Characterizing Temperature Effects for Pavement Analysis and Design

M. R. THOMPSON, B. J. DEMPSEY, H. HILL, AND J. VOGEL

Pavement temperatures can be accurately quantified utilizing the Climatic-Materials-Structural (CMS) computer model developed at the University of Illinois. Required CMS inputs (for temperature modeling) are *(a)* thermal properties of materials and soils, *(b)* air temperature data, *(c)* solar radiation data, and *(d)* wind velocity data. In this paper the development and use of a comprehensive Illinois Climatic Data Base for Pavements are presented. Air temperature data are summarized on a weekly basis and solar radiation and wind velocity data are presented in the form of a monthly state map. Illustrative, applications-oriented examples are presented for *(a)* strength–degree-day curing relations for pozzolanic stabilized base materials, *(b)* asphalt concrete moduli–pavement temperature effects, and *(c)* temperature gradients in portland cement concrete slabs. The emphasis here is on the concepts and techniques used to establish the Illinois Climatic Data Base for Pavements. The illustrative information demonstrates the versatility and usefulness of the climatic data base and heat-transfer model procedures in pavement analysis and design. The procedures and techniques described can be used to establish a climatic data base for other states or locations. The climatic data base and heat-transfer model approach is recommended for quantifying temperature effects in flexible and rigid pavement analysis and design.

Pavement temperature is an important consideration in pavement analysis and design. Examples of significant temperature effects follow. Strength development in pozzolanic stabilized base (PSB) materials is dependent on available degree-days of curing (degree-days based on pavement temperatures above 40°F). Figure 1 shows compressive strength–degree-day relations for typical lime-flyash and cement-flyash mixtures. Freeze-thaw action affects decreases in the strength of stabilized base material. Residual strength after cyclic or freeze-thaw action is primarily controlled by the cured stabilized material strength before freeze-thaw *(1)*, as shown in Figure 2. Asphalt concrete (AC) moduli are temperature dependent. Figure 3 shows AC moduli–temperature relations for a proposed full-depth AC thickness design procedure *(2)*. Temperature gradients in portland cement concrete (PCC) pavements are important in considering "slab-curling" effects. Large curling stresses and loss of support develop from PCC slab temperature gradients. PCC slab gradients show large daily and seasonal variability.

It is apparent that pavement temperature is an extremely important factor in pavement analysis and design. Current research at the University of Illinois is focused on the mechanistic analysis and design of flexible and rigid pavements. To facilitate the appropriate consideration of pavement temperature effects, an Illinois Climatic Data Base was developed. In this paper are described the data base and how it can be used with a previously developed heat-transfer model to characterize important pavement temperature effects.

M. R. Thompson, B. J. Dempsey, and H. Hill, Department of Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, Ill. 61801. J. Vogel, Climate Information Unit, Illinois State Water Survey, Mail Code 674, Champaign, Ill. 61801.

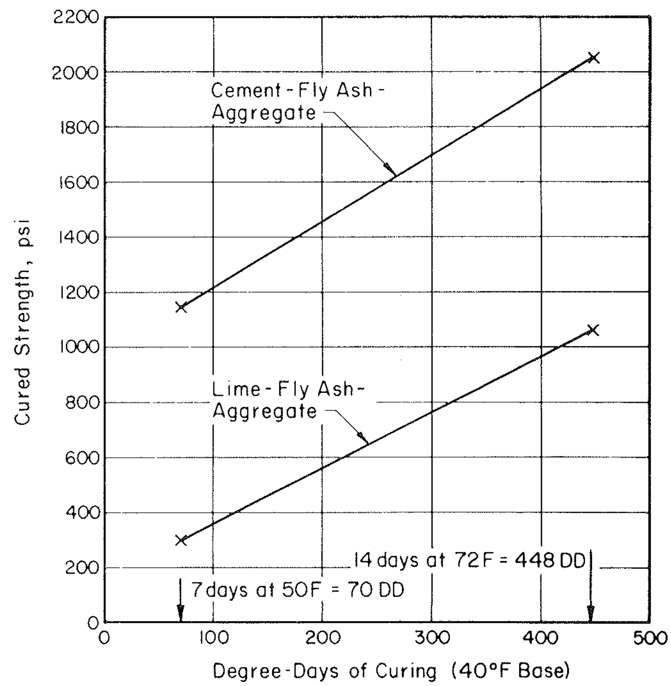

FIGURE 1 Strength–degree-day relations for PSB materials.

HEAT-TRANSFER MODEL

The heat-transfer model used in this study was originally developed at the University of Illinois *(3)* and is used in the Climatic-Materials-Structural (CMS) program *(4)*, which can be run on an IBM PC-AT computer. The heat-transfer model uses a finite-difference solution to the one-dimensional, Fourier heat-transfer equation for transient heat flow to compute pavement temperatures as a function of time. Energy balance procedures developed by Scott *(5–7)* and Berg *(8)* are used to relate the pavement surface temperatures to climatic parameters. Further details concerning the program are available in Dempsey et al *(3)*.

compressive strength (f_c') of 5,330 psi ($R = 9.17 \sqrt{f_c'}$). The nonlinear temperature stress is thus 17 percent of the flexural strength. This stress is not in itself sufficient to cause a pavement to crack or fail. The nonlinear temperature stress is independent of the compressive strength of the concrete. At the design strength of the concrete (3,000 psi) and using the previously derived relationship for the modulus of rupture, the nonlinear temperature stress would be 22 percent of the flexural strength. At an early curing time when the flexural strength is low, this stress may be more critical.

It should be cautioned that these results are only applicable to the conditions that obtained on the test road at Gainesville, Florida. Their extension to other climates, thicknesses of pavements, coarse aggregates, and base materials is not advisable until further research has been conducted.

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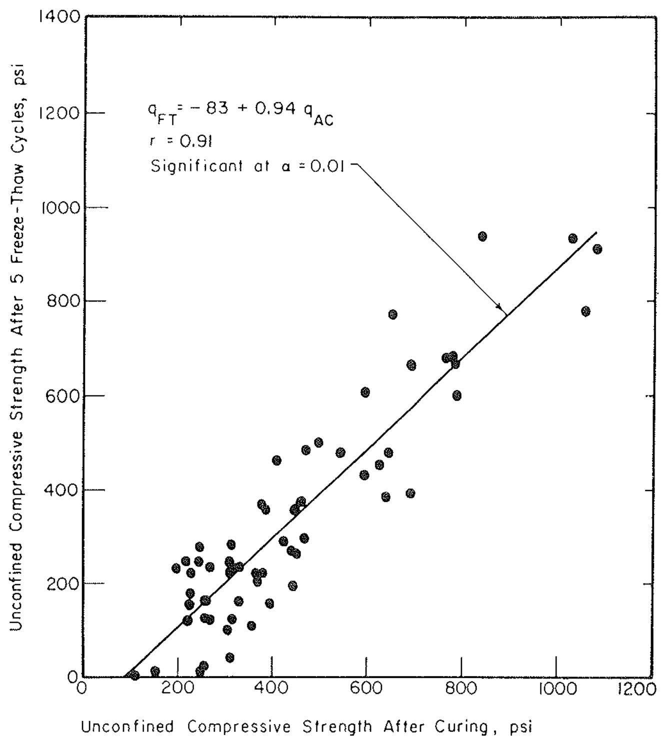

FIGURE 2 Freeze-thaw strength: cured strength relation for stabilized materials.

Inputs to the heat-transfer model are climatic data and thermal properties of the paving materials and soils. The climatic data inputs are maximum and minimum daily air temperature, percent sunshine, and wind speed. Thermal property inputs are thermal conductivity, heat capacity, and latent heat of fusion. The model recognizes three sets of thermal properties depending on whether the material is in an unfrozen, freezing, or frozen condition. The procedures for determining the thermal properties of pavement materials have been described in detail elsewhere *(3, 9)*. The methods developed by Kersten *(10)* are well suited for determining the thermal properties of the base, subbase, and subgrade soils.

The climatic data inputs are not readily available in a suitable format. To facilitate the application of the heat-transfer model to various pavement-related problems, a comprehensive climatic data base was recently developed for Illinois as part of the University of Illinois–Illinois Department of Transportation Highway Planning and Research Program.

CLIMATIC DATA BASE

Temperature

Historical temperature data for the following 23 weather stations in and adjacent to Illinois were obtained from the National Oceanographic and Atmospheric Administration (NOAA).

Anna	LaHarpe
Belleville	Moline
Cairo	Mt. Vernon
Carbondale	Ottawa
Charleston	Peoria
Chicago	Quincy
Decatur	Rockford
Effingham	Springfield
Fairfield	St. Louis
Freeport	Urbana
Harrisburg	Whitehall
Kankakee	

The lengths of the records varied from 15 to 93 years, and all but one were 63 years or longer. After extensive interactions with Illinois State Water Survey climatologists and careful consideration of the nature of pavement temperature problems, it was concluded that a weekly analysis of temperature data was adequate. Average and standard deviation values for the

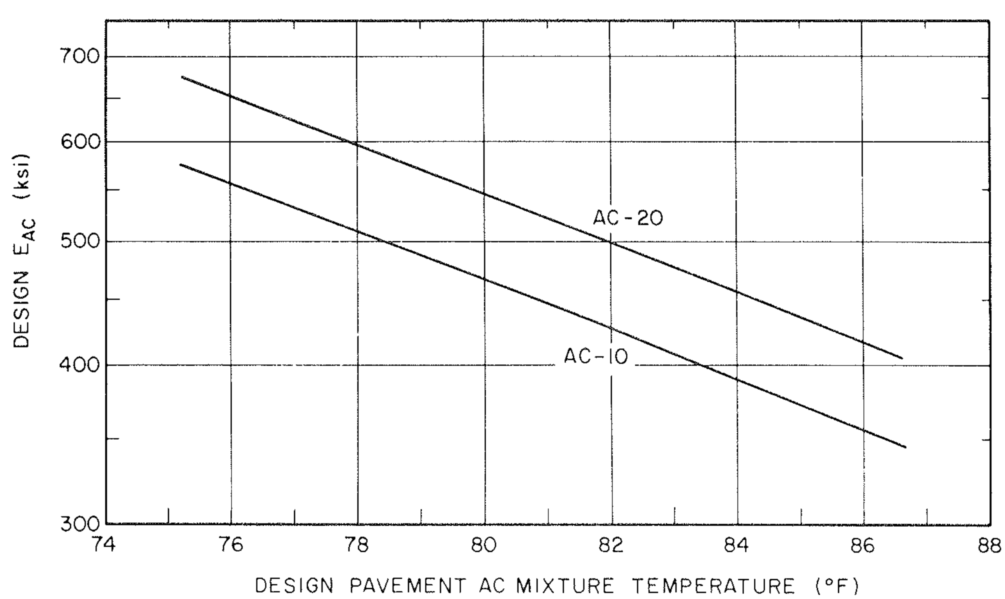

FIGURE 3 Asphalt concrete modulus-temperature relations.

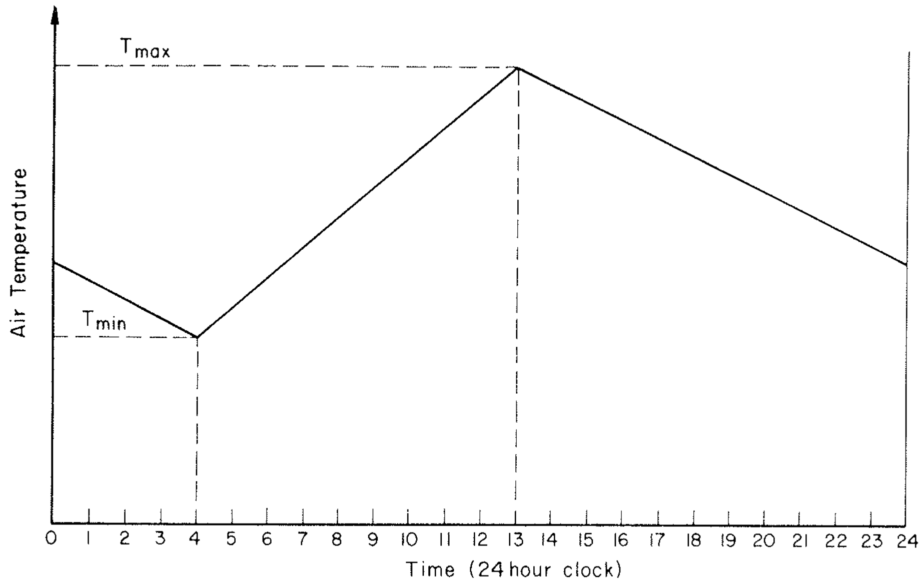

FIGURE 4 Diurnal temperature relation for heat-transfer model.

daily high, daily low, and daily mean temperatures were calculated using the NOAA data and a special computer program developed by the Illinois State Water Survey. Diurnal effects (which vary throughout the year) are considered by assuming that the maximum temperature occurs at 1:00 p.m. and the minimum temperature occurs at 4:00 a.m. as shown in Figure 4. Seven repetitions of the diurnal temperature cycle constitute a week's input to the heat-transfer model.

Percent Sunshine

NOAA data tapes for selected weather stations, in and adjacent to Illinois, were analyzed on a monthly basis to establish "percent sunshine" information. Percent sunshine data are available for only major weather stations. As much as possible, long-term records (37 to 89 years) were used. Comparisons were made for 20-year periods to ensure the continuity of the data set. The percent sunshine data are presented for each month in terms of isolines of percent sunshine on a map of Illinois, as shown in Figure 5. Typical standard deviations for the monthly percent sunshine data are from 6 to 13 percent.

Average Wind Speed

Average daily wind speed data (1965–1974, 20- to 25-ft recorder heights) for available National Weather Service stations in and around Illinois were evaluated by Illinois State Water Survey climatologists to establish average wind speeds for each month. The data are presented as isolines of average wind speed on a map of Illinois, as shown in Figure 6. Average monthly wind speed data do not vary by more than about 2 to 3 mph for various Illinois locations or months of the year. Heat-transfer model temperature calculations are not particularly sensitive to such small variations.

Combined Climatic Data Base

The most detailed available information is the temperature data for the 23 Illinois locations. Temperature data are much more variable (relatively) than either percent sunshine or wind speed.

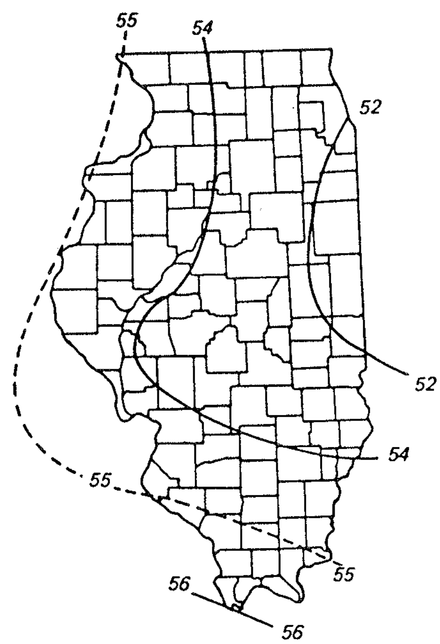

FIGURE 5 Percent sunshine data for March.

Thus most temperature-related pavement considerations are primarily controlled by air temperature inputs. Percent sunshine and wind speed data for each station were determined from the appropriate monthly maps for each location and added to the temperature data base (weekly values). The combined climatic data base was stored on floppy discs to facilitate data input for heat-transfer model calculations. A typical climatic data summary for Urbana, Illinois, is given in Table 1.

APPLICATIONS

Pozzolanic Stabilized Base Strength Development

Barenberg and Thompson *(11)* recommend using strength–degree-day (DD) relations for predicting the strength of

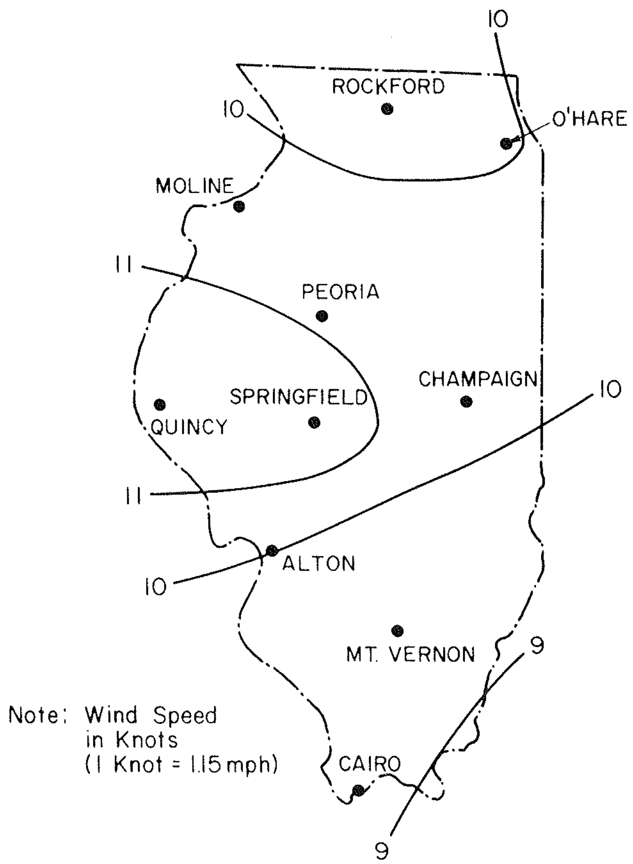

FIGURE 6 Wind speed data for March.

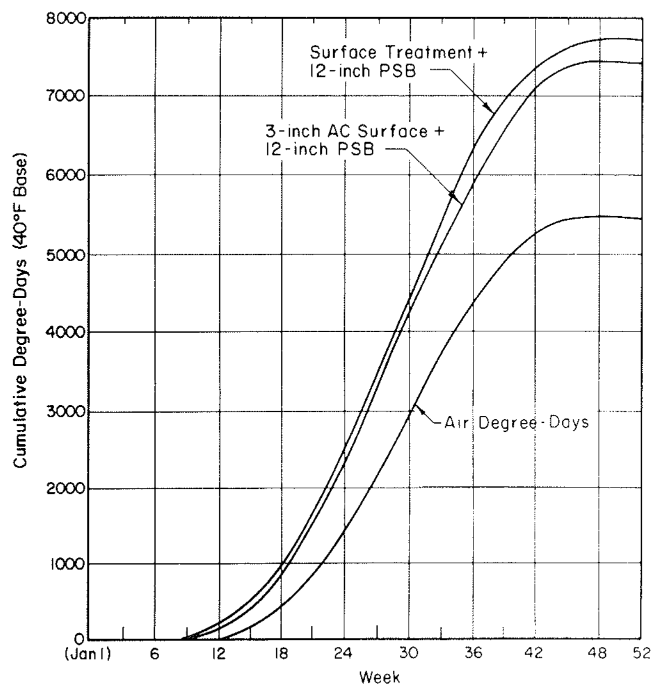

FIGURE 7 Degree-day–time data for Urbana, Illinois.

pozzolanic stabilized base (PSB) materials (DD based on 40°F reference temperature). The Illinois Department of Transportation uses strength-DD concepts for establishing late season (fall) construction cutoff dates for pozzolanic stabilized base materials.

A critical input to predicting PSB strength development in the field is the available DD during the curing period. The heat-transfer model has been previously used for DD calculations. PSB materials strength-DD relations vary depending on the flyash and activator (lime, cement, cement kiln dust, lime kiln dust) incorporated in the mixture. PSB mixture proportions also influence the strength-DD relation. Figure 1 data are for identical PSB mixes (3.5 percent activator, 9 percent flyash, 87.5 percent aggregate) with either lime or cement used as the activator. Two typical PSB pavements (3-in. AC surface + 12-in. PSB; bituminous surface treatment + 12-in. PSB; thermal properties given in Table 2) were evaluated for three Illinois locations (Rockford, Urbana, Cairo) that cover extremes of temperature in Illinois. Cumulative PSB layer DD-time relations for Urbana are shown in Figure 7. Air DD (40°F base) data are also shown. It is obvious that PSB DDs are responding primarily to air DDs. Statistical analyses of the middepth average PSB temperature and the air temperature indicated the PSB layer temperature can be accurately predicted from air temperature. The regression equations are

For 3-in. AC surface

$$T_{mix} = 2.9 + 1.08\,AT$$

$$R^2 = 0.996,\ SEE = 1.2$$

For bituminous surface treatment

$$T_{mix} = 1.15\,AT - 0.8$$

$$R^2 = 0.996,\ SEE = 1.4$$

T_{mix} is temperature (°F) at middepth of 12-in. stabilized base layer and AT is average air temperature (°F).

The stabilized layer temperatures predicted from air temperature can be used to calculate pavement DD. The air temperature DD procedure was compared with the heat-transfer model data. The maximum error in cumulative DD (for a year of data) was about 1.5 percent. The effect of depth within the stabilized layer on cumulative DD is negligible (approximately 1 DD/week per inch of depth). The equations are considered quite adequate for routine strength-DD predictions. The air DD procedure expedites the development of DD information for a particular location because the only needed climatic inputs are readily available average air temperature data.

AC Pavement Temperature

Figure 3 shows the large effect of temperature on AC modulus. The Shell *(12)* and the Asphalt Institute *(13)* pavement design procedures include procedures for estimating AC modulus–temperature relations. For given mixture and loading conditions, the AC temperature is the primary factor controlling modulus. Thus good AC pavement temperature input data are essential in flexible pavement analysis and design.

TABLE 1 CLIMATIC DATA BASE FOR URBANA, ILLINOIS

	LOW TEMP. (F)		HIGH TEMP. (F)		MEAN TEMP. (F)			
WEEK*	AVERAGE	STNDEV	AVERAGE	STNDEV	AVERAGE	STNDEV	SUN (%)	WIND (MPH)
1	26.28	7.16	43.26	8.61	34.77	7.66	52.0	11.5
2	28.78	6.12	46.25	7.99	37.51	6.82	52.0	11.5
3	30.87	6.90	49.32	8.83	40.10	7.66	52.0	11.5
4	33.55	6.51	52.96	8.82	43.25	7.47	52.0	11.5
5	35.75	5.74	55.47	7.95	45.61	6.57	56.0	12.1
6	37.51	5.00	57.99	7.12	47.75	5.78	56.0	12.1
7	40.93	6.05	62.18	7.59	51.56	6.66	56.0	12.1
8	43.77	5.51	64.96	6.42	54.36	5.69	56.0	12.1
9	45.72	5.48	67.24	6.96	56.48	5.94	62.0	12.1
10	47.90	5.71	69.48	7.33	58.69	6.29	62.0	12.1
11	49.38	4.51	70.57	5.74	59.97	4.86	62.0	12.1
12	52.58	5.50	74.39	6.47	63.49	5.71	62.0	12.1
13	54.72	5.66	76.31	5.96	65.52	5.53	62.0	12.1
14	57.87	4.90	79.31	6.10	68.59	5.28	69.0	12.7
15	59.18	4.50	80.88	5.42	70.03	4.57	69.0	12.7
16	60.57	4.27	82.48	5.06	71.52	4.36	69.0	12.7
17	62.52	4.70	83.87	5.17	73.20	4.70	69.0	12.7
18	63.37	4.18	85.13	4.73	74.25	4.27	74.0	10.4
19	63.55	4.46	85.64	4.54	74.60	4.15	74.0	10.4
20	64.60	3.83	86.54	4.37	75.57	3.80	74.0	10.4
21	64.76	3.70	86.35	4.23	75.55	3.62	74.0	10.4
22	64.58	4.24	86.30	4.51	75.44	4.13	69.0	09.2
23	63.74	4.21	85.42	4.44	74.58	3.94	69.0	09.2
24	63.02	3.91	84.44	4.36	73.73	3.75	69.0	09.2
25	62.26	4.38	83.44	4.15	72.85	3.96	69.0	09.2
26	60.65	4.58	83.09	4.54	71.87	4.23	69.0	09.2
27	60.26	5.20	82.21	5.22	71.24	4.78	66.0	08.1
28	58.18	4.79	81.01	5.56	69.59	4.84	66.0	08.1
29	55.46	5.49	78.22	5.89	66.84	5.34	66.0	08.1
30	52.47	5.58	75.47	5.70	63.97	5.15	66.0	08.1
31	49.04	5.72	72.69	5.93	60.87	5.30	64.0	07.5
32	47.03	6.12	69.92	6.20	58.48	5.74	64.0	07.5
33	45.30	5.57	67.95	6.90	56.62	5.89	64.0	07.5
34	41.90	6.55	63.48	7.94	52.69	6.86	64.0	07.5
35	39.24	6.07	59.85	7.97	49.55	6.64	64.0	07.5
36	36.90	6.02	56.12	6.82	46.51	6.03	50.0	08.6
37	33.90	5.88	51.83	6.98	42.87	6.12	50.0	08.6
38	32.55	7.02	50.10	7.56	41.33	6.90	50.0	08.6
39	28.15	5.83	44.10	6.46	36.13	5.85	50.0	08.6
40	26.28	7.35	42.07	7.85	34.17	7.39	41.0	10.4
41	24.00	8.22	39.14	8.21	31.57	8.02	41.0	10.4
42	21.12	9.13	36.14	8.46	28.63	8.60	41.0	10.4
43	21.57	8.35	36.14	7.66	28.85	7.80	41.0	10.4
44	20.08	8.05	35.53	7.12	27.80	7.32	45.0	11.5
45	18.18	9.37	33.78	8.66	25.98	8.83	45.0	11.5
46	17.90	9.79	33.48	9.13	25.69	9.33	45.0	11.5
47	19.08	9.32	35.01	8.42	27.05	8.71	45.0	11.5
48	16.84	10.41	33.32	9.65	25.08	9.85	45.0	11.5
49	17.50	9.75	33.59	8.38	25.55	8.87	49.0	11.5
50	19.17	10.03	35.25	9.11	27.21	9.40	49.0	11.5
51	21.37	8.27	37.86	7.84	29.61	7.82	49.0	11.5
52	23.87	7.43	39.98	7.90	31.93	7.48	49.0	11.5
53	23.87	7.43	39.98	7.90	31.93	7.48	49.0	11.5

*NOTE: WEEK 1 BEGINS MARCH FIRST

TABLE 2 THERMAL PROPERTIES OF MATERIALS

Material	Density (pcf)	Moisture Content (%)	Thermal Conductivity (BTU/Hr-Ft-°F)			Heat Capacity (BTU/lb-°F)		
			Unfrozen	Freezing	Frozen	Unfrozen	Freezing	Frozen
Asphalt concrete	148	2.0	0.7	0.7	0.7	0.22	1.44	0.22
Stabilized base	146	9.4	1.92	2.22	2.52	0.24	6.19	0.19
Portland cement concrete	150	3.0	1.25	1.29	1.33	0.22	2.16	0.22
Cohesive subgrade	129	17.0	0.92	1.02	1.13	0.29	10.49	0.22

TABLE 3 PAVEMENT TEMPERATURE AND *MMAT* FOR 12-IN. FULL-DEPTH AC PAVEMENT (°F)

	JAN.	FEB.	MARCH	APRIL	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
ROCKFORD, IL												
MMAT*	21.0	24.6	35.6	48.5	59.4	69.1	74.0	71.9	64.2	52.3	38.4	26.0
1.5 in	25.1	29.2	41.5	56.7	69.5	80.3	85.5	82.3	72.1	57.5	42.3	29.5
Temp @ 6.0 in	27.8	29.9	40.5	54.8	67.2	77.8	83.3	81.1	72.3	58.7	44.4	32.0
10.5 in	30.3	30.7	39.7	53.1	65.0	75.3	81.2	79.9	72.3	59.8	46.4	34.3
URBANA, IL												
MMAT*	26.1	28.8	39.5	51.4	61.8	71.3	75.2	73.2	66.7	55.0	41.2	30.1
1.5 in	29.7	33.5	45.7	59.7	71.9	81.9	85.8	82.8	74.9	61.1	45.7	33.5
Temp @ 6.0 in	31.4	33.9	44.7	57.8	69.6	79.4	83.8	81.6	74.8	62.1	47.6	35.7
10.5 in	33.1	34.4	43.9	56.1	67.4	77.0	81.7	80.6	72 3	63.0	49.5	37.7
CAIRO, IL												
MMAT*	35.9	39.2	48.4	59.4	68.3	77.0	80.5	78.6	72.2	61.2	48.7	38.9
1.5 in	39.3	43.9	54.7	68.0	81.7	88.4	92.2	89.5	80.9	67.4	53.2	42.4
Temp @ 6.0 in	40.1	43.8	53.4	65.9	76.6	85.7	89.9	88.0	80.5	68.1	54.7	44.1
10.5 in	40.9	43.7	52.2	63.8	74.2	83.1	87.6	86.5	80.0	68.7	56.1	45.6

* MMAT - Mean Monthly Air Temperature

A typical 12-in. full-depth AC pavement (see Table 2 for material thermal properties) was analyzed for Rockford, Urbana, and Cairo, Illinois. Average monthly AC temperatures for 1.5-, 6-, and 10.5-in. depths in the full-depth section are summarized in Table 3. Mean monthly air temperature (*MMAT*) data are also included in Table 3 for comparison purposes. Linear regression analyses indicated that AC pavement temperature could be accurately predicted from air temperature data. The regression equations (developed from the combined data base for Rockford, Urbana, and Cairo) are

For 1.5-in. depth

$$T_{AC} = 1.15\ MMAT - 0.6$$
$$R^2 = 0.996,\ SEE = 1.4$$

For 6-in. depth

$$T_{AC} = 1.08\ MMAT + 2.9$$
$$R^2 = 0.999,\ SEE = 0.8$$

For 10.5-in. depth

$$T_{AC} = 1.0\ MMAT + 6.3$$
$$R^2 = 0.994,\ SEE = 1.5$$

where T_{AC} is AC mixture temperature (°F) and *MMAT* is mean monthly air temperature (°F); the average air temperature for a shorter time period, perhaps a week, would also be suitable.

Note the consistent progression (with depth) of the *MMAT* coefficients and the intercepts for the regression equations. The coefficient decreases and the intercept increases with depth. An equation that includes a depth parameter was developed:

$$T_{AC} = (0.76\ Z - 1.7) + (1.18 - 0.017\ Z)\ MMAT$$

where Z is depth from AC pavement surface in inches.

A comparison of the Shell *MMAT*–pavement temperature relation and the heat-transfer model data is shown in Figure 8.

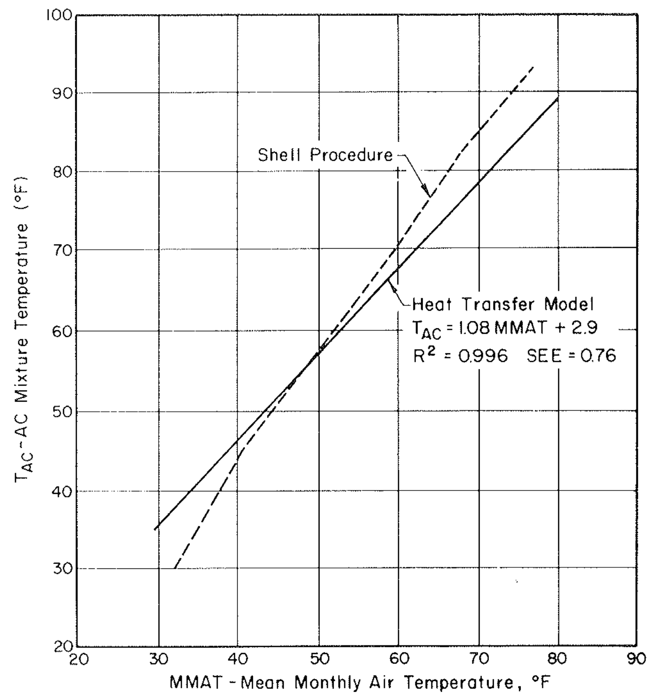

FIGURE 8 Comparison of Shell and heat-transfer model predictions.

The Shell-predicted pavement temperatures are in general larger, particularly at higher *MMAT*.

The Asphalt Institute procedure *(13)* based on Witczak's study *(14)* for estimating AC pavement temperatures is

$$MMPT = MMAT\ \ 1 + \left(1\ \ \frac{1}{z+4}\right) - \frac{34}{z+4} + 6$$

where

MMPT = mean monthly pavement temperature (°F),
MMAT = mean monthly air temperature (°F), and
z = depth in pavement layer (in.).

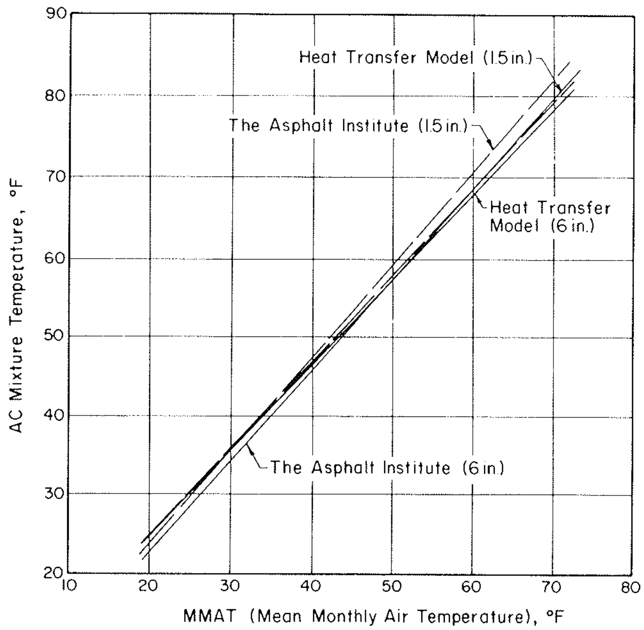

FIGURE 9 Comparison of the Asphalt Institute and heat-transfer model predictions.

Figure 9 shows comparisons between the Asphalt Institute procedure and the regression equations developed from the heat-transfer model data for the combined Rockford, Urbana, and Cairo data base. The agreement is excellent. It is encouraging to achieve such good concurrence between a theoretical heat flow model and a procedure derived from the statistical analysis of a comprehensive field-measured temperature data base.

Portland Cement Concrete (PCC) Pavement Curling

Temperature variations with depth through a PCC slab produce curling. The PCC slab can curl up, or down, or remain flat depending on the temperature gradient. There are large diurnal and seasonal variations in PCC slab gradients. The CMS heat-transfer model and Urbana, Illinois, climatic data were used to establish typical temperature-depth relations for a 9-in. PCC slab. Thermal properties of the PCC and subgrade soil are given in Table 4. Typical diurnal effects are shown in Figures 10–12 for April, July, and November.

TABLE 4 TEMPERATURE EFFECTS ON FWD DEFLECTION (9-in. PCC slab)

Time	8-Kip Deflection[a] (mils)	Air Temperature (°F)
7:45 a.m.	26.0	69
9:00 a.m.	17.5	76
10:30 a.m.	12.5	79
11:30 a.m.	9.0	83
1:00 p.m.	11.0	84
2:00 p.m.	8.0	87
3:00 p.m.	9.5	85
4:00 p.m.	10	82

[a]Edge loading at a transverse joint (dowel load transfer).

It is apparent that PCC temperature-depth relations are complex. A constant gradient (maximum temperature difference/slab depth) is obviously not the general case. In future University of Illinois studies, procedures will be developed to more accurately characterize temperature and depth relations and

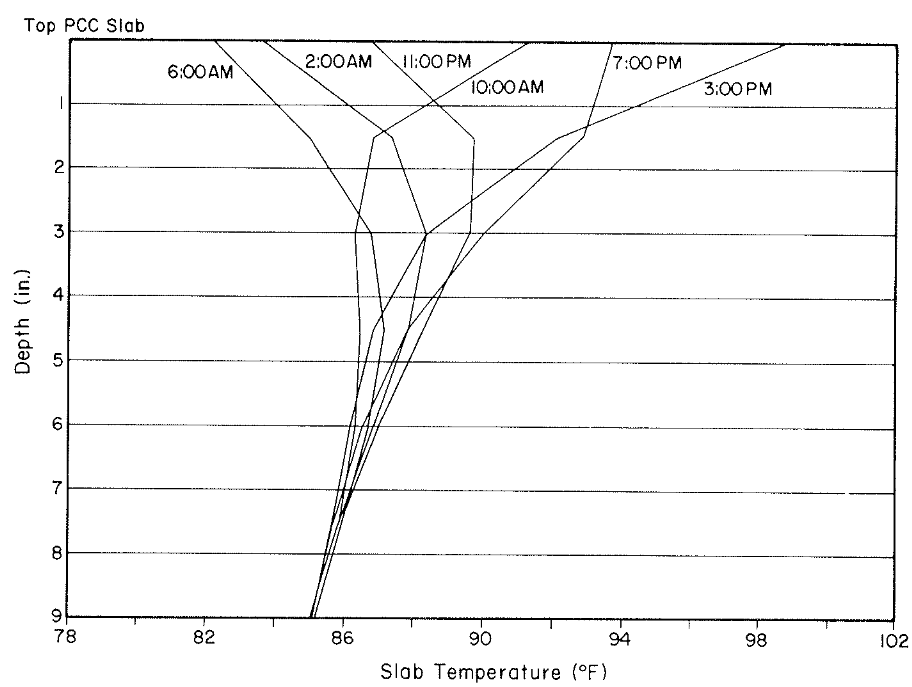

FIGURE 10 Temperature distribution in PCC slab (April, Urbana, Illinois).

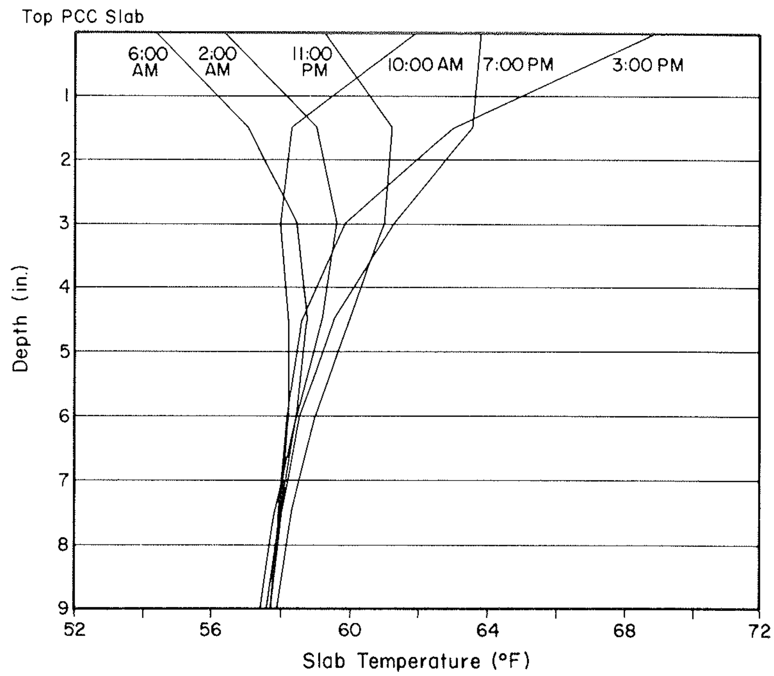

FIGURE 11 Temperature distribution in PCC slab (July, Urbana, Illinois).

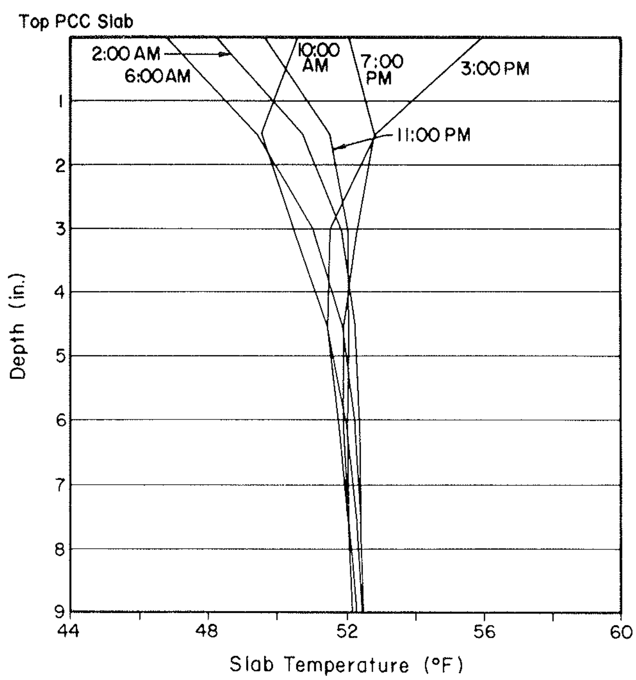

FIGURE 12 Temperature distribution in PCC slab (November, Urbana, Illinois).

PCC slab curling mechanics. Curling stresses should be included in the analysis and design of PCC pavements. The nondestructive testing deflection data in Table 4 demonstrate the significant effect of temperature on the structural response of pavement. The increased early morning deflections are due to the curled-up condition of the PCC slab and the accompanying loss of slab support.

SUMMARY

Pavement temperatures can be accurately quantified with the CMS computer model developed at the University of Illinois. Required CMS inputs for temperature modeling are *(a)* thermal properties of materials and soils, *(b)* air temperature data, *(c)* solar radiation data, and *(d)* wind velocity data.

In this paper the development and use of a comprehensive Illinois Climatic Data Base for Pavements are presented. Air temperature data are summarized on a weekly basis and solar radiation and wind speed data are presented in the form of a monthly state map.

Illustrative applications-oriented examples are presented for

- Strength–degree-day curing relations for pozzolanic stabilized base materials,
- Asphalt concrete moduli–pavement temperature effects, and
- Temperature gradients in portland cement concrete slabs.

The emphasis in the paper is on the concepts and techniques used to establish the Illinois Climatic Data Base for Pavements. The illustrative information demonstrates the versatility and usefulness of the Climatic Data Base and heat-transfer model procedures in pavement analysis and design.

The procedures and techniques described can be used to establish a climatic data base for other states and locations. The climatic data base–CMS model approach is recommended for quantifying temperature effects in flexible and rigid pavement analysis and design.

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