the temperature is shown in figure 11. Equation 3 and equation 4 were used to calculate SHRP estimates at 25 mm of depth. Figure 11 shows that SHRP estimates are, on average, 5 degrees higher for this depth.

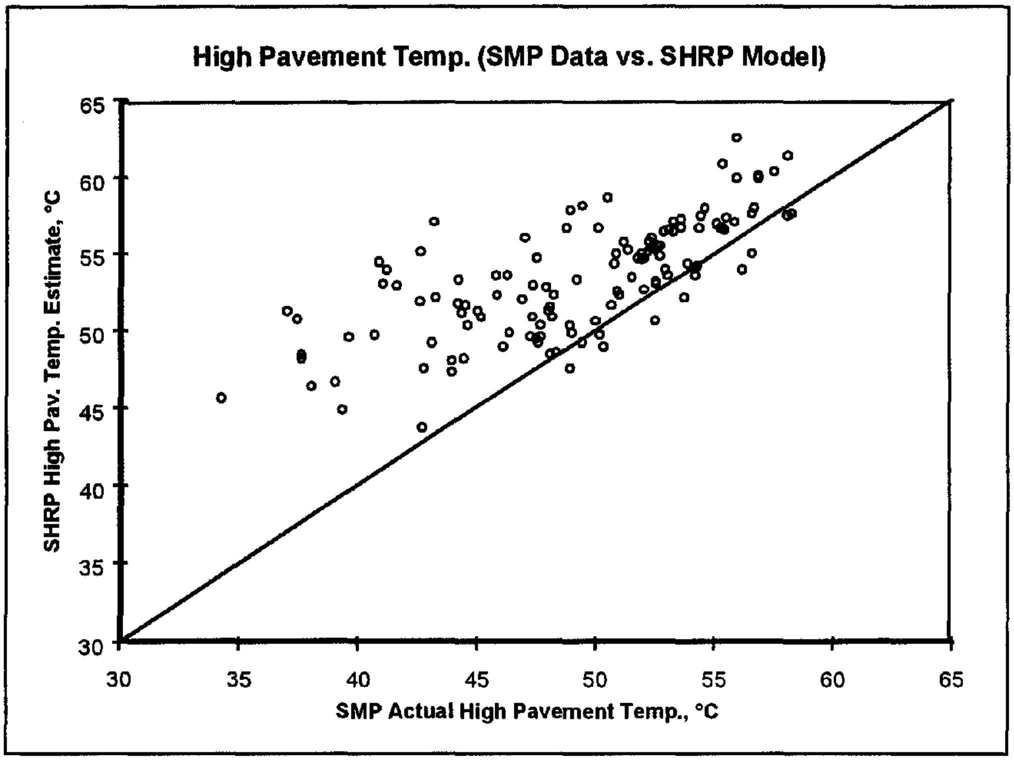

Figure 11 – SHRP High Pavement Temperature Estimate vs. SMP Actual High Pavement Temperature at 25 mm of Depth.

The difference between SMP high air temperature and temperature at a depth of 20 mm in the monthly high-temperature data base for different ranges of latitudes and air temperatures is shown in table 5. The SHRP equation was used for estimating the pavement temperature in the monthly high-temperature data base (the results are listed in table 6).

Table 5 - Average Difference Between SMP High Air Temperature and Pavement Temperature at a Depth of 25 mm for Different Latitude and Air Temperature Ranges.

	Air Temperature				
Lat	20 to 25	25 to 30	30 to 35	35 to 40	40 to 45
<30	.	.	20.2	19.1	.
30-35	.	.	19.8	19.6	.
35-40	14	22.5	18.2	18.7	14.8
40-45	16.5	18.2	17.8	16.4	.
>45	16.9	17.5	14.7	12.1	.

Table 6 - Average Difference Between High Air Temperature and SHRP Estimated Pavement Temperature at a Depth of 20 mm for Different Latitude and Air Temperature Ranges.

	Air Temperature				
Lat	20 to 25	25 to 30	30 to 35	35 to 40	40 to 45
<30	.	.	22.4	22.4	.
30-35	.	.	21.8	21.6	.
35-40	21.4	21.3	21	20.8	20.6
40-45	19.9	19.7	19.4	19.4	.
>45	17.7	18.3	17.9	18.5	.

From table 5 and table 6 it is evident that the SHRP temperature differences are higher than those measured by the SMP data. The average pavement temperature for a 35 to 40 °C air temperature range and latitudes of greater than 45 degrees was 18.5 degrees higher than the air temperature according to the SHRP model (table 6), compared to 12.1 degrees in SMP data (table 5). The largest difference between the data in table 5 and table 6 is at high temperatures and high latitudes. The SHRP model estimated temperatures were 1 to 6 degrees higher than the SMP data.

6. LTPP LOW PAVEMENT TEMPERATURE MODEL

A range of statistical analyses were performed on the data in the Seasonal Asphalt Concrete Pavement Temperature (SAPT) monthly low-temperature data base to develop a model for estimating low pavement temperatures at various depths below the AC surface layer.

6.1. Data Check for Outliers

The SAPT monthly low-temperature data base was thoroughly checked to detect outliers. Data problems due to sensor malfunction or other problems during data collection were anticipated. To minimize data errors, a series of graphs were developed and were visually inspected to detect data points that appeared to be suspicious. As a result of these checks, a set of rules (figure 12) were developed and applied to the SAPT monthly low-temperature data base.

The first rule in figure 12 limits the data to pavement temperatures of -65 °C to 10 °C for the top sensor. The second rule ensures that the difference between pavement and air temperatures is less than 35 °C, while the third rule ensures that the pavement temperatures increase with depth. Rules 4 through 13 were used to identify unreasonable (outlier) data found during visual inspection.

```
1.  Tpav>-65 and Tpav<10
2.  (Tpav-Tair)<35
3.  Tpav>Tair and Tpav<Tpavm and Tpavm<Tpavb
4.  sec='48SE'
5.  sec='30SA'
6.  sec='27SB'  year=94  month='Jan'
7.  sec='27SC'  year=94  month='Jan'
8.  sec='90SA'  year=94  month='Jan'
9.  sec='50SA'  year=95  month='Mar'
10. sec='49SB'  year=94  month='Mar'
11. sec='23SA'  year=95  month='Mar'
12. sec='23SA'  year=94  month='Dec'
13. sec='08SA'  year=94  month='Mar'
```

Figure 12 - SAPT Low Monthly Temperature Data Base Data Checks.

6.2. SAPT Low Monthly Temperature Data Base

The filtering of the monthly low-temperature data base resulted in a total of 411 temperature data points for model development. The data are tabulated in tables 7 and 8 by month and section. Table 7 includes the monthly low air and pavement temperatures at a depth of 25 mm below the surface of the AC layer (top). The mid-layer (mid) and bottom layer (bot) temperatures are listed in table 8.

Table 7 - Monthly Low Air and Pavement Temperatures for the Top Sensor (°C).

	1993		1994										1995					
Section	Dec		Jan		Feb		Mar		Nov		Dec		Jan		Feb		Mar	
	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top
08SA	-18	-10	-16	-9	-19	-11	.	.	-15	-8	-14	-9	-14	-8	-9	-4	-6	1
09SA	-15	-11	-21	-14	-15	-11	-12	-7	.	.	.	.	.	.	-19	-11	.	.
16SB	-19	-10	-22	-13	-22	-14	-10	-4	-11	-5	-17	-12	-24	-17	-18	-8	.	.
23SA	-25	-17	-37	-24	-29	-19	-22	-13	.	.	.	.	-29	-18	-28	-18	.	.
25SA	-16	-13	-24	-20	-19	-14	-13	-8	.	.	.	.	.	.	-22	-14	.	.
27SA	-33	-23	-40	-30	-32	-25	-19	-11	-16	-8	-27	-17	-28	-21	-24	-15	-30	-19
27SB	-33	-25	.	.	-33	-27	-16	-12	-11	-9	-26	-19	-27	-24	-28	-24	-28	-22
27SC	-32	-25	.	.	-36	-29	-20	-13	-12	-9	-27	-18	-28	-24	-31	-24	-31	-21
33SA	-19	-14	-32	-22	-23	-16	-19	-12	-12	-5	-15	-10	-16	-10	-23	-15	-13	-5
35SA	.	.	.	.	.	.	.	.	1	5	-4	1	-7	-2	-2	1	-7	-2
40SA	.	.	.	.	.	.	0	5	.	.	.	.	.	.	.	.	.	.
46SB	.	.	.	.	.	.	.	.	-14	-10	-15	-13	-24	-18	-22	-12	-28	-21
48SA	-9	-2	-17	-6	-16	-7	0	1	.	.	.	.	.	.	.	.	.	.
48SB	-6	0	-8	-2	-7	-1	-2	3	2	9	-2	3	.	.	.	.	.	.
48SF	-2	2	-4	3	-6	0	3	8	.	.	.	.	0	5	3	8	1	6
48SG	0	5	-4	5	-3	3	0	9	.	.	0	7	5	8	.	.	3	9
49SB	-12	-6	-14	-6	-15	-6	.	.	-5	-3	.	.	.	.	.	.	-1	1
50SA	.	.	-39	-26	-35	-22	-21	-11	-15	-6	-17	-10	-23	-14	-30	-20	.	.
56SA	-10	-9	-20	-12	-27	-17	-12	-6	-14	-9	-19	-12	-16	-15	-22	-13	-17	-11
83SA	-34	-25	-38	-32	-38	-31	-18	-14	-20	-13	-30	-21	.	.	.	.	-12	-9
90SA	-38	-24	.	.	-42	-33	-25	-17	-23	-16	-33	-24	-34	-25	-28	-21	-33	-23

Table 8 - Monthly Low Pavement Temperature at the Bottom and Mid-Depth of the AC Layer (°C).

	1993		1994										1995					
Section	Dec		Jan		Feb		Mar		Nov		Dec		Jan		Feb		Mar	
	Bot	Mid	Bot	Mid	Bot	Mid	Bot	Mid	Bot	Mid	Bot	Mid	Bot	Mid	Bot	Mid	Bot	Mid
08SA	-6	-8	-3	-7	-6	-9	.	.	-4	-6	-4	-7	-3	-6	0	-2	4	2
09SA	-4	-7	-6	-9	-5	-8	-1	-4	.	.	.	.	.	.	-4	-8	.	.
16SB	-6	-8	-6	-9	-8	-11	0	-2	-1	-4	-8	-10	-12	-15	-5	-7	.	.
23SA	-11	-14	-18	-21	-14	-16	-9	-11	.	.	.	.	-13	-15	-14	-16	.	.
25SA	-8	-10	-15	-17	-8	-11	-3	-5	.	.	.	.	.	.	-10	-13	.	.
27SA	-20	-21	-26	-28	-21	-22	-7	-8	-5	-6	-13	-15	-17	-19	-10	-12	-15	-17
27SB	-19	-22	.	.	-22	-25	-5	-9	-3	-6	-12	-15	-17	-21	-17	-21	-14	-18
27SC	-20	-23	.	.	-24	-26	-7	-10	-5	-7	-13	-16	-19	-22	-19	-22	-16	-19
33SA	-9	-12	-15	-19	-10	-13	-7	-10	-1	-3	-4	-7	-5	-8	-10	-13	-3	-5
35SA	.	.	.	.	.	.	.	.	7	6	3	2	0	-1	3	1	0	-1
40SA	.	.	.	.	.	.	9	7	.	.	.	.	.	.	.	.	.	.
46SB	.	.	.	.	.	.	.	.	-5	-7	-9	-10	-13	-15	-7	-9	-15	-17
48SA	2	0	-1	-4	-2	-5	5	3	.	.	.	.	.	.	.	.	.	.
48SB	5	3	3	1	4	2	7	5	12	11	6	4	.	.	.	.	.	.
48SF	7	5	8	6	4	3	14	11	.	.	.	.	10	8	12	10	10	9
48SG	6	5	7	5	4	3	11	10	.	.	8	7	9	8	.	.	10	9
49SB	-2	-4	-1	-4	-2	-4	.	.	-1	-1	.	.	.	.	.	.	3	2
50SA	.	.	-20	-23	-17	-19	-8	-9	-3	-5	-5	-8	-10	-12	-15	-18	.	.
56SA	-7	-8	-9	-11	-14	-15	-3	-4	-6	-8	-9	-11	-13	-14	-10	-12	-8	-9
83SA	-22	-24	-30	-31	-28	-30	-11	-13	-10	-11	-18	-19	.	.	.	.	-6	-7
90SA	-23	-24	.	.	-32	-33	-16	-16	-15	-16	-23	-23	-24	-25	-21	-21	-22	-23

Table 9 lists the ranges of data in the low monthly temperature data base. Air temperatures ranged from 4.6 to -41.5 °C, while pavement temperatures were between 13 and -33 °C. Pavement depths (sensor locations) were between 25.4 mm and 274 mm. Elevations ranged from 11 to 1586 m, with a mean of 568 m. Latitudes were between approximately 27 degrees (Texas) and approximately 52 degrees (Canada).

Table 9 - Ranges of Data in the Low-Temperature Model Data Base.

Variable	N	Mean	Std Dev	Minimum	Maximum
T_{pav}	411	-9.13212	10.06175	-33.01	13.67
T_{air}	411	-17.9542	11.23884	-41.53	4.61
Lat	411	41.69345	6.70621	26.983	51.908
H	411	87.80613	68.00613	25.4	274.32
Elev	411	568.146	556.6791	11	1586

6.3. *Correlation Analysis of Low-Temperature Variables*

Correlation analysis was performed on the data in the SAPT monthly low-temperature data base to find the potential variables to be considered for the model. Variables that were considered in the correlation analysis were air temperature (T_{air}), latitude (Lat), elevation (Elev), pavement temperature (T_{pav}), and depth into the AC layer (H). Non-linear transformations of some of the variables were also considered. The results of the correlation analysis are listed in table 10.

Table 10 shows that both T_{air} and Lat had a good correlation with T_{pav} (r=0.96 and 0.85, respectively). T_{air} and Lat were also highly correlated (r=0.82). The correlation between T_{pav} and H was not very strong (r=0.05), but the log transform of H (*log*H) was slightly better correlated (r=0.07). The correlation between T_{pav} and Elev was almost nonexistent (r=0.01).

Table 10 - Pearson Correlation Coefficients (r) for the Low-Temperature Data Base.

	T_{pav}	T_{air}	Lat	Lat^2	*log*Lat	H	H^2	*log*H	T_{air}*Lat	T_{air}*H	Elev
T_{pav}	1.	0.96	-0.85	-0.85	-0.84	0.05	0.02	0.07	0.93	0.47	0.01
T_{air}	0.96	1.	-0.82	-0.82	-0.81	-0.09	-0.09	-0.08	0.99	0.58	0.05
Lat	-0.85	-0.82	1.	1.	1.	0.13	0.14	0.11	-0.78	-0.5	0.1
Lat^2	-0.85	-0.82	1.	1.	0.98	0.13	0.14	0.11	-0.76	-0.51	0.07
*log*Lat	-0.84	-0.81	1.	0.98	1.	0.13	0.13	0.12	-0.78	-0.49	0.13
H	0.05	-0.09	0.13	0.13	0.13	1.	0.96	0.97	-0.07	-0.75	-0.11
H^2	0.02	-0.09	0.14	0.14	0.13	0.96	1.	0.86	-0.07	-0.74	-0.09
*log*H	0.07	-0.08	0.11	0.11	0.12	0.97	0.86	1.	-0.08	-0.71	-0.11
T_{air}*Lat	0.93	0.99	-0.78	-0.76	-0.78	-0.07	-0.07	-0.08	1.	0.56	0.02
T_{air}*H	0.47	0.58	-0.5	-0.51	-0.49	-0.75	-0.74	-0.71	0.56	1.	0.09
Elev	0.01	0.05	0.1	0.07	0.13	-0.11	-0.09	-0.11	0.02	0.09	1.

From the correlation analysis, it appeared that T_{air}, Lat, and H could be major factors in the model. To find the type of correlation between these variables (independent variables) and the dependent variable (T_{pav}), the dependent variable was graphed against the independent variables (T_{air}, Lat, and H). Figure 13 shows the relation between T_{pav} and T_{air} to be linear. Figure 14, on the other hand, shows the relation between T_{pav} and Lat to be non-linear. As figure 15 shows, the relation between T_{pav} and H is also somewhat non-linear.

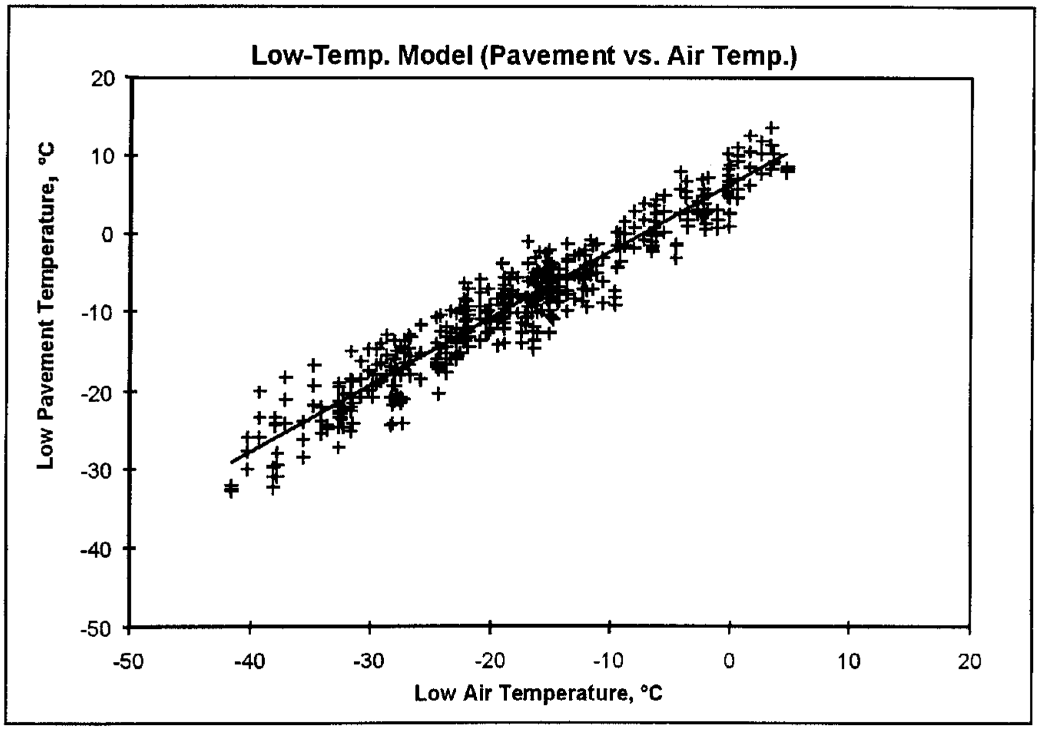

Figure 13 - Low Pavement Temperature vs. Low Air Temperature.

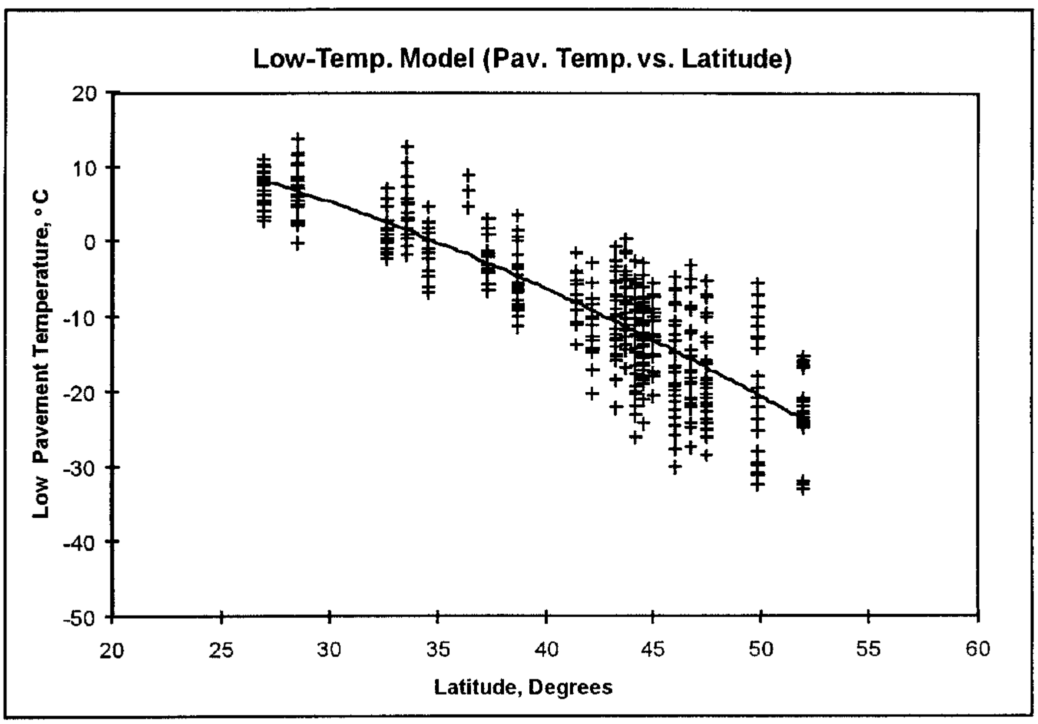

Figure 14 - Low Pavement Temperature vs. Latitude.

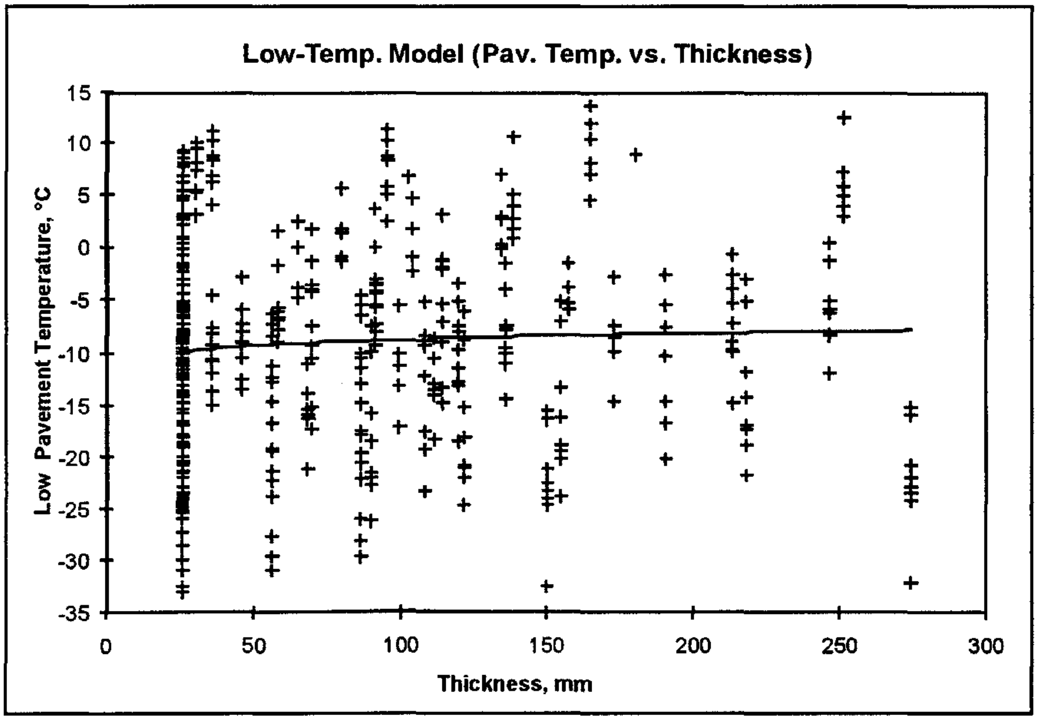

Figure 15 - Low Pavement Temperature vs. Thickness.

6.4. Variable Selection for the Low-Temperature Model

In order to select independent variables for the low-temperature model, a stepwise regression method was used. (A stepwise regression procedure selects the strongest variables for a model based on a statistical procedure.) Several linear, non-linear, and interaction terms, as shown in figure 16, were considered in the stepwise procedure.

Model: $T_{pav} = T_{air}$, Lat, Lat^2, *log*Lat, H, H^2, *log*H, AirH, LatH, AirLat, Elev, AE, LE

Where: *log*Lat= Logarithm (base 10) of Lat
*log*H= Logarithm (base 10) of (H+25)
AirLat= Interaction term between T_{air} and Lat
AirH= Interaction term between T_{air} and H
LatH= Interaction term between Lat and H
AE= Interaction term between T_{air} and Elev
LE= Interaction term between Lat and Elev

Figure 16 - Stepwise Formulation for the Low-Temperature Model.

The final output of the statistical procedure is shown in figure 17. Of 13 possible terms, only the 6 variables shown in figure 14 met the 0.15 significance level. The strongest terms were T_{air}, *log*H, and Lat^2. The AirLat interaction term was also selected; however, it did not significantly improve the model's fit. The contribution of LatH to the R^2, however, was very low (0.0004). When *log*Lat was added to the model (entered), Lat^2 was no longer significant and thus was dropped (removed) from the model.

Variable Step	Number Entered	Partial Removed	Model In	R**2	R**2	F	Prob>F
1	Tair		1	0.9211	0.9211	4776.5993	0.0001
2	logH		2	0.0215	0.9427	153.1755	0.0001
3	LAT2		3	0.0139	0.9566	130.7668	0.0001
4	AIRLAT		4	0.0014	0.9580	13.4222	0.0003
5	LATH		5	0.0004	0.9584	3.8983	0.0490
6	LOGLat		6	0.0005	0.9589	4.8509	0.0282
7	LAT2		5	0.0000	0.9588	0.3973	0.5289

Figure 17 - Final Output of the Stepwise Regression for the Low-Temperature Model.

6.5. Low-Temperature Model Functional Form

Several model functional forms were considered for the low-temperature model. The linear and non-linear terms that proved to be significant during the correlation analysis and variable selection, and the Elev term (Elevation) were considered for these models. Models were judged based on their goodness of fit (R^2), their variability [standard error of estimate (SEE)], and their boundary conditions. Models took the general form shown in equation 6. Table 11 includes the regression coefficients for all possible terms in the model, R^2, and the SEE for all models considered.

$$T_{pav} = a + \sum C_i * T_i \qquad (6)$$

Where:
- T_{pav}= Pavement temperature at a depth, °C.
- a= Intercept of the model (constant).
- T_i= *i*th term.
- C_i= Regression coefficient of the *i*th term.

Equation 6 - LTPP Low Pavement Temperature Functional Form.

Table 11 - Regression Coefficients for the Low-Temperature Models.

No.	Int.	T_{air}	Lat	Lat^2	*log*Lat	H	H^2	*log*H	T_{air}*Lat	T_{air} * H	Elev	R^2	SEE
1	22.90	1.1543			-19.29			6.24	-18.83		-1.5E-4	0.958	2.065
2	-2.68	0.9872		-0.0032				6.25	-11.60			0.958	2.072
3	-7.77	0.7205	0.3261	-0.0081				6.23				0.957	2.097
4	2.70	0.7223	0.2669	-0.0072		0.0484	-0.00011					0.957	2.099
5	2.38	0.7233	0.2846	-0.0074		0.0481	-0.00010				5.3E-5	0.956	2.102
6*	-1.56	0.7182		-0.0040				6.26				0.956	2.104
7	7.75	0.7208		-0.0039		0.0498	-0.00011					0.956	2.103
8	7.57	0.7076		-0.0039		0.0517	-0.00011			0.00014		0.956	2.102
9	7.54	0.7065		-0.0039		0.0518	-0.00011			0.00014	6.6E-5	0.956	2.104
10	-1.58	0.7178		-0.0040				6.27			2.2E-5	0.956	2.106
11	7.52	0.9860		-0.0033		0.0251			-12.42	0.00017		0.955	2.135
12	30.92	0.7362			-24.33			6.28				0.954	2.164
13	31.83	0.7316			-25.09			6.34			2.0E-4	0.954	2.164
14	8.62	0.6900		-0.0041		0.0268				0.00027		0.954	2.169
15	8.61	0.6895		-0.0041		0.0269				0.00027	3.0E-5	0.953	2.171
16	14.63	0.7210	-0.3047			0.0215						0.952	2.208
17	14.70	0.7187	-0.3091			0.0216					1.1E-4	0.952	2.210

* Best Model

Although the Elev term did not prove to be significant during the correlation analysis and variable selection, it was still considered for the model. The regression coefficients derived for the Elev term in the table 11 models were very small – the term becomes practically insignificant. Thus, the use of the Elev term in the model was irrelevant. Adding the AirLat term to the model marginally improved the model. When the model was tested, however, the boundary conditions were found to be unreasonable.

6.6. LTPP Low-Temperature Model

The LTPP low-temperature model was developed based on the results of the statistical analyses performed on the data in the SAPT low-temperature monthly data base. The following terms were found to be best for the model:

> Air Temperature (T_{air}): From the correlation analysis, it was found that T_{air} had the highest correlation with the pavement temperature (T_{pav}) and that the relation was linear. In the variable selection process, T_{air} was also found to be the strongest term in the model.
>
> Latitude (Lat): In the correlation analysis, the next best term in the model was found to be Lat. The relation between Lat and T_{pav} was found to be non-linear. Therefore, the terms Lat^2 and *log*Lat were added to the model in the variable selection

procedure. It was found that Lat^2 was the better term when AirLat was not added to the model; otherwise, *log*Lat was selected as the better term.

Depth (H): H was found to have a weak correlation with T_{pav}. Since the relation seemed to be somewhat non-linear, the terms H^2 and *log*(H+25) were considered. It was found by trial and error that the term *log*(H+25) provides a better fit to the data.

In addition to the terms discussed above, the AirLat interaction term was also considered. Although this term slightly improved the model statistics, it failed to provide good boundary conditions when the model was tested. Therefore, based on the fit of the models and variability, it was decided that model number 6 in table 11 (also equation 7) was the best model. When this model was tested for values within the range of the data selected as non-outliers, it proved to produce reasonable results.

$$T_{pav} = -1.56 + 0.72\, T_{air} - 0.004\, Lat^2 + 6.26\, log_{10}(H+25) \qquad (7)$$

Where:
- T_{pav}= Low AC pavement temperature below the surface, °C.
- T_{air}= Low air temperature, °C.
- Lat= Latitude of the section, degrees.
- H= Depth to surface, mm.
- R^2= 96%
- N= 411
- RMSE= 2.1

Equation 7 - LTPP Low Pavement Temperature Model.

6.7. Residual Analysis of the Low-Temperature Model

The residuals (actual pavement temperature minus predicted temperature) of the model were plotted against the main factors and are shown in figures 18 through 20. The residuals seem to be randomly distributed with no obvious trend. The residuals of the model ranged from -4.9 to 5.5, with a standard error of 2.1 °C. Figure 21 shows the predicted pavement temperature vs. actual temperature.

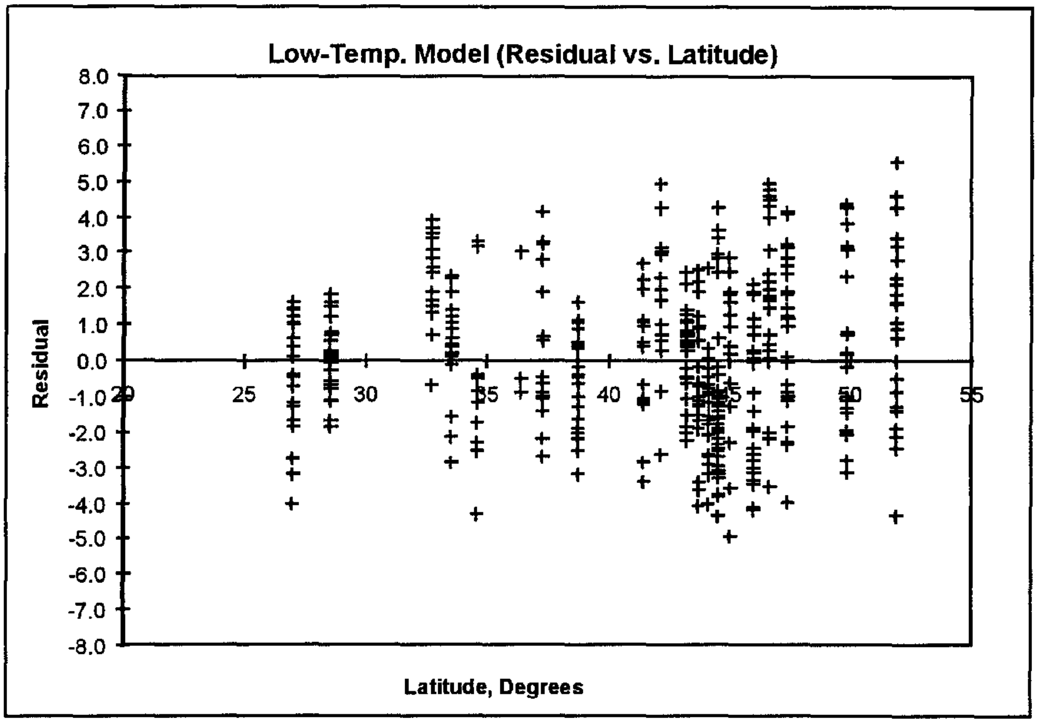

Figure 18 - Residual of the Low-Temperature Model vs. Latitude.

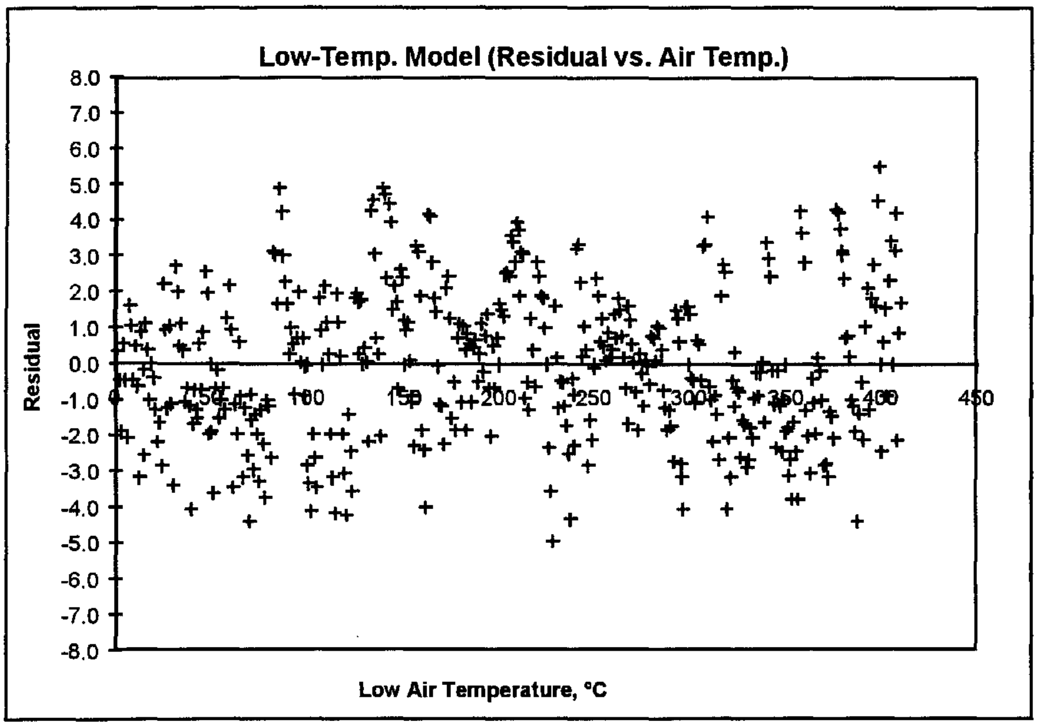

Figure 19 - Residual of the Low-Temperature Model vs. Low Air Temperature.

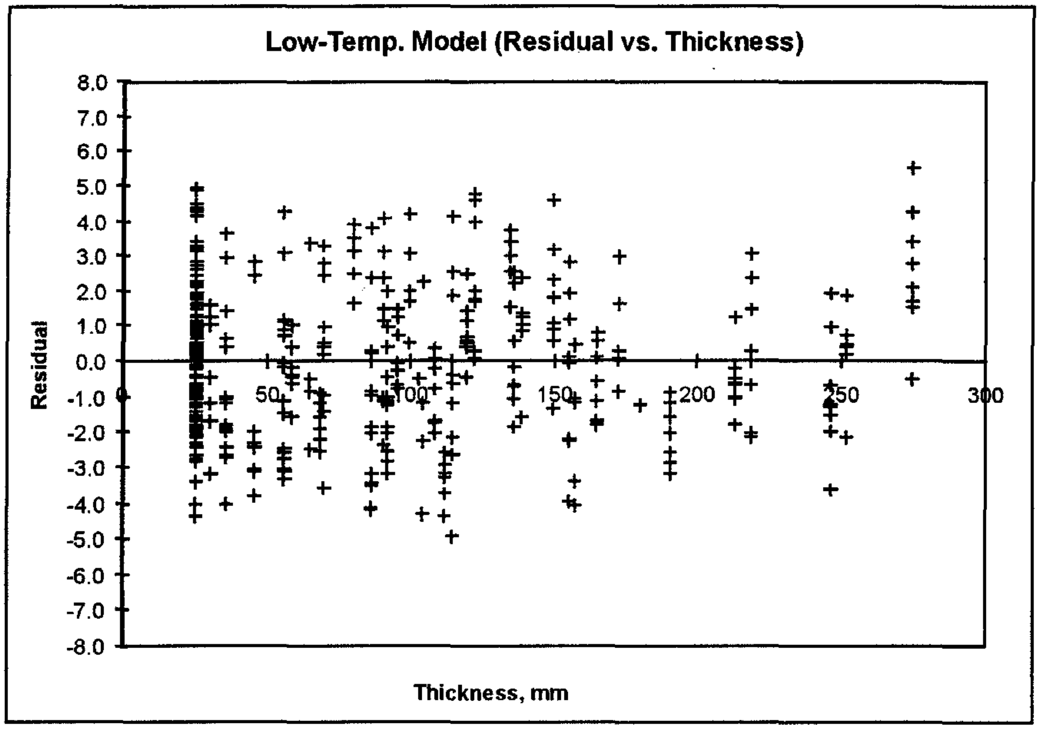

Figure 20 - Residual of the Low-Temperature Model vs. Thickness.

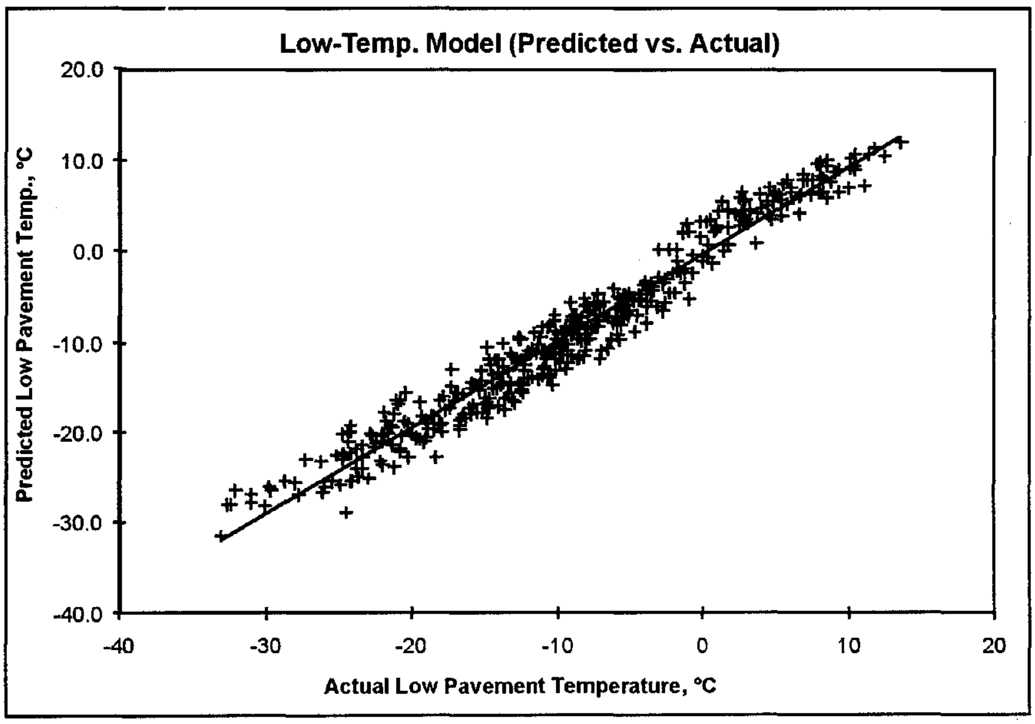

Figure 21 - Predicted Low Pavement Temperature vs. Actual Low Pavement Temperature.

7. LTPP HIGH PAVEMENT TEMPERATURE MODEL

As with the low pavement temperature model, a range of statistical analyses were performed on the data in the SAPT monthly high-temperature data base to develop a model for estimating high pavement temperature at various depths below the AC surface layer.

7.1. Data Check for Outliers

The SAPT monthly high-temperature data base was thoroughly checked for outliers. As a result of this check, a set of rules (figure 22) was developed and applied to the SAPT monthly high-temperature data base. Rule 1 limits the data to air temperatures greater than 20 °C, while rule 2 limits the pavement temperatures to less than 60 °C. These rules were set to eliminate excessively large or small temperature values. Rule 3 is for setting a limit on the difference between air and pavement temperatures (7 to 25 degrees). Rule 4 is to ensure that the pavement temperature decreases with depth. Rules 5 through 9 are for eliminating the data that were found visually to be unreasonable.

```
1. Tair>20
2. Tpav<60
3. Tpav-Tair>7  and Tpav-Tair<25
4. Tpav>Tpavm   and Tpavm>Tpavb
5. sec='08SA'
6. sec='90SA'   Month='Jun'
7. sec='48SE'   year=94  H=2.4
8. sec='48SF'   year=94  Month='May'
9. sec='33SA'   year=94  Month='Sep'
```

Figure 22 - Data Checks for the High-Temperature Data Base.

7.2. SAPT High Monthly Temperature Data Base

Filtering the high monthly temperature data base resulted in 309 temperature data points for model development. These data were tabulated by month and section in table 12. The mid-layer and bottom temperatures are listed in table 13. Data ranges are listed in table 14. The air temperature in the data base ranged from 21 °C to approximately 47 °C, while pavement temperature ranged from 31.4 °C to 58.3 °C. The ranges for latitude, depth, and elevation were similar to those in the low-temperature data base.

Table 12 - Monthly High Air and Pavement Temperatures for the Top Sensor (°C).

	1993		1994										1995					
Section	**Aug**		**May**		**June**		**July**		**August**		**Sept**		**May**		**June**		**July**	
	Bot	Mid	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top
09SA	.	.	29	45	33	52	32	53	26	48	25	43	28	49	34	52	.	.
16SB	.	.	28	49	33	52	35	54	35	53	30	43	21	43	.	.	.	.
23SA	.	.	30	46	34	51	28	50	29	48	24	39	31	47	32	54	.	.
25SA	23	34	31	48	35	54	35	53	26	48	25	44	31	51	36	55	.	.
27SA	.	.	29	50	34	53	30	54	.	.	27	43	27	48	32	54	.	.
27SB	.	.	27	47	27	50	27	47	.	.	26	38	27	48	29	47	.	.
27SC	.	.	28	46	27	49	27	46	26	44	27	40	29	48	29	50	.	.
30SA	.	.	28	48	33	52	34	53	35	50	35	43	.	.	.	.	.	.
33SA	.	.	30	43	37	49	30	47	31	44	.	.	33	48	36	49	.	.
35SA	.	.	.	.	.	.	39	57	38	56	30	48	33	51	36	54	.	.
40SA	.	.	33	53	39	57	36	58	40	58	30	51	29	53	35	55	.	.
46SB	.	.	.	.	.	.	37	50	35	49	33	43	26	44	30	48	.	.
48SA	.	.	36	57	.	.	.	.	.	.	.	.	33	52	.	.	.	.
48SB	.	.	30	51	33	57	36	58	35	56	33	51	.	.	32	54	.	.
48SE	.	.	.	.	.	.	.	.	.	.	.	.	34	53	34	52	.	.
48SF	.	.	.	.	32	56	36	55	35	55	34	52	34	52	31	53	.	.
48SG	.	.	35	55	36	57	38	57	35	55	35	54	35	53	31	52	.	.
49SB	.	.	31	52	41	56	38	57	39	55	34	47	24	38	.	.	.	.
50SA	.	.	30	44	35	53	31	49	29	44	26	38	29	45	33	51	.	.
56SA	.	.	25	49	32	53	31	53	33	52	32	46	.	.	.	.	.	.
83SA	.	.	22	39	28	45	30	45	33	41	29	37	31	41	32	46	.	.
90SA	.	.	29	37	.	.	28	41	31	42	.	.	32	41	.	.	.	.

Table 13 - Monthly High Pavement Temperature at the Bottom and Mid-Depth of the AC Layer (°C).

	1993		1994										1995					
Section	**Aug**		**May**		**June**		**July**		**August**		**Sept**		**May**		**June**		**July**	
	Bot	Mid	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top	Air	Top
09SA	.	.	.	.	.	40	.	41	.	38	.	32	.	37	.	.	.	.
16SB	.	.	.	39	.	43	.	44	.	43	.	.	.	32	.	.	.	.
23SA	.	.	.	39	.	43	38	42	37	40	.	32	.	38	40	45	.	.
25SA	31	34	.	.	.	44	.	44	34	39	.	33	.	38	.	.	.	.
27SA	.	.	40	44	42	47	42	46	37	41	35	39	38	42	45	49	41	47
27SB	.	.	.	39	35	43	.	40	.	.	.	.	.	39	.	39	.	.
27SC	.	.	.	40	38	43	35	40	34	39	.	35	36	42	38	44	.	.
30SA	.	.	39	43	45	48	44	48	44	47	.	.	.	.	.	.	.	.
33SA	.	.	.	.	.	.	.	39	.	.	.	.	.	.	.	.	.	.
35SA	.	.	.	.	.	.	53	56	51	54	43	45	45	48	49	52	.	.
40SA	.	.	41	46	.	51	45	50	.	48	.	40	.	40	.	43	.	.
46SB	.	.	.	.	.	.	.	.	.	42	.	.	34	38	39	42	.	.
48SA	.	.	45	49	.	55	48	53	.	.	.	.	41	43	.	.	.	.
48SB	.	.	40	44	44	48	46	51	44	49	41	45	.	40	41	45	.	.
48SE	.	.	.	.	.	.	.	.	.	.	.	.	44	49	44	49	.	.
48SF	.	.	.	.	41	47	44	48	44	48	42	45	.	46	42	46	.	.
48SG	.	.	50	52	52	54	53	54	52	53	47	50	49	51	47	49	.	.
49SB	.	.	40	45	.	51	48	51	47	51	.	43	.	34	.	.	.	.
50SA	.	.	.	37	.	46	.	42	.	38	.	.	.	37	.	43	.	.
56SA	.	.	42	46	47	50	45	49	45	49	.	42	.	.	.	.	.	.
83SA	.	.	32	36	37	41	38	41	.	.	.	.	.	38	.	43	.	.
90SA	.	.	.	37	.	.	35	40	39	41	.	.	.	40	.	.	.	.

Table 14 - Ranges of Data for the High-Temperature Model.

Variable	N	Mean	Sum	Minimum	Maximum
T_{pav}	309	45.66673	14111	31.4	58.27
T_{air}	309	31.50324	9734.5	21.12	46.92
Lat	309	40.46939	12505	26.983	51.908
H	309	68.48136	21161	25.4	274.32
Elev	309	495.98058	153258	11	1586

7.3. Correlation Analysis of High-Temperature Variables

A correlation matrix with similar variables that was considered for the low-temperature model was created (table 15). Once again, T_{air} and Lat showed a good correlation with T_{pav} (r=0.67 and -0.49, respectively). The non-linear terms of Lat and Lat^2 had an even better correlation (r=0.5). The correlation between T_{pav} and H was a lot stronger than for the low-temperature model (r=0.5). The non-linear terms for H and *log*H had an even stronger correlation (r=-0.56). The correlation between T_{pav} and Elev was insignificant. The correlation between T_{air} and Lat was nonexistent (r=0).

Table 15 - Pearson Correlation Coefficients for the High-Temperature Model.

	T_{pav}	T_{air}	Lat	Lat^2	*log*Lat	H	H^2	*log*H	T_{air}*Lat	T_{air}*H	Elev
T_{pav}	1.	0.67	-0.49	-0.5	-0.48	-0.5	-0.39	-0.56	0.	-0.38	0.07
T_{air}	0.67	1.	-0.54	-0.54	-0.53	-0.04	-0.02	-0.04	0.23	0.13	0.09
Lat	-0.49	-0.54	1.	1.	1.	-0.03	-0.04	-0.02	0.69	-0.13	0.23
Lat^2	-0.5	-0.54	1.	1.	0.99	-0.03	-0.04	-0.02	0.68	-0.13	0.21
*log*Lat	-0.48	-0.53	1.	0.99	1.	-0.03	-0.04	-0.01	0.7	-0.12	0.25
H	-0.5	-0.04	-0.03	-0.03	-0.03	1.	0.94	0.97	-0.07	0.98	-0.09
H^2	-0.39	-0.02	-0.04	-0.04	-0.04	0.94	1.	0.83	-0.07	0.93	-0.1
*log*H	-0.56	-0.04	-0.02	-0.02	-0.01	0.97	0.83	1.	-0.06	0.94	-0.06
T_{air}*Lat	0.	0.23	0.69	0.68	0.7	-0.07	-0.07	-0.06	1.	-0.04	0.34
T_{air}*H	-0.38	0.13	-0.13	-0.13	-0.12	0.98	0.93	0.94	-0.04	1.	-0.07
Elev	0.07	0.09	0.23	0.21	0.25	-0.09	-0.1	-0.06	0.34	-0.07	1.

From this analysis, it appeared that T_{air}, Lat, and H could be major factors in the model. To find the type of relation between these variables (independent variables) and the dependent variable (T_{pav}), the dependent variable was graphed against independent variables (T_{air}, Lat, and H). Figure 23 shows that the relation between T_{pav} and T_{air} appears to be linear. On the other hand, figures 24 and 25 show that the relation between T_{pav} and Lat and the relation between T_{pav} and H are non-linear.

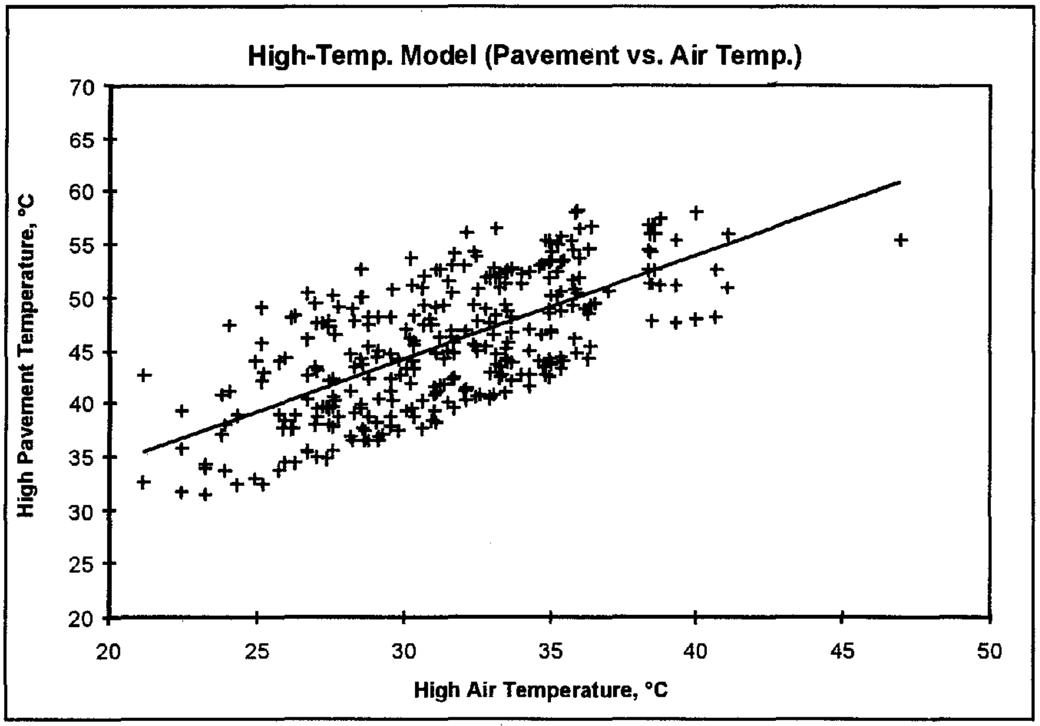

Figure 23 - High Pavement Temperature vs. High Air Temperature.

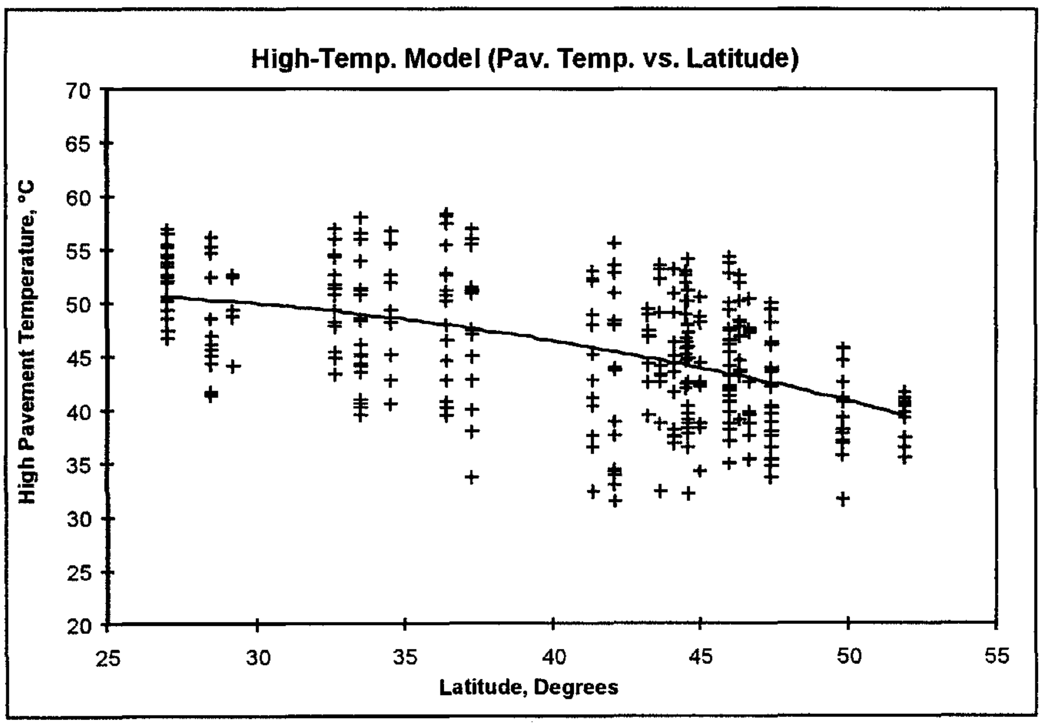

Figure 24 - High Pavement Temperature vs. Latitude.

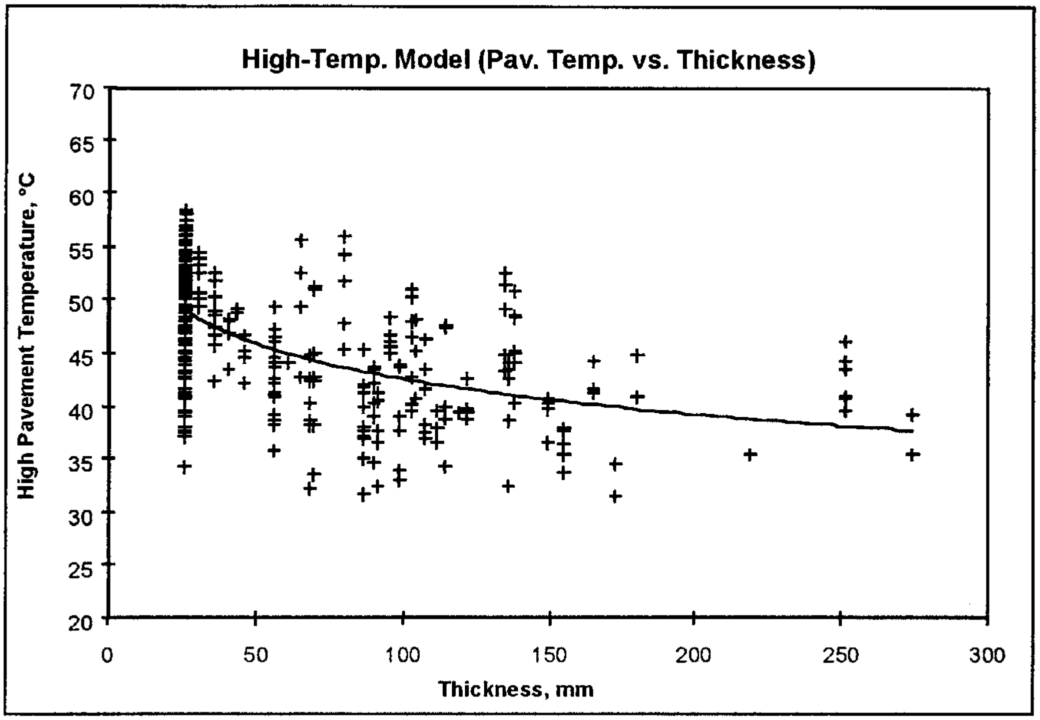

Figure 25 - High Pavement Temperature vs. Thickness.

7.4. Variable Selection for the High-Temperature Model

In order to select independent variables for the high-temperature model, a stepwise regression method was used. Several linear, non-linear, and interaction terms, as shown in figure 16, were considered in the stepwise procedure. The final output of the statistical procedure is shown in figure 26. Of 13 possible terms, only the 6 variables shown in figure 26 met the 0.15 significance level. The strongest terms were T_{air}, *log*H, and Lat^2. The contribution of other terms to R^2 was very low.

Variable Step	Entered	Removed	Number In	Partial R**2	Model R**2	F	Prob>F
1	AIR		1	0.4506	0.4506	251.7646	0.0001
2	LOGH		2	0.2767	0.7273	310.4991	0.0001
3	LAT2		3	0.0344	0.7617	43.9930	0.0001
4	AIRLATH		4	0.0163	0.7780	22.3262	0.0001
5	LOGLAT		5	0.0041	0.7821	5.7595	0.0170
6	AIRLAT		6	0.0042	0.7863	5.9810	0.0150

Figure 26 - Final Output of the Stepwise Regression for the High-Temperature Model.

7.5. *High-Temperature Model Functional Form*

Several functional forms (similar to those developed for the low-temperature model) were considered for the high-temperature model. Models took the general form of equation 6 and their regression coefficients are shown in table 16. Incorporating Elev into the model slightly increased the fit; however, since the coefficient is very low, this term becomes insignificant.

Table 16 - Regression Coefficients for the High-Temperature Models.

No.	Int.	T_{air}	Lat	Lat^2	*log*Lat	H	H^2	*log*H	T_{air}*Lat	T_{air} * H	Elev	R^2	SEE
1	22.46	0.7521	0.5427	-0.0096		-0.133	0.00035				3.9E-4	0.765	3.003
2	20.53	0.7648	0.6239	-0.0105		-0.133	0.00035					0.764	3.003
3	33.53	0.7196		-0.0027		-0.145	0.00034			0.00047	5.4E-4	0.762	3.017
4	-29.6	1.7270			49.72			-15.3	-0.02361		4.4E-4	0.762	3.018
5	31.95	0.7692		-0.0025		-0.130	0.00034					0.762	3.020
6	33.06	0.7332		-0.0025		-0.147	0.00034			0.00054		0.761	3.023
7	45.85	0.7728	0.4646	-0.0085				-15.2				0.761	3.029
8	54.77	0.7596		-0.0026				-15.1			4.8E-4	0.760	3.032
9*	54.32	0.7759		-0.0025				-15.1				0.759	3.036
10	55.01	0.7379		-0.0029				-15.1	0.00092			0.759	3.041
11	76.30	0.7741			-16.66			-15.0			5.5E-4	0.756	3.058
12	73.9	0.7938			-15.30			-15.0				0.755	3.064
13	30.77	0.7283		-0.0025		-0.083				0.00082		0.711	3.329
14	31.06	0.7193		-0.0026		-0.081				0.00078	3.5E-4	0.710	3.330
15	33.01	0.7741	-0.2000			-0.056					4.2E-4	0.710	3.335
16	30.42	0.7483		-0.0023		-0.083			-0.00050	0.00083		0.710	3.335
	32.31	0.7888	-0.1886			-0.056						0.710	3.335

* Best Model

7.6. *LTPP High-Temperature Model*

The following terms were selected for the high pavement temperature model based on the results of the correlation analysis, variable selection, and trial models:

> Air Temperature (T_{air}): T_{air} had the highest correlation with pavement temperature (T_{pav}) and the relation was found to be linear. In the variable selection process, T_{air} was also found to be the strongest term in the model.
>
> Latitude (Lat): The relation between Lat and T_{pav} was found to be rather strong and non-linear. Therefore, the terms Lat^2 and *log*Lat were considered in the variable selection. It was found that Lat^2 was the better term.
>
> Depth (H): H was found to have a stronger correlation with T_{pav}. Since the relation was non-linear, the terms H^2 and *log*(H+25) were considered. It was found by trial and error that *log*(H+25) provides a better fit to the data.

Based on the fit and variability of the model, it was decided that model number 9 in table 16 (also equation 8) was the best practical model. When this model was tested for values within the range of the data base, it proved to produce reasonable results.

$$T_{pav} = 54.32 + 0.78\, T_{air} - 0.0025\, Lat^2 - 15.14\, log_{10}(H+25) \quad (8)$$

Where: T_{pav}= High AC pavement temperature below the surface, °C.
T_{air}= High air temperature, °C.
Lat= Latitude of the section, degrees.
H= Depth to surface, mm.
R^2= 76%
N= 309
RMSE= 3.0

Equation 8 - LTPP High Pavement Temperature Model.

7.7. Residual Analysis of the High-Temperature Model

The residuals of the high pavement temperature model vs. Lat, T_{air}, and H are shown in figures 27 through 29, respectively. The residuals seem to be randomly distributed with Lat and T_{air}. They were also randomly scattered with thickness (H) up to a depth of 200 mm. At more than 200 mm of depth, however, the model tends to underestimate the temperature. This is due to the low-temperature differentials (between the top and bottom sensors) observed for some thicker pavements. The residuals ranged between -8.8 °C and 8.3 °C. Figure 30 shows the predicted vs. actual high pavement temperature.

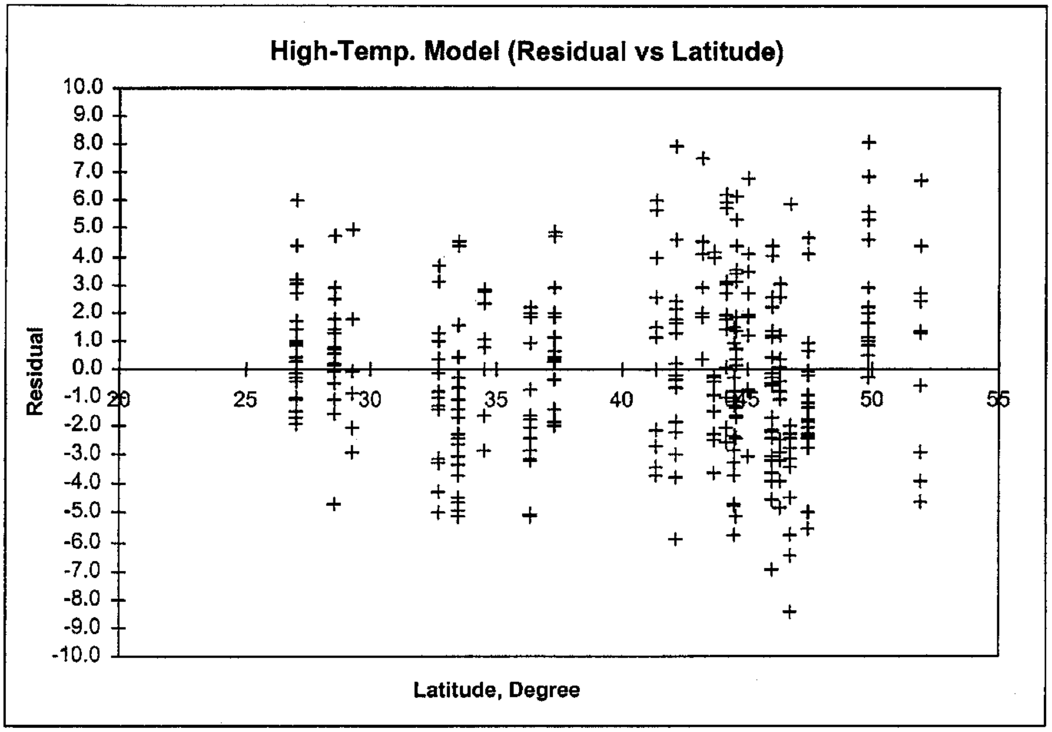

Figure 27 - Residual of High-Temperature Model Versus Latitude.

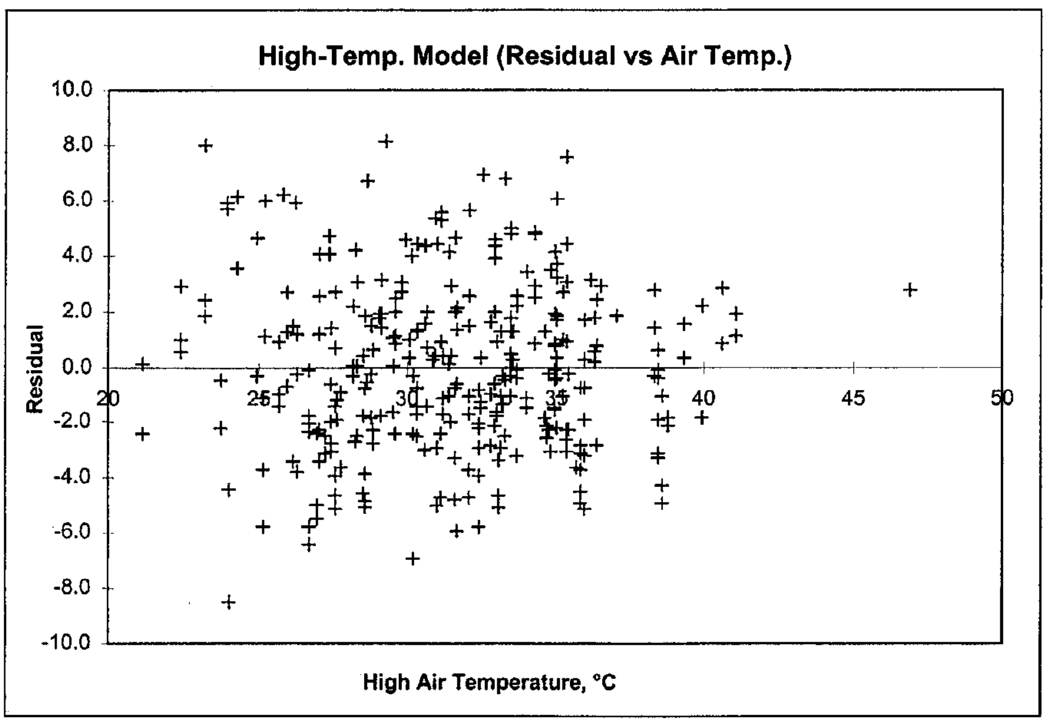

Figure 28 - Residual of High-Temperature Model Versus High Air Temperature.

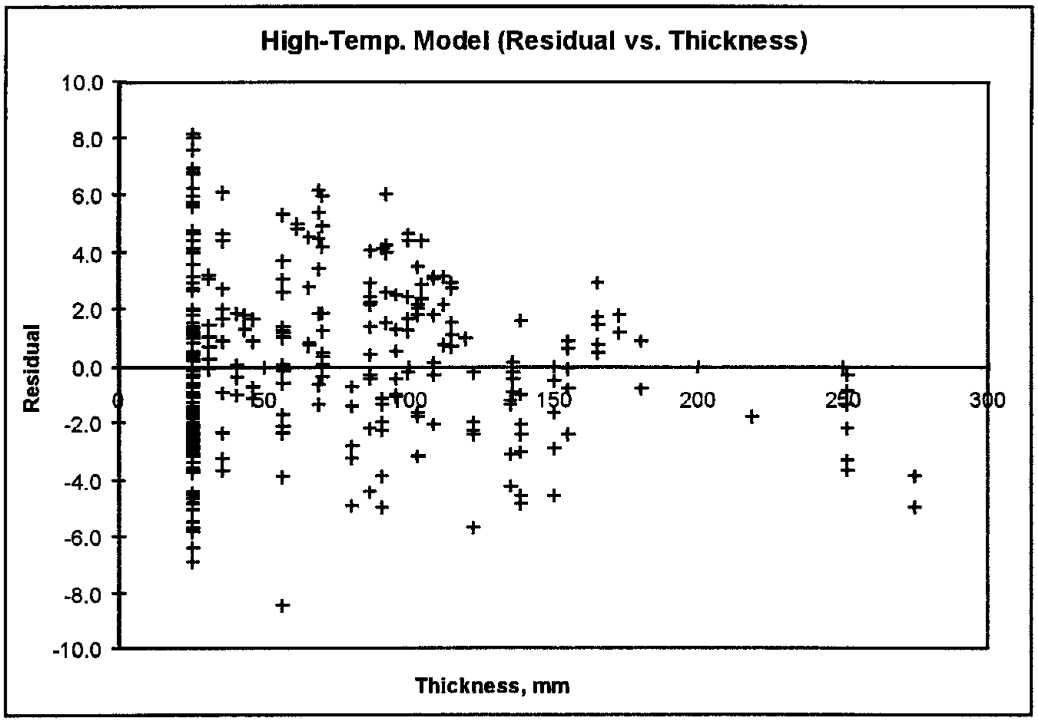

Figure 29 - Residual of the High-Temperature Model vs. Thickness.

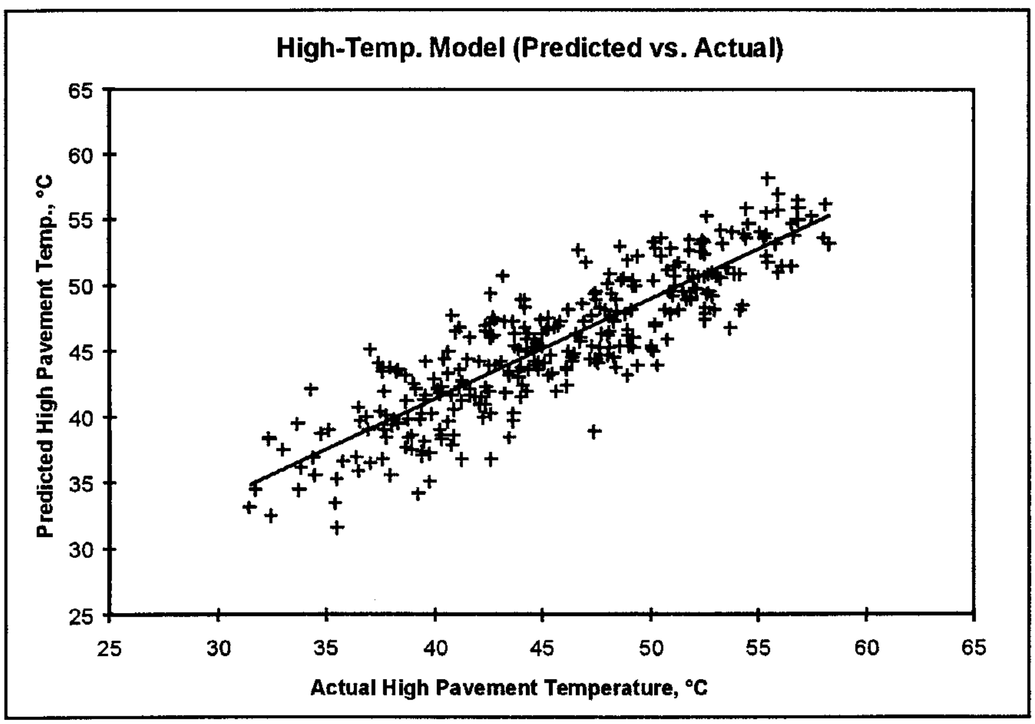

Figure 30 - Predicted High Pavement Temperature vs. Actual High Pavement Temperature.

8. COMPARING THE SHRP MODELS WITH THE LTPP MODELS

The existing high and low pavement temperature models used by SHRP and C-SHRP were compared with the models developed under this study (LTPP models) to demonstrate the differences between the models. Models were compared at 50-percent mean air and pavement reliability levels.

8.1. Comparing the SHRP and LTPP Low-Temperature Models

The existing SHRP and C-SHRP models (section 5.1) were used to derive the design low pavement temperature for determining low-temperature performance grades. Figure 31 shows the pavement surface temperature calculated using SHRP and C-SHRP models for any latitude, and the pavement surface temperature calculated using LTPP models for three different latitudes (30, 40, and 50 degrees for the Southern, Central, and Northern United States, respectively). As figure 31 shows, the low pavement temperature determined by the SHRP model (the equality line) can be as much as 15 degrees lower than the low pavement temperature estimated by the LTPP model for an air temperature of -40 °C. Thus, the current SHRP model is very conservative, especially at lower air temperatures.

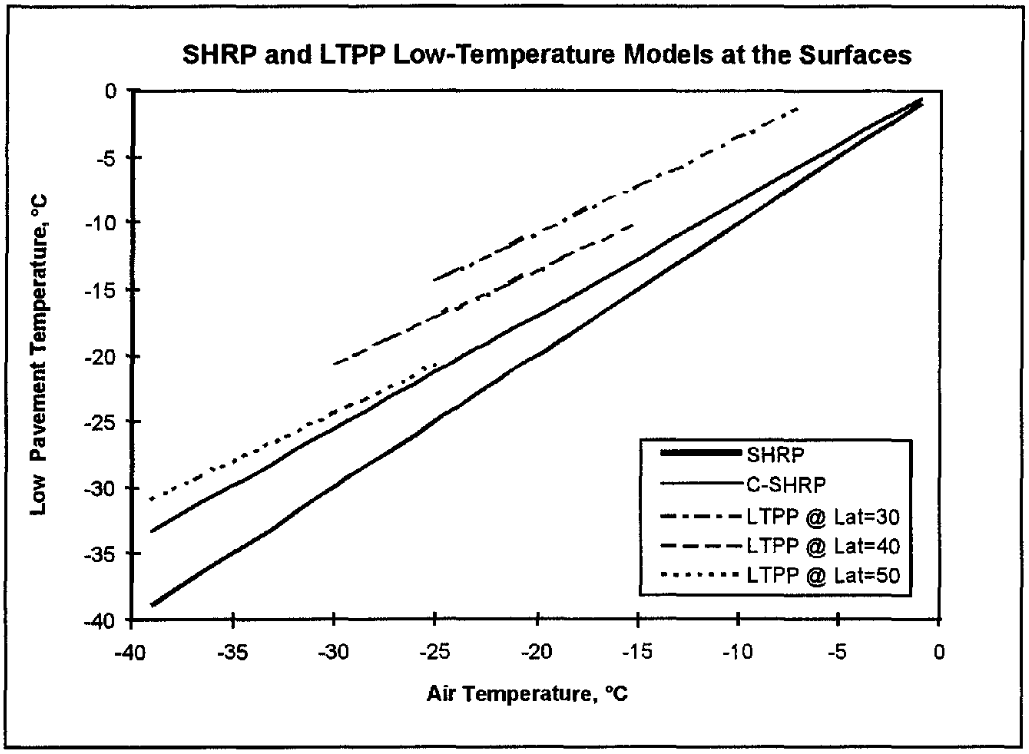

Figure 31 - Low Pavement Temperature at the Surfaces by the C-SHRP and LTPP Models.

Figure 31 also shows that the C-SHRP model, mainly developed from Canadian data, has relatively good agreement with the LTPP model at a latitude of 50 degrees, where most Canadian sites are located. However, the estimated temperatures by the C-SHRP model may be as much as 10 degrees lower than the LTPP model at lower latitudes (most parts of the United States), because the C-SHRP model does not include latitude. Therefore, the C-SHRP model is mainly applicable to higher latitudes (Northern United States and Canada).

8.2. Comparing the SHRP Low-Temperature Data With the LTPP Model

Limited low pavement temperature data were available at the time SHRP developed its low pavement temperature model. At that time, only a few pavement sites in Maryland, New York, South Dakota, and Saskatchewan had been instrumented with temperature probes. Data from these sites were used to develop the SHRP low pavement temperature model.[4] Due to the lack of sufficient data, SHRP decided on a very conservative estimate – low pavement temperature equals low air temperature.

Figure 32 shows the measured low-temperature data used by SHRP vs. the LTPP estimate.[4] As can be seen from figure 32, the LTPP model provided low pavement temperature estimates that were close to the original SHRP data. The LTPP estimates were in better agreement with the SHRP data closer to the surface layer.

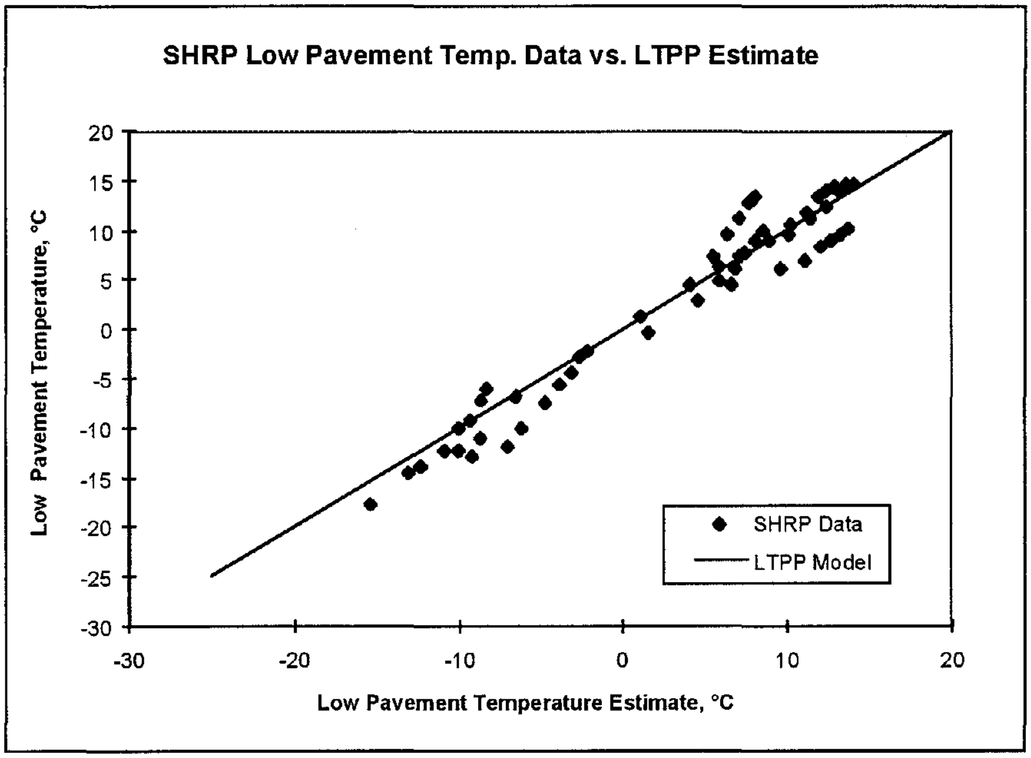

Figure 32 - SHRP Low Pavement Temperature Data vs. the LTPP Low Pavement Temperature Estimate.

8.3. Comparing the LTPP Low-Temperature Model With SMP Data

To achieve a better range of data, low monthly temperature data were used to develop the low pavement temperature model. To show the feasibility of using the model for yearly estimates, the yearly low SMP temperature vs. the LTPP estimate is shown in figure 33. It shows that the LTPP estimates are generally 1 °C lower than the SMP yearly low pavement temperature data. Therefore, using the monthly data has resulted in a more conservative estimate of the low pavement temperature and has provided higher model reliability than reported.

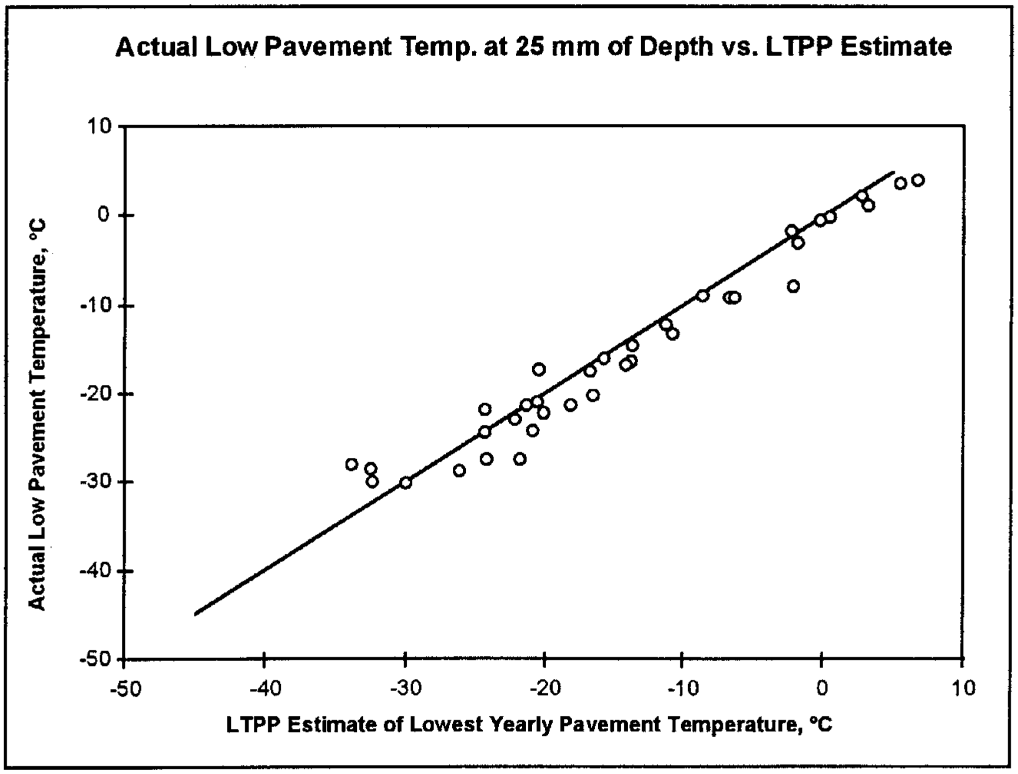

Figure 33 - Actual Low Pavement Temperature vs. LTPP Estimate at 25 mm of Depth.

8.4. Comparing the SHRP and LTPP High-Temperature Models

The SHRP high pavement temperature model was compared with the LTPP model. Figure 34 shows high pavement temperature at a depth of 20 mm vs. air temperature for the SHRP and LTPP models at two different latitudes. As can be seen from figure 34, the SHRP and LTPP models are in good agreement for air temperatures of less than 25 °C. At higher temperatures, however, the SHRP estimate may be as much as 5 degrees higher than the LTPP estimate.

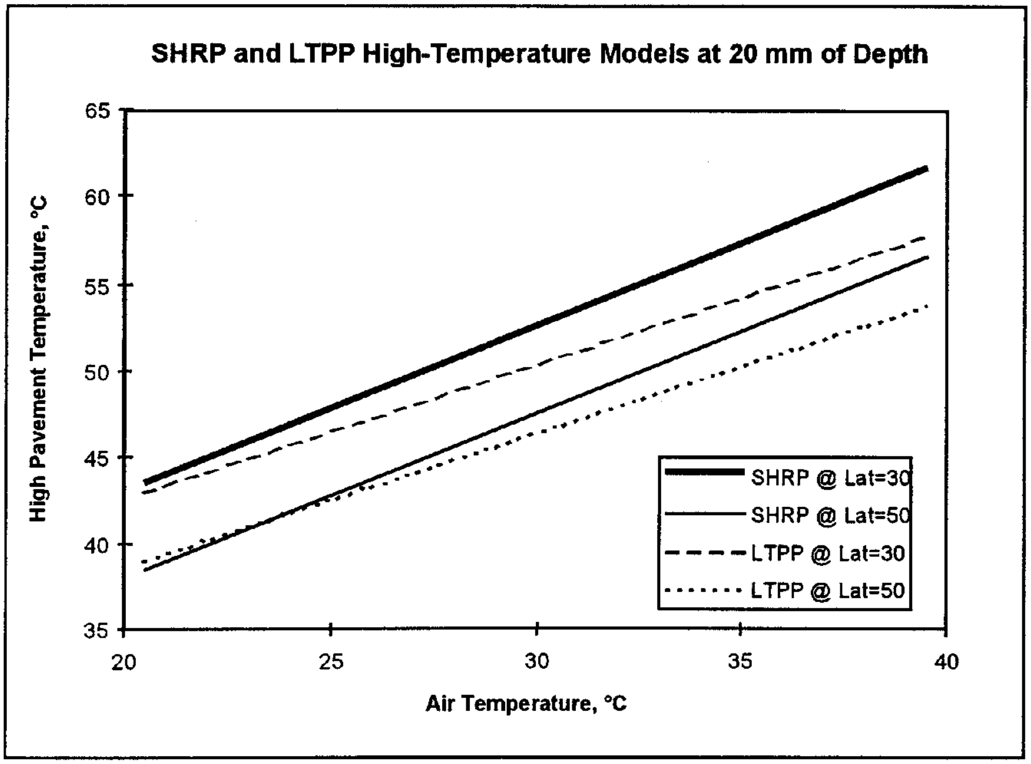

Figure 34 - High Pavement Temperatures at 20 mm of Depth by the SHRP and LTPP Models.

8.5. Comparing the LTPP High-Temperature Model With SMP Data

Monthly high-temperature data were used to develop LTPP high-temperature models; however, the high mean 7-day temperature is used for calculating high-temperature performance grades. Figure 35 shows the high mean 7-day temperature vs. high pavement temperature. It illustrates that there is a good correlation between high yearly temperatures and high mean 7-day averages.

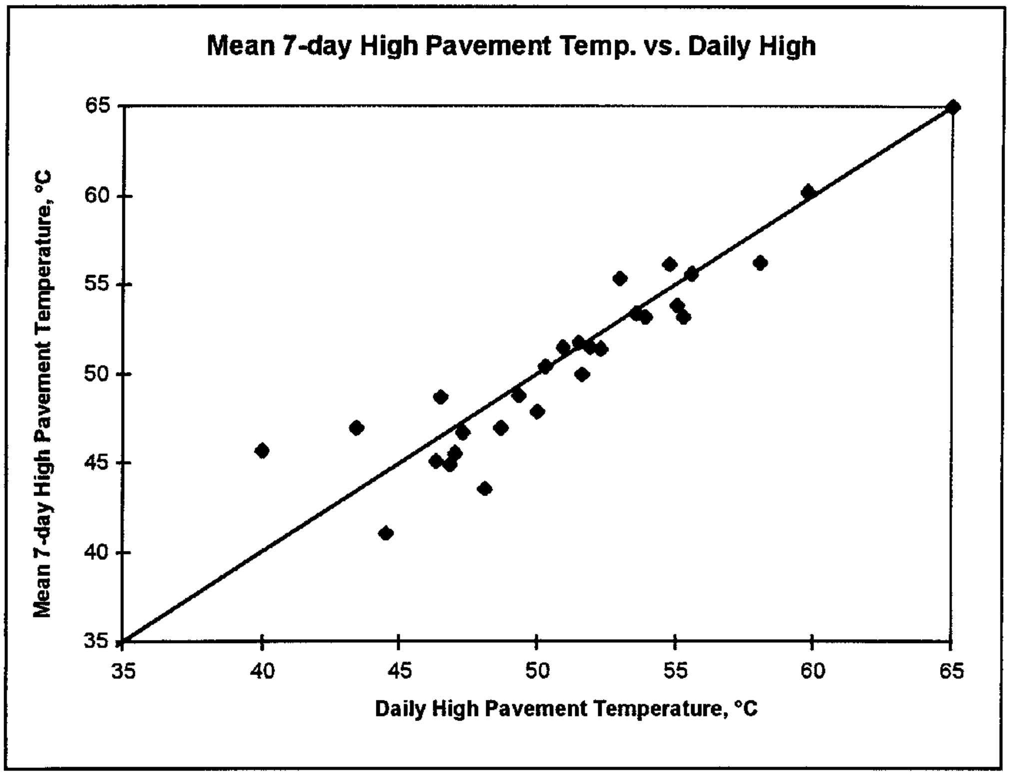

Figure 35 - Mean 7-Day High Pavement Temperature vs. Daily High Pavement Temperature.

Figure 36 shows the SMP yearly high mean 7-day temperature and the LTPP estimated temperature. It shows that the LTPP estimated temperatures are within 5 degrees of the actual SMP data.

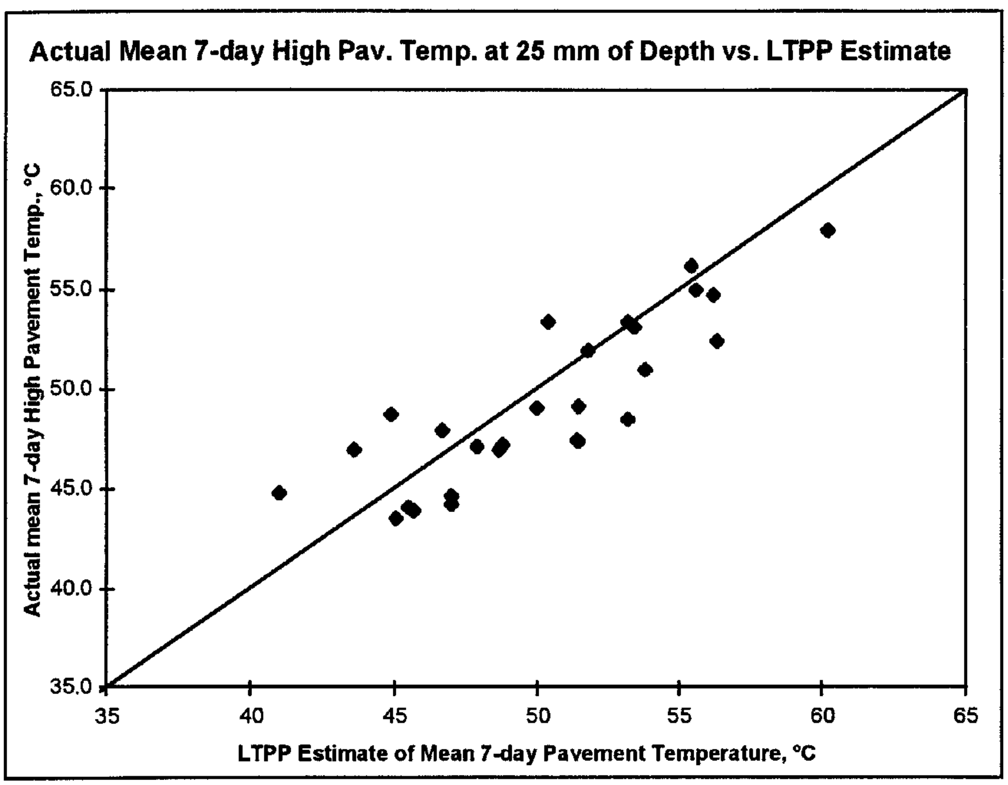

Figure 36 - Actual Mean 7-Day High Pavement Temperature vs. the LTPP Estimate at 25 mm of Depth.

8.6. Comparing the Temperature Profiles of the SHRP and LTPP Models

Pavement temperature profiles (pavement temperature vs. depth) for SHRP and LTPP low- and high-temperature models are compared in this section. Figure 37 shows low pavement temperature vs. depth for SHRP and LTPP models. Both temperature profiles are shown for the surface temperature of 0 °C. The LTPP model shows more non-linear behavior, especially close to the surface of the pavement. The LTPP pavement temperature leveled out at higher depths, while the SHRP temperature increased at a higher rate at depths of greater than 200 mm.

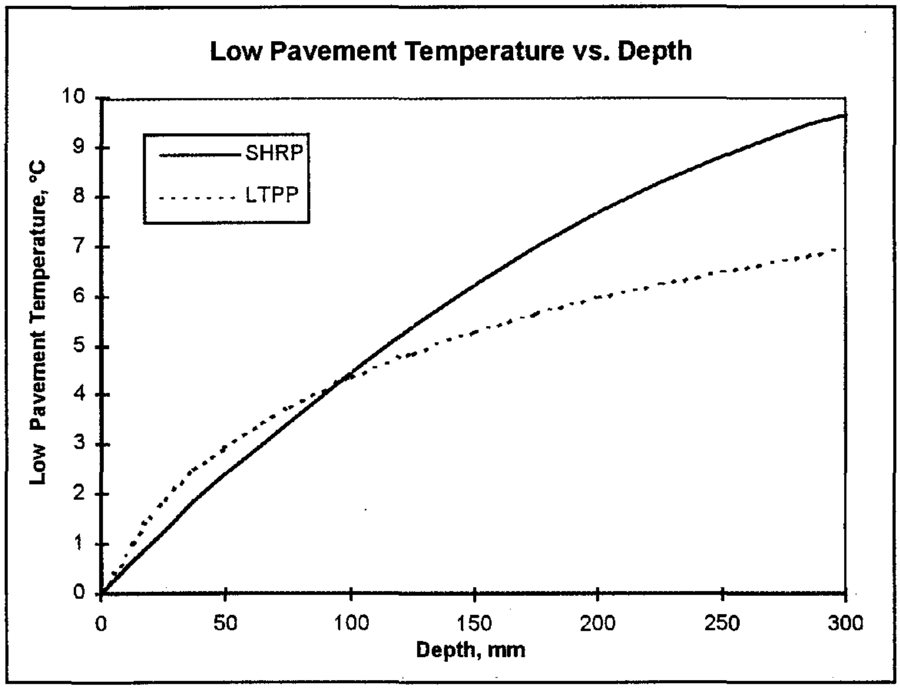

Figure 37 - Low Pavement Temperature Profile vs. Depth for the SHRP and LTPP Models.

The high pavement temperature profiles for LTPP and SHRP models for the surface temperature of 50 °C are shown in figure 38. The LTPP model agrees with the SHRP model close to the surface (depth of less than 100 mm). At higher depths, however, the LTPP model leveled out, while the SHRP model did not.

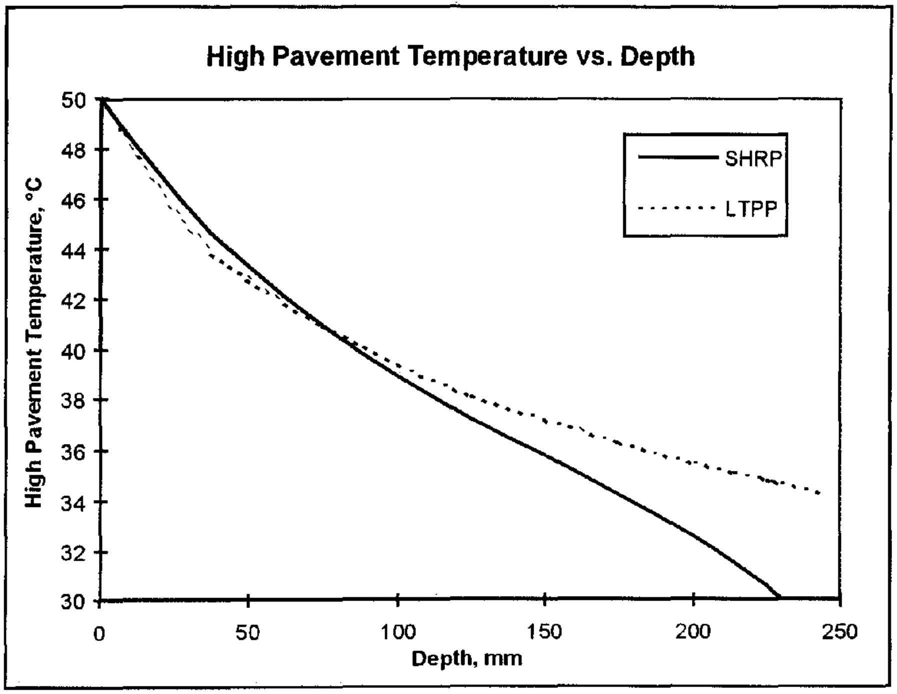

Figure 38 - High Pavement Temperature Profile vs. Depth for the SHRP and LTPP Models.

9. Pavement Temperature Reliability

Two different types of variability can be considered when determining design pavement temperatures – mean air temperature and estimated pavement temperature. The standard deviation of the mean air temperature (low and high) is used for air temperature variability, and the Root Mean Square Error (RMSE) of the model is considered for pavement temperature model (low and high) variability.

The LTPP low-temperature model (equation 7) may be used for calculating low pavement temperatures at 50-percent reliability levels. However, at reliability levels higher than 50 percent, a more rigorous equation should be used. Equation 9 includes the reliability term and should be used to calculate low pavement temperatures at a desired level of reliability. SHRP and LTPP estimated temperatures at different reliability levels are shown in figure 39.

$$T_{pav} = -1.56 + 0.72\,T_{air} - 0.004\,\mathrm{Lat}^2 + 6.26\,log_{10}(H+25) - z\,(4.4 + 0.52\,(\sigma_{air})^2)^{1/2} \quad (9)$$

Where: T_{pav}= Low AC pavement temperature below the surface, °C.
T_{air}= Mean annual low air temperature, °C.
Lat= Latitude of the section, degrees.
H= Depth to surface, mm.
σ_{air}= Standard deviation of the mean low air temperature, °C.
z= From the standard normal distribution table, z = 2.055 for 98% reliability.

Equation 9 - LTPP Low Pavement Temperature Model With Reliability.

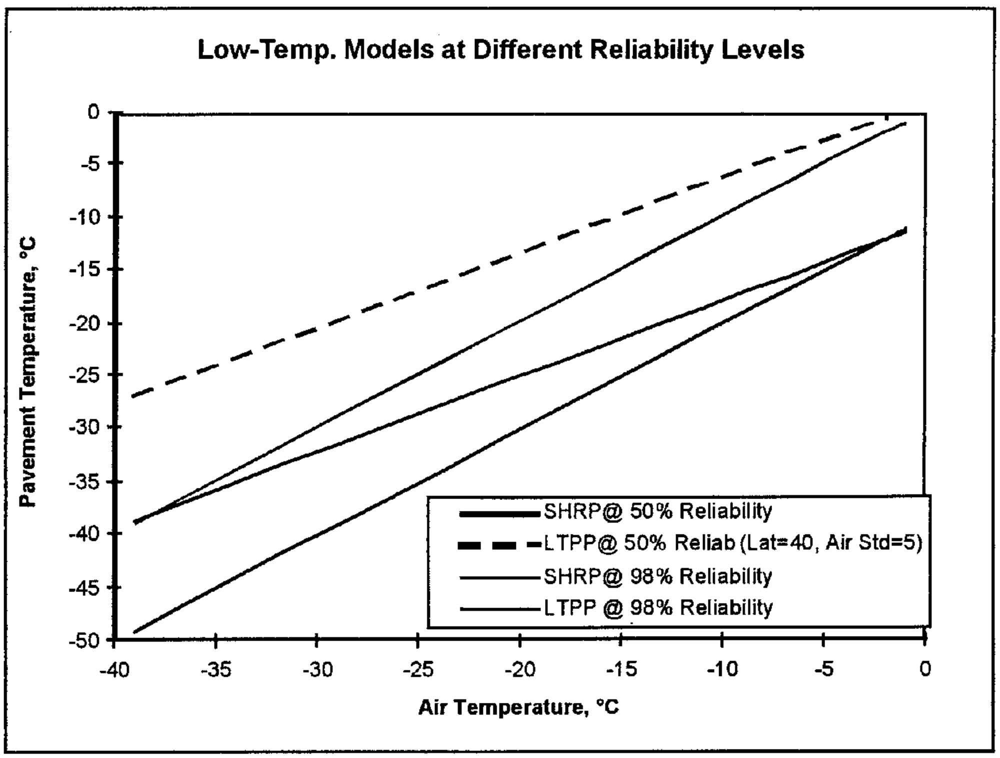

Figure 39 - SHRP and LTPP Models at Different Reliability Levels (Surface Condition).

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The last term in equation 9 is the error term, which is related to the uncertainty in estimating the correct pavement temperature. The error term was subtracted from the low pavement temperature equation to provide higher reliability. Two different variabilities – mean air temperature and the model – cause the uncertainty. These variabilities are designated by the standard deviation of the mean air temperature (σ_{air}) and the SEE of the model (σ_{model}). The variability in estimated pavement temperature (σ_{pav}) due to both mean air temperature and model variability is calculated as follows:

$$\sigma_{pav} = (\sigma_{model}{}^2 + (0.72\ \sigma_{air})^2)^{1/2}$$

Substituting the value of σ_{model} (2.1 °C) in the above equation and reworking the equation yields:

$$\sigma_{pav} = (2.1^2 + 0.72^2\ \sigma_{air}{}^2)^{1/2}$$
$$\sigma_{pav} = (4.4 + 0.52\ \sigma_{air}{}^2)^{1/2}$$

The error term in equation 7 is calculated from the pavement temperature variability (σ_{pav}) and the number of standard deviations (z) in a one-way distribution for a desired reliability as follows:

$$\varepsilon = z\ (4.4 + 0.52\ \sigma_{air}{}^2)^{1/2}$$

The following example shows the application of the low-temperature model to a real condition. The temperature data from a weather station (site) in Urbana, IL, are used in the following example:

Weather Station / County	=	Urbana / Champaign
Latitude	=	40.10 degrees
Years of Climatic Data	=	87 years
Mean of Annual Low Temperature	=	-23 °C
Low-Temp. Standard Deviation	=	3.9 °C

The calculation of 50-percent and 98-percent reliability low pavement surface temperatures follows. Note that z is zero for 50-percent reliability (error term equals zero) and 2.055 for 98-percent reliability.

$$T_{pav} = -1.56 + (0.72 * -23) - (0.004 * 40.1^2) + 6.26\ log_{10}(0+25) - 0\ (4.4 + 0.52 * 3.9^2)^{1/2}$$
50% Reliability Surface T_{pav} = -15.80 °C

$$T_{pav} = -1.56 + (0.72 * -23) - (0.004 * 40.1^2) + 6.26\ log_{10}(0+25) - 2.055\ (4.4 + 0.52 * 3.9^2)^{1/2}$$
98% Reliability Surface T_{pav} = -15.80 - 7.21 = -23.01 °C

The 98-percent reliability low pavement temperature at a depth of 75 mm (about 3 in) for this site is calculated as follows:

$$T_{pav} = -1.56 + (0.72 * -23) - (0.004 * 40.1^2 + 6.26\ log_{10}(75+25) - 2.055\ (4.4 + 0.52 * 3.9^2)^{1/2}$$
98% Reliability T_{pav} @ 75 mm = -19.24 °C

Figure 39 shows that SHRP's estimated temperature at 98-percent reliability (for surface conditions at a latitude of 40 degrees) could be up to 10 degrees lower than the LTPP estimate at a similar level of reliability.

Equation 10 was used to calculate the high pavement temperature at reliability levels of greater than 50 percent. For high temperatures, pavement temperatures were increased for higher reliability.

$$T_{pav} = 54.32 + 0.78\, T_{air} - 0.0025\, Lat^2 - 15.14\, log_{10}(H+25) + z\,(9 + 0.61\, \sigma_{air}^2)^{1/2} \qquad (10)$$

Where:

	T_{pav}=	High AC pavement temperature below the surface, °C.
	T_{air}=	High air temperature, °C.
	Lat=	Latitude of the section, degrees.
	H=	Depth to surface, mm.
	σ_{air}=	Standard deviation of the high 7-day mean air temperature, °C.
	z=	From the standard normal distribution table, z = 2.055 for 98% reliability.

Equation 10 - LTPP High Pavement Temperature Model With Reliability.

The last term in equation 10 (the error term) is related to the pavement temperature reliability and is calculated similarly to the low-temperature model. The term was derived as follows:

$$\sigma_{pav} = (\sigma_{model}^2 + (0.78\, \sigma_{air})^2)^{1/2}$$

Substituting the value of σ_{model} (3.0 °C) in the above equation and reworking the equation yields:

$$\sigma_{pav} = (3.0^2 + 0.78^2\, \sigma_{air}^2)^{1/2}$$
$$\sigma_{pav} = (9.0 + 0.61\, \sigma_{air}^2)^{1/2}$$

The error term in equation 8 (ε) is calculated from the pavement temperature standard deviation (σ_{pav}) and the number of standard deviations (z, one tail) for a desired reliability level as follows:

$$\varepsilon = z\,(9.0 + 0.61\, \sigma_{air}^2)^{1/2}$$

Please note that the error term adds to the high pavement temperature model, thus increasing the pavement temperature as reliability increases. The following example shows the application of the high-temperature model to a real condition. The temperature data from a weather station (site) in Urbana, IL, are used in this example as listed below:

Weather Station / County	=	Urbana / Champaign
Latitude	=	40.10 degrees
Years of Climatic Data	=	87 years
High 7-Day Mean Air Temperature	=	33 °C
Mean High Standard Deviation	=	1.7 °C

The calculation of 50-percent and 98-percent reliability high pavement temperatures at a depth of 20 mm follows. Note that z is zero for 50-percent reliability (error term equals zero) and 2.055 for 98-percent reliability.

$$T_{pav} = 54.32 + (0.78 * 33) - (0.0025 * 40.1^2) - 15.14\ log_{10}(20+25) + 0\ (9 + 0.61 * 1.7^2)^{1/2}$$

50% Reliability @ 20 mm T_{pav} = 51.01 °C

$$T_{pav} = 54.32 + (0.78 * 33) - (0.0025 * 40.1^2) - 15.14\ log_{10}(20+25) + 2.055\ (9 + 0.61 * 1.7^2)^{1/2}$$

98% Reliability @ 20 mm T_{pav} = 57.75 °C

Figure 40 shows that SHRP's estimated temperature at 50-percent reliability (for a depth of 20 mm and a latitude of 40 degrees) can be up to 4 degrees higher than the LTPP estimate at a similar level of reliability. At 98-percent reliability, however, the LTPP estimate was higher than SHRP's. This is because the pavement temperature model variability was not considered in the SHRP model.

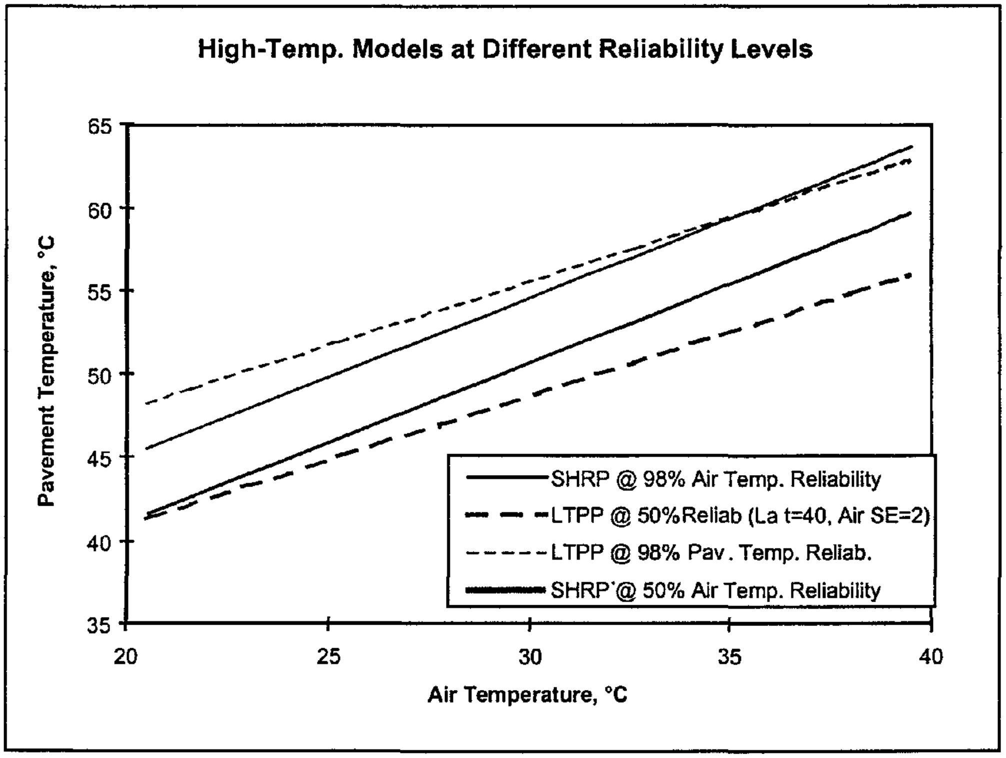

Figure 40 - SHRP and LTPP Models at Different Reliability Levels (Depth of 20 mm).

10. COMPARING PERFORMANCE GRADES DERIVED FROM THE LTPP AND SHRP MODELS

In this section, the LTPP and SHRP low and high pavement temperature models are used to calculate the design low and high pavement temperatures from air temperatures for selected weather stations throughout the United States and Canada. The asphalt performance grades are determined from the calculated pavement temperatures at different reliability levels. The differences in the resulting asphalt performance grades between the SHRP and LTPP models are demonstrated.

10.1. Comparing Performance Grades for Sample Weather Stations

One weather station for each State or Province (62 weather stations) was randomly selected from a pool of 7,801 weather stations in the United States and Canada. This data base provided a reasonable range of data for testing the LTPP models. SHRP and LTPP models were used to calculate low and high pavement temperatures from air temperatures for the sample weather stations.

The low and high air and pavement temperatures at a 50-percent reliability level and the calculated performance grades for 50-percent and 98-percent reliability levels are listed in table 17. The resulting low-temperature performance grades using LTPP models are one or two performance grades higher than SHRP models. The resulting high-temperature performance grades using LTPP models are similar to SHRP performance grades more than half the time, and are typically one performance grade lower in other cases.

The calculated high and low pavement temperatures using SHRP and LTPP models at a 50-percent reliability level vs. air temperature are shown in figures 41 and 42, respectively. Figures 41 and 42 show that for these weather stations, the high pavement temperatures calculated using the LTPP model are generally 2 to 3 degrees lower than the SHRP model. The low temperatures from the LTPP model are about 7 to 8 degrees higher than the SHRP model.

Table 17 - SHRP and LTPP Pavement Temperatures and Performance Grades for Selected Weather Stations.

State	Weather Station	Latitude	Air High	Air Low	SHRP Pav. High	SHRP Pav. Low	LTPP Pav. High	LTPP Pav. Low	50% PG SHRP	50% PG LTPP	98% PG SHRP	98% PG LTPP
AK	Juneau AP	58.4	23.0	-22.0	37.3	-22.0	38.7	-22.3	40-22	40-28	46-34	46-34
AL	Headland	31.4	36.0	-9.0	58.1	-9.0	54.9	-3.2	64-10	58-10	64-16	64-10
AR	El Dorado FAA AP	33.2	37.0	-11.0	58.8	-11.0	55.4	-5.1	64-16	58-10	64-22	64-16
AZ	Fort Thomas 2 SW	33.0	40.0	-10.0	61.7	-10.0	57.8	-4.4	64-10	58-10	64-16	70-16
BC	Rock Creek	49.1	34.0	-31.0	51.7	-31.0	49.8	-24.8	52-34	52-28	64-46	64-40
CA	Alturas R S	41.5	35.0	-24.0	55.0	-24.0	52.3	-17.0	58-28	58-22	64-40	64-28
CO	Rangely 1 E	40.1	36.0	-31.0	56.3	-31.0	53.4	-21.6	58-34	58-22	64-46	64-34
CT	Shepaug Dam	41.7	30.0	-24.0	50.2	-24.0	48.3	-17.1	52-28	52-22	58-34	58-28
DE	Milford 2 WSW	38.9	34.0	-16.0	54.7	-16.0	52.0	-10.4	58-16	58-16	64-22	64-22
FL	Avon Park 2 W	27.6	36.0	-2.0	58.6	-2.0	55.5	2.7	64-10	58-10	64-10	64-10
GA	Experiment	33.3	34.0	-12.0	55.9	-12.0	53.0	-5.9	58-16	58-10	64-28	64-16
HI	Pahala	19.2	29.0	12.0	52.4	12.0	51.0	14.4	58-10	52-10	58-10	58-10
IA	Rathbun Dam	40.8	34.0	-27.0	54.2	-27.0	51.6	-18.9	58-28	52-22	58-40	64-28
ID	Glenns Ferry	42.9	38.0	-20.0	57.5	-20.0	54.3	-14.6	58-22	58-16	64-34	64-28
IL	Waterloo	38.3	35.0	-20.0	55.8	-20.0	52.9	-13.1	58-22	58-16	64-40	64-28
IN	Valparaiso Waterworks	41.5	33.0	-25.0	53.1	-25.0	50.7	-17.7	58-28	52-22	58-34	58-28
KS	Atwood	39.8	37.0	-26.0	57.4	-26.0	54.2	-17.9	58-28	58-22	64-34	64-28
KY	Warsaw Markland Dam	38.8	33.0	-21.0	53.8	-21.0	51.3	-13.9	58-22	52-16	58-34	64-28
LA	Galliano	29.5	34.0	-4.0	56.5	-4.0	53.6	0.8	58-10	58-10	64-16	64-10
MA	Knightville Dam	42.3	31.0	-26.0	51.0	-26.0	49.0	-18.7	52-28	52-22	58-34	58-28
MB	Rossburn	50.7	29.0	-37.0	46.3	-37.0	45.5	-29.7	52-40	46-34	52-52	58-46
MD	Assateague Island N S	38.2	32.0	-13.0	53.0	-13.0	50.6	-8.0	58-16	52-10	58-22	58-16
ME	Millinocket FAA AP	45.7	30.0	-30.0	49.0	-30.0	47.5	-22.7	52-34	52-28	58-40	58-34
MI	Harbor Beach 1 SSE	43.8	29.0	-22.0	48.6	-22.0	47.1	-16.3	52-22	52-22	52-34	58-28
MN	Farmington 3 NW	44.7	32.0	-32.0	51.2	-32.0	49.3	-23.8	52-34	52-28	58-40	58-34
MO	Mountain Grove 2 N	37.2	35.0	-20.0	56.1	-20.0	53.1	-12.7	58-22	58-16	64-34	64-22
MS	Pascagoula 3 NE	30.4	34.0	-7.0	56.3	-7.0	53.5	-1.5	58-10	58-10	64-16	64-10
MT	East Anaconda	46.1	30.0	-28.0	48.9	-28.0	47.4	-21.5	52-28	52-22	58-40	58-34
NC	Elizabeth City FAA AP	36.3	33.0	-10.0	54.4	-10.0	51.7	-5.3	58-10	52-10	58-16	64-16
ND	Sheyenne	47.8	33.0	-34.0	51.1	-34.0	49.3	-26.4	52-34	52-28	58-46	58-40
NE	Red Willow Dam	40.3	36.0	-27.0	56.3	-27.0	53.3	-18.8	58-28	58-22	64-34	64-28
NF	Juniper	46.5	28.0	-36.0	46.8	-36.0	45.7	-27.4	52-40	46-28	52-46	58-40
NH	Windham 3 NW	42.8	32.0	-27.0	51.8	-27.0	49.7	-19.6	52-28	52-22	58-40	58-28
NJ	Somerville 3 NW	40.6	33.0	-19.0	53.3	-19.0	50.9	-13.1	58-22	52-16	58-28	58-22
NM	Clovis 13 N	34.6	36.0	-18.0	57.6	-18.0	54.4	-10.6	58-22	58-16	64-28	64-22
NS	Sheffield Mills	45.1	28.0	-23.0	47.3	-23.0	46.0	-17.5	52-28	52-22	52-28	58-28
NT	Wrigley A	63.2	27.0	-45.0	38.7	-45.0	40.4	-41.2	40-46	46-46	46-na	52-na
NV	Dyer 4 SE	37.6	37.0	-21.0	57.9	-21.0	54.6	-13.6	58-22	58-16	64-34	64-22
NY	Massena CAA AP	44.9	30.0	-32.0	49.2	-32.0	47.6	-23.9	52-34	52-28	58-46	58-34
OH	Cambridge State Hosp	40.1	33.0	-22.0	53.5	-22.0	51.0	-15.1	58-22	52-16	58-34	58-28
OK	Woodward	36.4	39.0	-19.0	60.0	-19.0	56.4	-11.8	64-22	58-16	64-28	64-22
ON	Peterborough A	44.2	30.0	-32.0	49.4	-32.0	47.8	-23.7	52-34	52-28	58-40	58-34
OR	Albany 1 N	44.7	33.0	-9.0	52.2	-9.0	50.0	-7.3	58-10	52-10	58-22	58-22
PA	Lock Haven	41.1	33.0	-21.0	53.2	-21.0	50.8	-14.7	58-22	52-16	58-34	58-28
PE	Alberton	46.8	27.0	-26.0	45.8	-26.0	44.9	-20.3	46-28	46-22	52-40	52-28
PI	Canton Island	2.8	32.0	22.0	53.8	22.0	54.2	23.0	58-10	58-10	58-10	64-10
PQ	St. Hippolyte	46.0	28.0	-36.0	47.0	-36.0	45.8	-27.2	52-40	46-28	52-46	58-34
PR	Coloso	18.4	33.0	12.0	56.2	12.0	54.2	14.5	58-10	58-10	58-10	64-10
PR	Vieques Island	18.1	33.0	16.0	56.2	16.0	54.2	17.4	58-10	58-10	58-10	64-10
SC	Darlington	34.3	36.0	-11.0	57.6	-11.0	54.4	-5.4	58-16	58-10	64-22	64-16
SD	Hot Springs	43.4	36.0	-30.0	55.4	-30.0	52.7	-22.0	58-34	58-22	64-40	64-34
SK	Glaslyn CDA EPF	53.3	27.0	-45.0	43.3	-45.0	43.2	-36.6	46-46	46-40	52-na	52-46
TN	Unicoi 3 SW	36.2	31.0	-20.0	52.5	-20.0	50.2	-12.4	58-22	52-16	58-34	58-22
TX	Weslaco 2 E	26.1	37.0	-2.0	59.7	-2.0	56.4	3.0	64-10	58-10	64-10	64-10
UT	Garrison	38.9	36.0	-23.0	56.6	-23.0	53.6	-15.4	58-28	58-16	64-34	64-28
VA	Covington Filt Plant	37.8	33.0	-18.0	54.0	-18.0	51.5	-11.5	58-22	52-16	58-28	58-22
VT	Burlington WSO AP	44.5	30.0	-28.0	49.4	-28.0	47.7	-20.9	52-28	52-22	58-40	58-28
WA	Colville AP	48.5	34.0	-24.0	51.8	-24.0	49.9	-19.5	52-28	52-22	58-40	58-34
WI	Oconto 4 W	44.9	31.0	-28.0	50.2	-28.0	48.4	-21.0	52-28	52-22	58-40	58-34
WV	Huntington Sew Trmt Plt	38.4	33.0	-17.0	53.9	-17.0	51.3	-11.0	58-22	52-16	58-28	64-22
WY	Gas Hills 4 E	42.8	30.0	-28.0	49.9	-28.0	48.1	-20.3	52-28	52-22	58-40	58-34

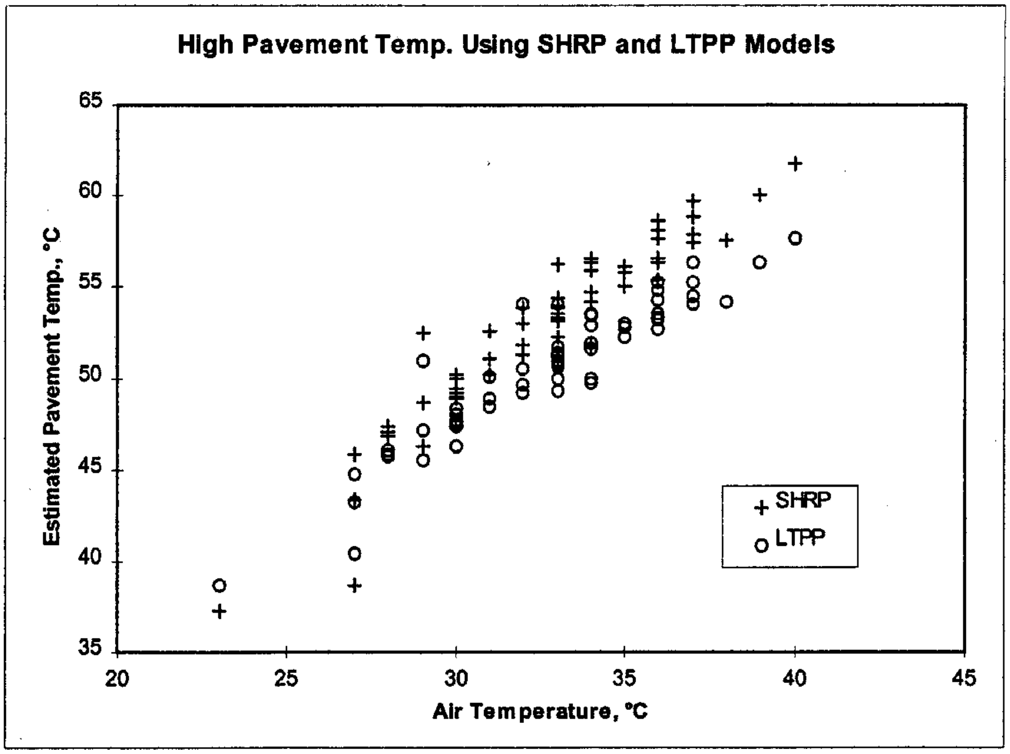

Figure 41 - SHRP and LTPP Estimated High Pavement Temperatures vs. Air Temperature for Sample Weather Data.

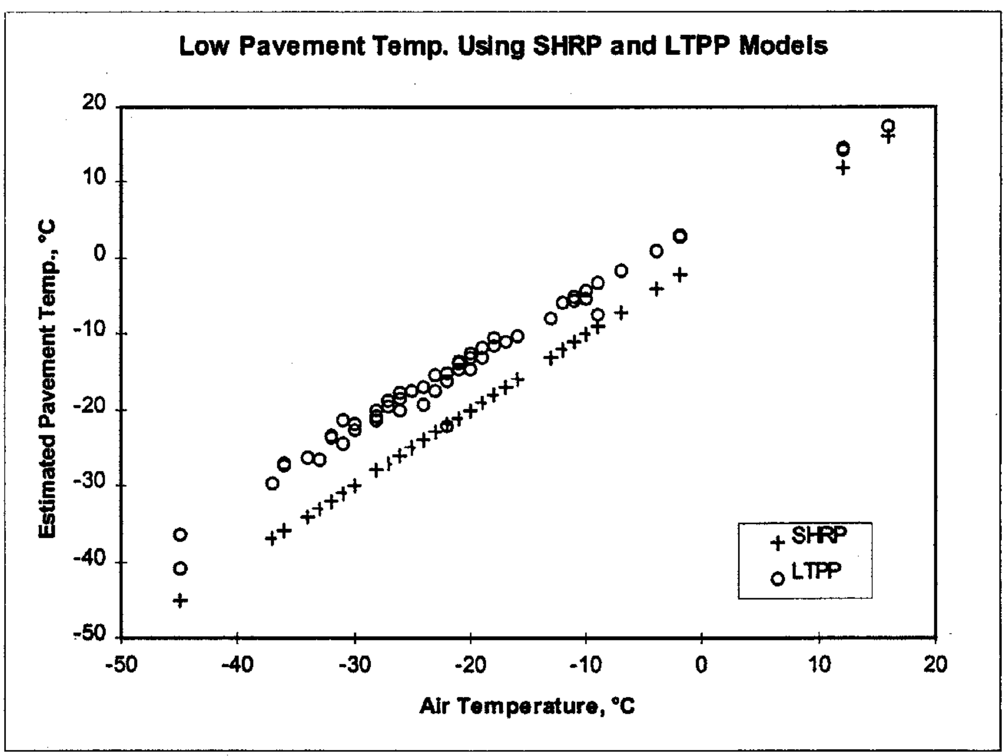

Figure 42 - SHRP and LTPP Estimated Low Pavement Temperatures vs. Air Temperature for Sample Weather Data.

10.2. Comparing Performance Grades for All Weather Stations

The performance grades for weather data in all weather stations in the data base were determined using the SHRP and LTPP models at different reliability levels.[3] The 50-percent and 98-percent reliability performance grades are tabulated in table 18 and table 19 for low temperatures and table 20 and table 21 for high temperatures. They show that low-temperature performance grades determined using LTPP models are usually one to two performance grades higher than performance grades determined by the SHRP procedure, while the high-temperature performance grades are usually one performance grade lower.

Table 18 also shows that at a 50-percent reliability low temperature, a performance grade of -40 was determined for 790 weather stations using the SHRP procedure. Performance grades determined using the LTPP models were significantly different – only 21 had a performance grade of -40, while 513 had a performance grade of -34, and the remaining 256 weather stations had a performance grade of -28.

Table 18 - 50% Reliability Low-Temperature Performance Grades for 7,801 Weather Stations (SHRP vs. LTPP).

	LTPP Performance Grade									
SHRP PG	**-10**	**-16**	**-22**	**-28**	**-34**	**-40**	**-46**	**-52**	**-58 (NA)**	**Total**
-10	**1236**	82	.	.	.	.	.	.	.	1318
-16	901	**172**	10	.	.	.	.	.	.	1083
-22	29	1353	**166**	3	.	.	.	.	.	1551
-28	.	197	1259	**45**	1	.	.	.	.	1502
-34	.	.	236	966	**32**	.	.	.	.	1234
-40	.	.	.	256	513	**21**	.	.	.	790
-46	.	.	.	.	91	135	**47**	2	1	276
-52	.	.	.	.	.	.	30	**13**	**2**	45
-58 (NA)	.	.	.	.	.	.	.	**2**	.	2
Total	2166	1804	1671	1270	637	156	77	17	3	7801

The difference in performance grades at 98-percent mean air temperature reliability (table 19) was even more significant. From a total of 1,329 weather stations with a SHRP performance grade of -40, only 13 had the same performance grade using LTPP models; 762 weather stations (more than half) had a performance grade of -34 and 554 (almost 40 percent) had a performance grade of -28. The difference is even more dramatic for lower performance grades (performance grades of -46 and -52).

Table 19 - 98% Reliability Low-Temperature Performance Grades for 7,801 Weather Stations (SHRP vs. LTPP).

	LTPP Performance Grade									
SHRP PG	**-10**	**-16**	**-22**	**-28**	**-34**	**-40**	**-46**	**-52**	**-58 (NA)**	**Total**
-10	**457**	13	.	.	.	.	.	.	.	470
-16	419	**196**	41	.	.	.	.	.	.	656
-22	7	735	**197**	3	.	.	.	.	.	942
-28	.	132	794	**72**	1	.	.	.	.	999
-34	.	.	444	1181	**21**	1	.	.	.	1647
-40	.	.	.	554	762	**13**	.	.	.	1329
-46	.	.	.	.	559	454	**16**	.	.	1029
-52	.	.	.	.	2	307	164	**35**	**2**	510
-58 (NA)	.	.	.	.	.	2	105	**70**	**42**	219
Total	883	1076	1476	1810	1345	777	285	105	44	7801

The total number of weather stations that fall into a 50-percent low-temperature performance grade is shown in figure 43. It shows that substantially fewer performance grades of -34 were determined with LTPP models than with the SHRP procedure. The same trend exists for lower performance grades (-40, -46, and -52). More than 2,300 performance grades of -34 and lower were determined by SHRP, while in only 887 cases (almost one-third) were the same performance grades determined by LTPP.

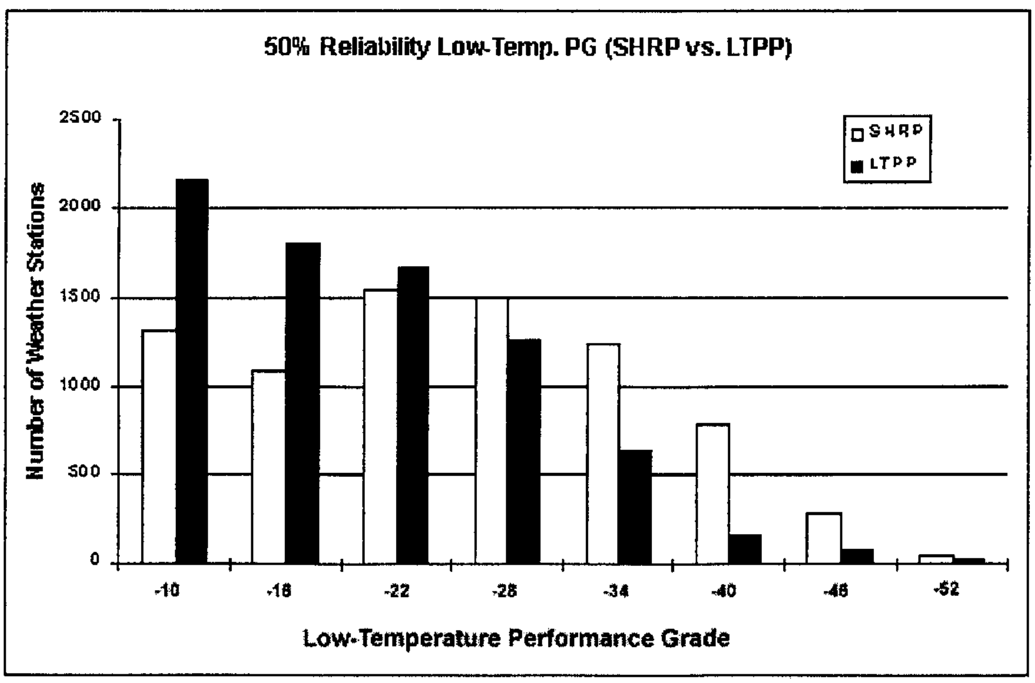

Figure 43 - Distribution of 50% Reliability Low-Temperature Performance Grades by the SHRP and LTPP Models.

Figure 44 shows the distribution of 98-percent reliability low-temperature performance grades. The figure shows that at 98-percent reliability, the LTPP low-temperature model determined that less than one-third of the weather stations had a performance grade of -34 or lower, while the SHRP model determined that about 60 percent of the weather stations had a performance grade of -34 or lower. This comparison indicates that the impact of LTPP models in determining low-temperature performance grades is very significant, especially at lower air temperatures.

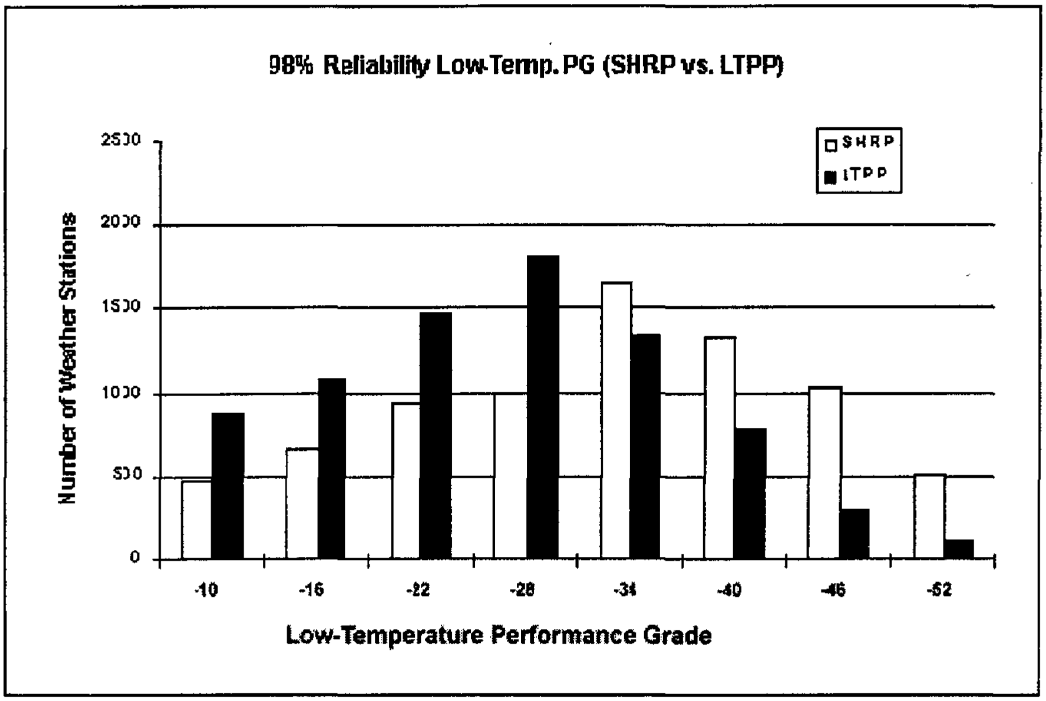

Figure 44 - Distribution of 98% Reliability Low-Temperature Performance Grades by the SHRP and LTPP Models.

Table 20 shows that at a 50-percent reliability level, the SHRP high-temperature model determined a performance grade of 52 for 2,383 weather stations, while the LTPP model determined that 2,064 (more than 90 percent) had the same performance grade. Out of 3,228 cases of a SHRP performance grade of 58, almost half were one performance grade lower (performance grade of 52) with the LTPP model. From 1,043 cases of a SHRP performance grade of 64, more than 95 percent (990 cases) were a performance grade of 58 (one performance grade lower) using the LTPP model. The changes in high-temperature performance grades are not as significant for performance grades of 52 or lower; however, for a performance grade of 58 or higher, the LTPP performance grades are usually one performance grade lower than that for SHRP.

Table 20 - 50% Reliability High-Temperature Performance Grades for 7,801 Weather Stations (SHRP vs. LTPP).

	LTPP Performance Grade						
SHRP PG	**40**	**46**	**52**	**58**	**64**	**70 (NA)**	**Total**
40	**312**	57	.	.	.	.	369
46	.	**707**	.	.	.	.	707
52	.	319	**2064**	.	.	.	2383
58	.	.	1488	**1740**	.	.	3228
64	.	.	.	990	**53**	.	1043
70 (NA)	.	.	.	.	70	**1**	71
Total	312	1083	3552	2730	123	1	7801

Table 21 shows that 98-percent reliability high-temperature performance grades are sometimes one performance grade higher for performance grades of 52 or lower, and almost identical at a performance grade of 64. Using the LTPP models, about 85 percent of performance grades of 58 and 99 percent of performance grades of 64 have performance grades similar to the SHRP models.

Table 21 - 98% Reliability High-Temperature Performance Grades for 7,801 Weather Stations (SHRP vs. LTPP).

	LTPP Performance Grade						
SHRP PG	**40**	**46**	**52**	**58**	**64**	**70 (NA)**	**Total**
40	**47**	86	.	.	.	.	133
46	.	**86**	302	.	.	.	388
52	.	.	**513**	784	.	.	1297
58	.	.	.	**2623**	507	.	3130
64	.	.	.	8	**2583**	13	2604
70 (NA)	.	.	.	.	83	**166**	249
Total	47	172	815	3415	3173	179	7801

Figure 45 shows the distribution of 50-percent reliability high-temperature performance grades. The number of weather stations that fall into a performance grade of 64 is significantly less using LTPP models.

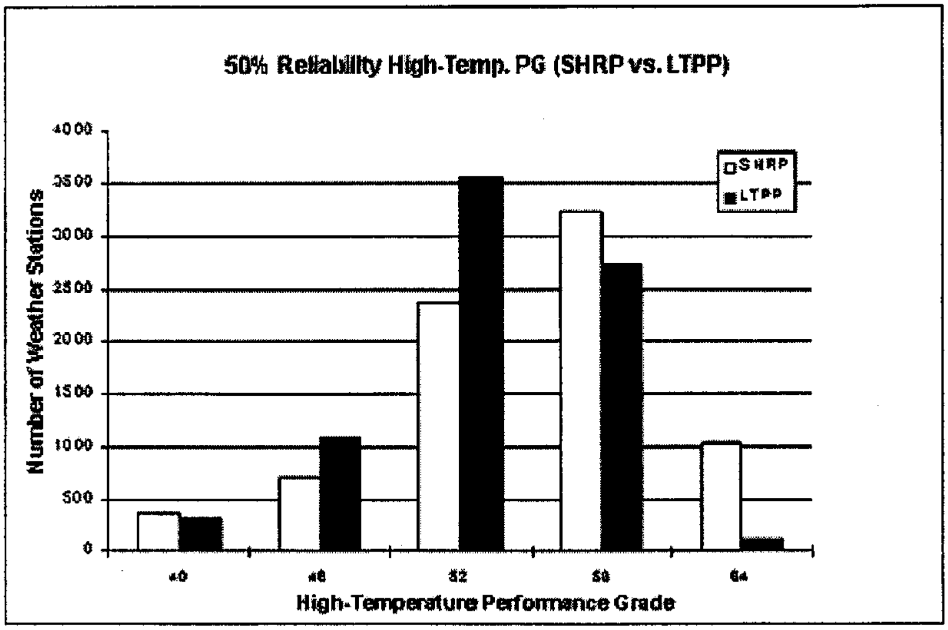

Figure 45 - Distribution of 50% Reliability High-Temperature Performance Grades by the SHRP and LTPP Models.

Figure 6 shows the distribution of 98-percent reliability high-temperature performance grades. The number of weather stations that fall into performance grades of 58 and 64 is slightly higher using the LTPP high-temperature model.

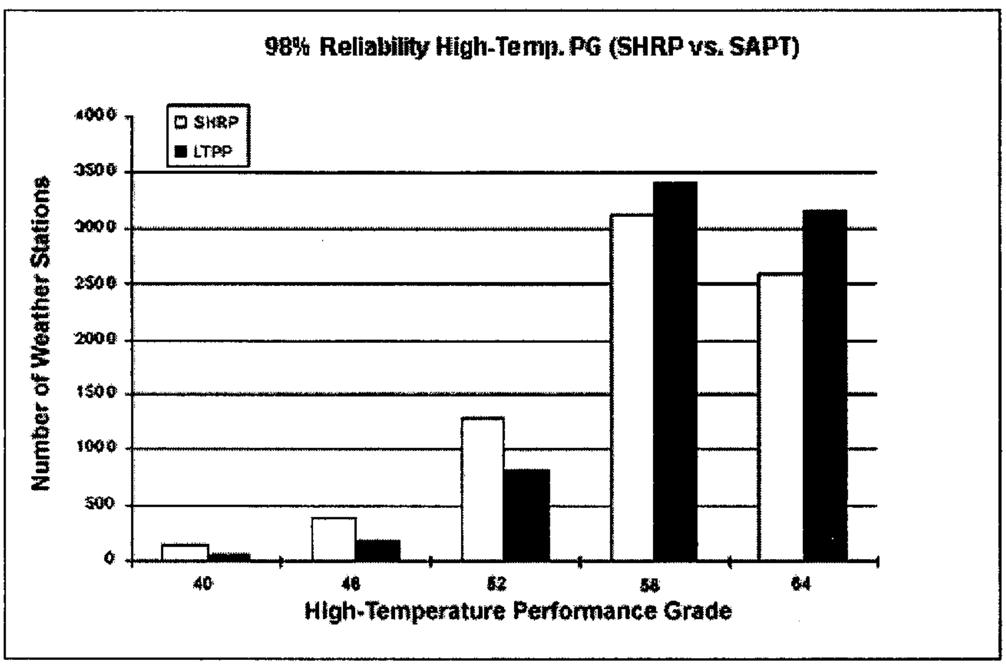

Figure 46 - Distribution of 98% Reliability High-Temperature Performance Grades by the SHRP and LTPP Models.

10.3. Change in Performance Grades for Different Reliability Levels

The change in asphalt low- and high-temperature performance grades due to different reliability levels is presented in this section. In order to demonstrate the effect of using different reliability levels in determining asphalt binder performance grades, SHRP and LTPP models were used to calculate the design low and high pavement temperatures using equations 9 and 10, respectively. Two different reliability levels were considered: 50 percent and 98 percent. The asphalt binder performance grade resulting from the calculated pavement temperatures was calculated.

The performance grades for weather data in all 7,801 weather stations in the SUPERPAVE data base were determined using the SHRP and LTPP models at 50-percent and 98-percent reliability levels.[(3)] The percentages of weather stations that changed their low- and high-temperature performance grades due to using the LTPP model at different reliability levels are listed in table 22.

Table 22 - Percentage of Weather Stations That Changed the Low-Temperature Performance Grade at Different Pavement and Air Temperature Reliability Levels.

		LTPP Performance Grade Change From SHRP			
Model	**Reliability**	**-1**	**0**	**+1**	**+2**
Low Temp.	**50%**	1	**22**	66	10
	98%	.	**13**	58	27
High Temp.	**50%**	36	**62**	.	.
	98%	1	**77**	21	.

Table 22 shows that in 66 percent of the cases, the 50-percent reliability low-temperature performance grades were one performance grade higher when using the LTPP model. In 10 percent of the cases, the performance grades were two performance grades higher; and for 22 percent of the weather stations, there was no change.

The impact of the changes on the 98-percent reliability low-temperature performance grade was even more significant. More than 58 percent of the performance grades increased by one performance grade and 27 percent increased by two performance grades (85 percent changed by one or two performance grades).

The number of weather stations that changed low-temperature performance grades due to the LTPP model is also shown in figure 47. This figure shows that the majority of weather stations were one or two performance grades higher at 50-percent and 98-percent reliability levels. Therefore, using the LTPP low pavement temperature model at different reliability levels results in performance grades that are generally one performance grade higher than the performance grades determined using the SHRP model.

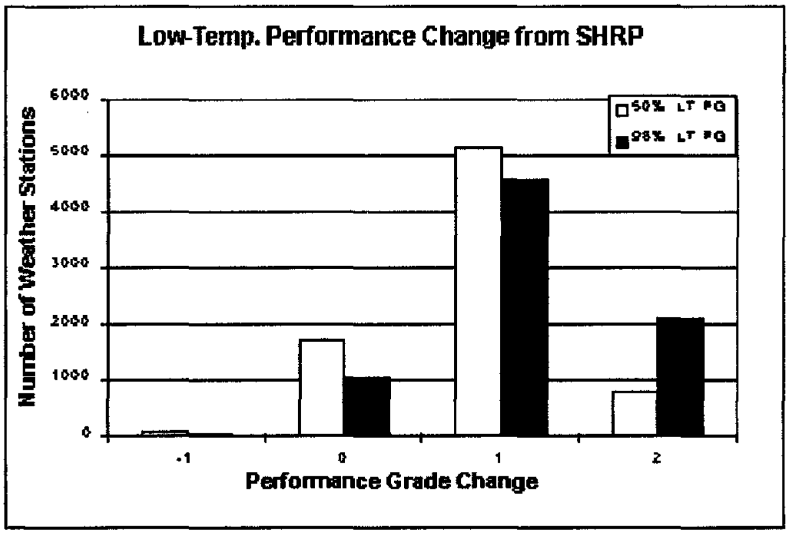

Figure 47 - Number of Weather Stations That Changed the Low-Temperature Performance Grades.

Table 22 shows that at a 50-percent reliability level, 36 percent of the high-temperature performance grades were one performance grade lower with the LTPP model than with the SHRP model. About 21 percent of the performance grades were one performance grade higher at the 98-percent reliability level. This is because model variability is not considered in the SHRP model; therefore, the LTPP model has more reliability built into the model and, hence, is more conservative. The number of weather stations that changed high-temperature performance grades due to the LTPP model is also shown in figure 48. This figure shows that the majority of weather stations had similar performance grades at 50-percent and 98-percent reliability levels. At the 50-percent reliability level, about one-third of the performance grades determined using LTPP were one performance grade lower than those for SHRP; while at the 98-percent reliability level, about one-quarter of the performance grades were one performance grade higher.

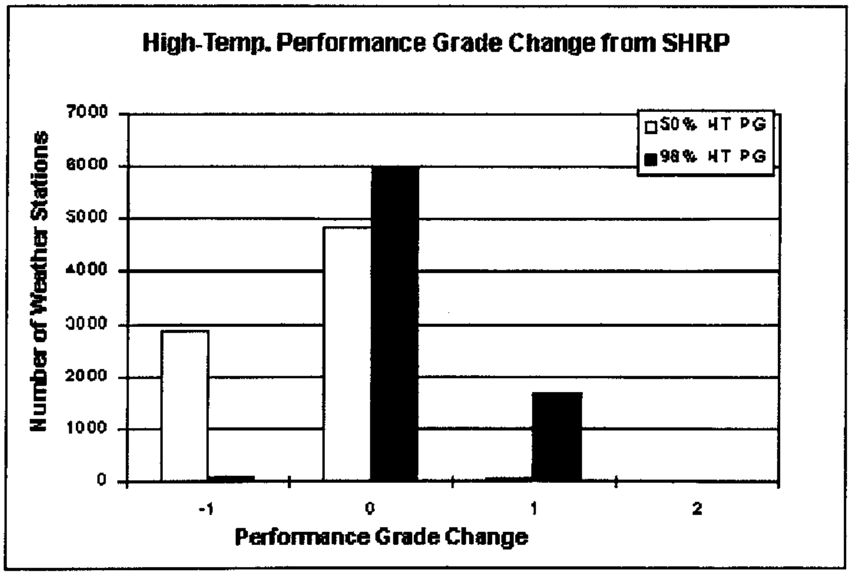

Figure 48 - Number of Weather Stations That Changed the High-Temperature Performance Grades.

11. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were made from this study:

1. The LTPP-SMP low pavement temperature data collected over a period of two winter seasons were up to 13 degrees higher than the air temperature. The difference was more significant at lower air temperatures and lower latitudes.

2. The low-temperature asphalt binder performance grade determined by the SHRP procedure is too conservative since it assumes that low pavement temperature equals low air temperature. The C-SHRP low pavement temperature model agreed with the LTPP low-temperature model at higher latitudes (approximately 50 degrees [Southern Canada]); however, the model estimates were too conservative at lower latitudes.

3. The low-temperature performance grades determined using the SHRP and LTPP models at different reliability levels were significantly different. More than two-thirds of the SHRP low-temperature performance grades were at least one performance grade higher than those determined using the LTPP model. The difference was more significant at performance grades of -34 and lower.

4. The LTPP-SMP high-temperature data generally agreed with SHRP high pavement temperature estimates up to air temperatures of 35 °C. At higher temperatures, however, SMP data were slightly lower. This is probably because the air temperature coefficient was set to 1 in the SHRP model.

5. The high-temperature performance grades determined using the SHRP and LTPP models agreed up to a performance grade of 52. At higher temperatures, the LTPP model required performance grades that were sometimes one performance grade lower.

Based on this study, it is recommended that:

1. The LTPP low- and high-temperature models should be updated as more SMP data become available. LTPP models should be verified with data from other experiments within the United States and Canada.

2. The LTPP low-temperature model for determining SUPERPAVE low-temperature asphalt binder performance grades should be adopted.

12. REFERENCES

1. Federal Highway Administration, *LTPP Seasonal Monitoring Program: Instrumentation Installation and Data Collection Guide*, Report No. FHWA-RD-94-110, Washington, D.C.

2. Robertson, W.D. "Using the SHRP Specification to Select Asphalt Binders for Low-Temperature Service" (unpublished).

3. Huber, G.A., *Weather Data Base for the SUPERPAVE Mix Design System*, Report No. SHRP-A-648A, Strategic Highway Research Program, February 1994.

4. Solaimanian, M. and P. Bolzan, *Analysis of the Integrated Model of Climatic Effects on Pavements: Sensitivity Analysis and Pavement Temperature Prediction*, Report No. SHRP-A-637, Strategic Highway Research Program.

5. Mohseni, A. and M. Symons, "Improved AC Pavement Temperature Models From LTPP Seasonal Data," presented at the 77th Annual TRB Conference, Washington, D.C., 1998.

6. Mohseni, A. and M. Symons, "Effect of Improved LTPP AC Pavement Temperature Models on SUPERPAVE Performance Grades," presented at the 77th Annual TRB Conference, Washington, D.C., 1998.

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