Calculation of Maximum Pavement Temperatures From Weather Reports

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Pavement temperatures are of interest in connection with stabilization of bituminous surfaces, curing and curling of portland cement concrete, and moisture movements in any type of pavement.

This paper presents a relation between pavement temperature and wind, precipitation, air temperature, and solar radiation, as controlled by the thermal properties of the pavements.

● **PAVEMENT** temperatures are of interest in connection with stability of bituminous surfaces, curing and curling of portland cement concrete, and moisture movements in any type of pavement.

In order to extrapolate directly observed temperatures to other localities and times, it would be convenient if pavement temperatures were correlated with standard weather reports.

The following discussion presents a relation between pavement temperatures and the wind, precipitation, air temperature, and solar radiation as controlled by the thermal properties of the pavement.

THEORY

For a semi-infinite mass in contact with air at a temperature $T_M + T_V \sin 0.262\,t$, the 24-hour periodic temperature of the mass is (1):

$$T = T_M + T_V \frac{H e^{-xC}}{\sqrt{(H+C)^2 + C^2}} \sin\left(0.262t - xC - \arctan \frac{C}{H+C}\right) \quad (1)$$

in which
- T = temperature of mass;
- T_M = mean effective air temperature, F;
- T_V = maximum variation in temperature from mean, F;
- t = time from beginning of cycle, hours;
- x = depth below surface, feet;
- $H = h/k$;
- h = surface coefficient, BTU per sq ft per hour, F;
- k = conductivity, BTU per sq ft per hour, F per ft;
- $C = \sqrt{0.131 \text{ per } c}$;
- c = diffusivity, ft sq per hour = $\frac{k}{sw}$;
- s = specific heat, BTU per pound F; and
- w = density, pounds per cu ft.

Figure 1 shows how the surface temperature varies with the air temperature.

For forced convection including average reradiation (2)

$$h = 1.3 + 0.62v^{3/4} \quad (2)$$

where v = wind velocity, mph, the average wind velocity is about 7.2 mph giving $h = 4.0$.

The surface also receives heat by solar radiation as indicated in Figure 2. The effective air temperature to include solar radiation (3) may be taken as:

$$T_E = T_a + \frac{b\,I}{h} \quad (3)$$

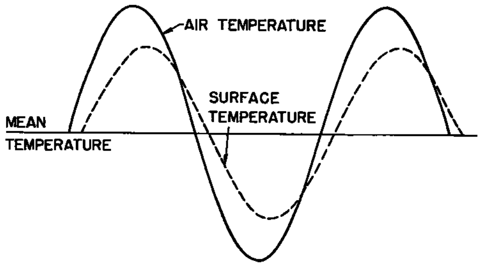

Figure 1. Surface temperature without radiation.

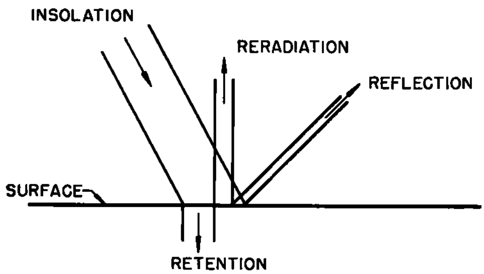

Figure 2. Distribution of insolation.

where T_E = effective air temperature, F;

T_a = air temperature, F;

b = absorptivity of surface to solar radiation;

I = solar radiation, BTU per sq ft hour.

The solar radiation received on a horizontal surface is reported in langleys per day or calories per square centimeter day, L, which is 3.69 BTU per sq ft day. There is an average net loss by long-wave reradiation (4) of about ⅓, so that R, the average contribution to effective air temperature, is:

$$R = 0.67b\ 3.69^{L}/24\ h \qquad (4)$$

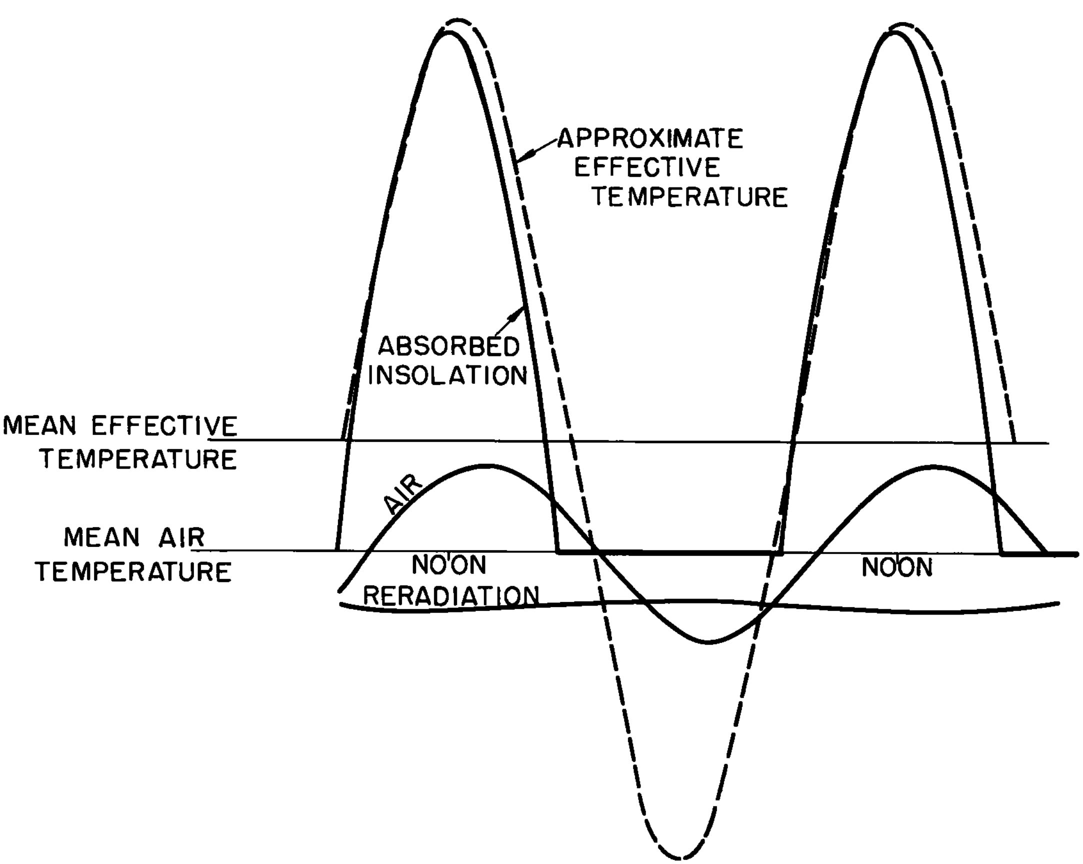

Figure 3. Effective temperature above horizontal surface.

The deviation of the radiation from this average may be roughly approximated by a sine wave with a half amplitude of 3R. Combining this with the air temperature, which is approximated by a sine wave with amplitude equal to the daily range in temperature, gives a sinusoidal effective temperature (see Figure 3). (A different curve is required for minimum temperature.) The maximum pavement temperature may then be calculated from equation 1, using

$$T_M = T_A + R \quad (5)$$

where T_A = average air temperature, F;

and $$T_V = 0.5\, T_R + 3R \quad (6)$$

where T_R = daily range in air temperature, F.

After a rain the evaporation of water would considerably decrease the maximum temperatures due to insolation. For instance, the evaporation of 0.1 in. of water requires 0.1 x 2.54 x 539 = 137 calories per sq centimeter which is a considerable portion of a summer day's radiation.

COMPARISONS FOR BITUMINOUS PAVEMENT

Calculated values will be compared with those observed on the surface of a bituminous concrete pavement at Hybla Valley, Virginia, with the following considered assumptions:

h = 3.6 for a sheltered area;
k = 0.7 average value from texts;
s = 0.22 for dry stone plus asphalt;
w = 140 from field data; and
b = 0.95 for black surface.

These values give H = 5.14, c = 0.0227, C = 2.40 and R = 0.027 L. Substituting in equation 1, using equations 5 and 6, the maximum surface temperature (when sine function is one and x is zero) is

$$T_A + R + F(0.5\, T_R + 3R) \quad (7)$$

where $$F = \frac{H}{\sqrt{(H+C)^2 + C^2}} = \frac{H \text{ per } C}{\sqrt{(H \text{ per } C+1)^2 + 1}}$$ as tabulated below:

H per C	F
1	0.447
1.5	0.557
2	0.633
2.5	0.686
3	0.727
3.5	0.759
4	0.784
4.5	0.804
5	0.822

For H per C = 5.14 per 2.40 = 2.14, F = 0.65.

Table 1 shows the ambient conditions, the observed surface temperature and values calculated from the above formula. The agreement as shown in Figure 4 is generally good considering that L was measured 20 miles from the pavement. Where local temperatures are not available, more day to day deviation should be expected. In the present case, a weather station at another inland location reported similar temperatures, whereas one near the river reported consistently different temperatures.

Since equation 1 assumes that the cycle of temperatures has prevailed for a long time, a lag may be expected after a sudden change in T_M. Thus, when T_M changes

TABLE 1

CALCULATION OF MAXIMUM SURFACE TEMPERATURE OF BITUMINOUS PAVEMENT, HYBLA VALLEY, VIRGINIA

	Ambient Condition			Observed Surface	Calculated Values		
Date	T_A	T_R	L	Temp.	R	0.65 (0.5 T_R + 3R)	Surface Temperature
1953	F	F	Lang.	F	F	F	F
May 21	69	28	526	122	14	37	120
22	71	18	270	103	7	20	98
23	70	7	616	118	17	35	122
24	61	31	479	113	13	35	109
25	68	25	268	104	7	22	97
26	74	29	462	122	12	34	120
27	60	12	494	106	13	30	103
28	50	32	747	116	20	50	120
29	56	37	715	126	19	50	125
30	64	30	381	118	10	30	104
July 31	84	20	526	133	14	34	132
Aug. 1	92	16	430	134	12	29	132
2	92	18	423	131	11	28	131
3	87	26	396	127	11	30	128
4	82	7	222	109	6	14	102
5	92	21	435	131	12	30	134

from 69 + 14 = 83 on May 21 to 71 + 7 = 78 on May 22, the observed temperature in Table 1 does not drop as much as calculated. Considering a sudden change in temperature, the lag, T_L, for large t and small x is (5):

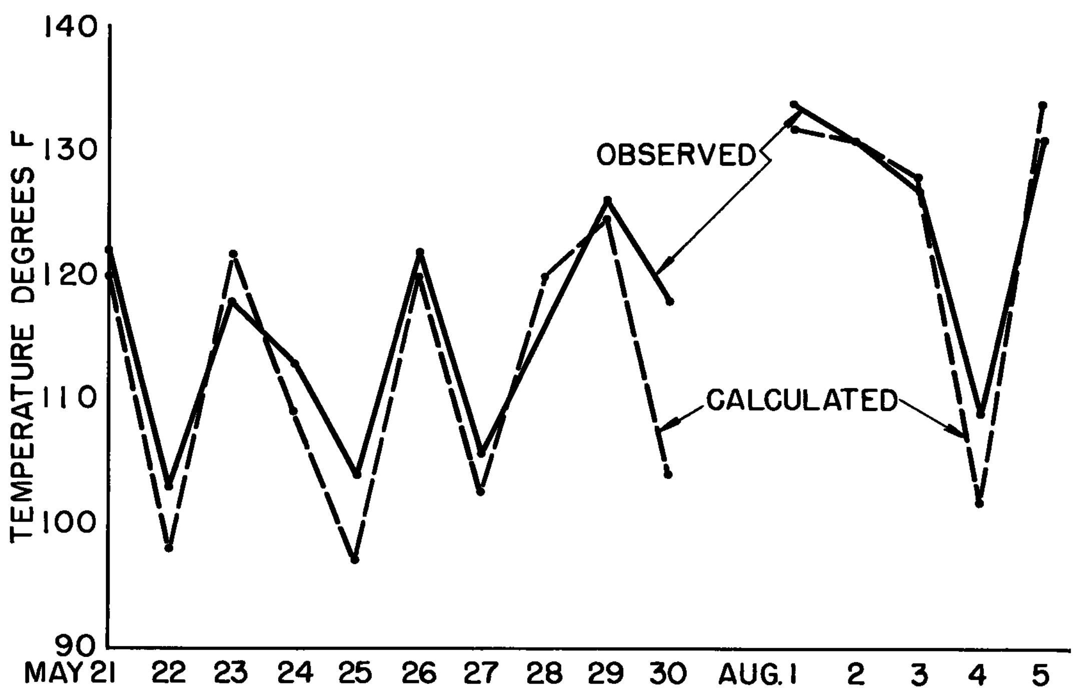

Figure 4. Bituminous pavement surface temperatures.

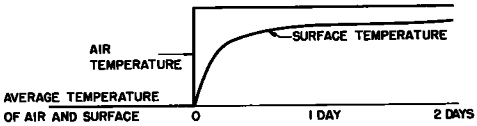

Figure 5. Lag in surface temperature.

$$T_L = \frac{x + 0.25}{\sqrt{\pi ct}} \qquad (8)$$

At the surface after 24 hours, the lag is about ⅛ the change in the mean, as illustrated in Figure 5, or 1 degree in the present case.

The larger deviations on May 25 and August 4 are probably due to less reradiation than the average because of clouds indicated by the low solar radiation received. The excessive deviation on May 30 is due to the fact that the radiation is averaged over the day in the calculations, whereas it was actually received before a rainstorm which started at 2:00 p.m.

TABLE 2

CALCULATED AND OBSERVED TEMPERATURES OF BITUMINOUS PAVEMENT IN IDAHO

	Ambient Condition			Maximum Temperature ¼ in Below Surface	
Date	T_A	T_R	L	Observed	Calculated
1953	F	F	Lang.	F	F
Sept 11	68	56	467	120	117
Oct. 19	52	21	325	68	80
Nov 19	22	30	233	48	48
Dec. 8	25	26	104	37	40
1954					
May 17	66	47	722	127	129

Using the same coefficients as above, except h = 4.4 for a bituminous pavement in an exposed location in Idaho, temperatures at a depth of ¼ in. were calculated and are shown in Table 2 compared to observed temperatures. From equation 1 the depth reduces the cyclic contribution by the factor $e^{-xC} = e^{-2.40 \text{ per } 48} = 0.95$, a reduction of 5 percent. The discrepancy in October is accounted for by clouds over the pavement which were not present at the nearest radiation station. The December calculated temperature is high because long-wave reradiation is under-estimated for winter months.

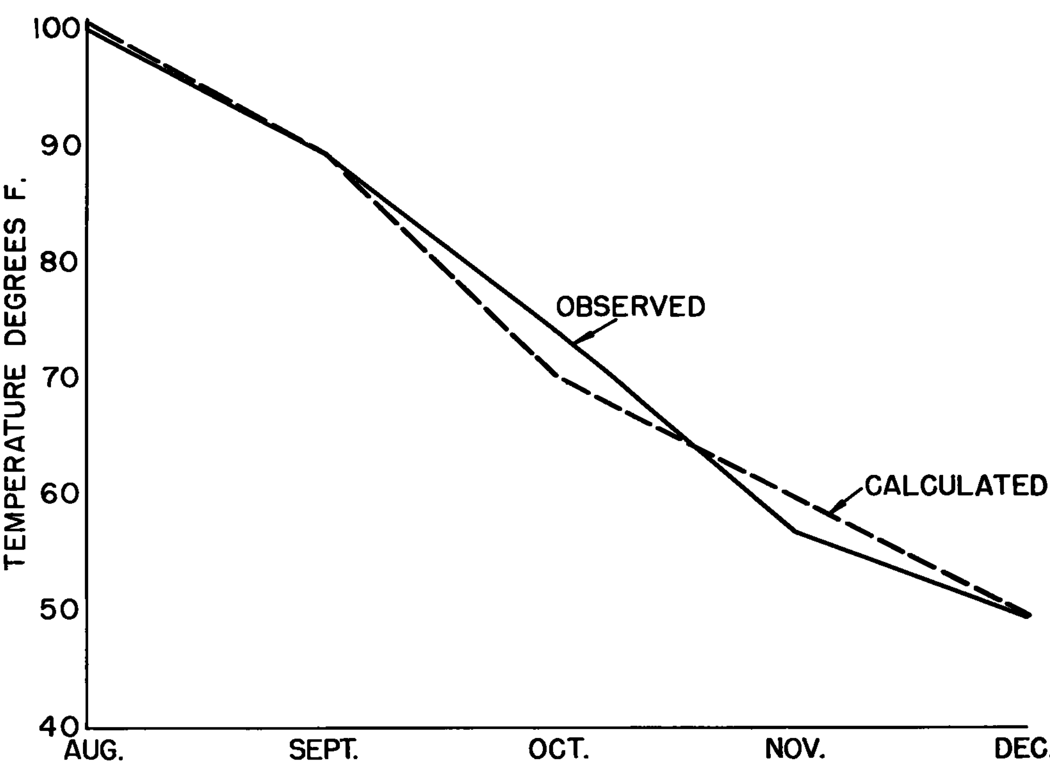

Figure 6. Average maximum temperatures--Bates road.

COMPARISON FOR CONCRETE PAVEMENT

Further comparison is available for two 6-in. portland cement concrete slabs at Langley, Virginia, to which the following values are assigned:

h = 4.4 for an exposed site;
s = 0.2 for good drainage; and
w = 150.

For sand and gravel concrete

k = 0.9 giving c = 0.030
b = 0.65 giving R = 0.015 L

For slag concrete

k = 0.45 giving c = 0.015
b = 0.70 giving R = 0.016 L.

TABLE 3

CALCULATION OF SURFACE TEMPERATURE OF PORTLAND CEMENT CONCRETE LANGLEY, VIRGINIA

	Ambient Conditions			Maximum Surface Temperature			
				Observed [a]		Calculated	
Date	T_A	T_R	L	Sand & Gravel	Slag	Sand & Gravel	Slag
1953	F	F	Lang	F	F	F	F
Aug 20	71	19	505	106	108	101	105
25	78	26	507	106	113	110	115
Sept 23	58	10	522	83	89	85	90

[a] 2 degrees added to off-peak readings

For the surface temperature equation 1 gives:

$$T_A + R + 0.67\ (0.5\ T_R + 3R) \text{ for sand and gravel; and}$$

$$T_A + R + 0.75\ (0.5\ T_R + 3R) \text{ for slag.}$$

Table 3 shows a reasonable correlation between observed and computed surface temperatures.

Table and Figure 6 show calculated and observed maximum temperatures for the Bates Road using locally observed temperatures (6) and monthly radiation values taken from published maps (7). The insolation is a function of season and latitude as shown in Figure 7 but modified by local atmospheric conditions. The radiation for "normal" days is taken as the average monthly radiation.

TABLE 4

CALCULATED AND OBSERVED MAXIMUM TEMPERATURES ON BATES ROAD

	Average Temperature for Normal Days						Calculated Pavement Temperature	
	Air			Pavement Maximum				
Month	Max.	Min.	Ave.	Surface	3.5 in. Deep	Average Radiation	Surface	3.5 in. Deep
1922	F	F	F	F	F	Langleys	F	F
Aug.	87	59	73	100	95	470	100.5	92
Sept.	80	52	66	89.5	85	320	89.5	82
Oct.	65	36	50.5	74.5	69.5	270	70.5	63.5
Nov.	58	33	45.5	57	54	170	60	55
Dec.	49	29	39	49.5	45.5	120	50	46

It is assumed that h = 4.8, c = 0.04, k = 1.2, b = 0.6 for poorly drained portland cement concrete, giving R = 0.013 L and maximum surface temperature equal

$$T_A + R + 0.66\ (0.5\ T_R + 3R)$$

Although equation 1 assumed homogeneous material, numerical calculations (8) indicate that a change of conductivity of as much as 50 percent below 7 in. (bottom of slab) has only a small effect on the temperature difference between the surface and a depth of 3.5 inches.

Table 5 shows a similar comparison for a concrete road in Kansas (9) using the same coefficients as assumed for sand and gravel concrete in Table 3.

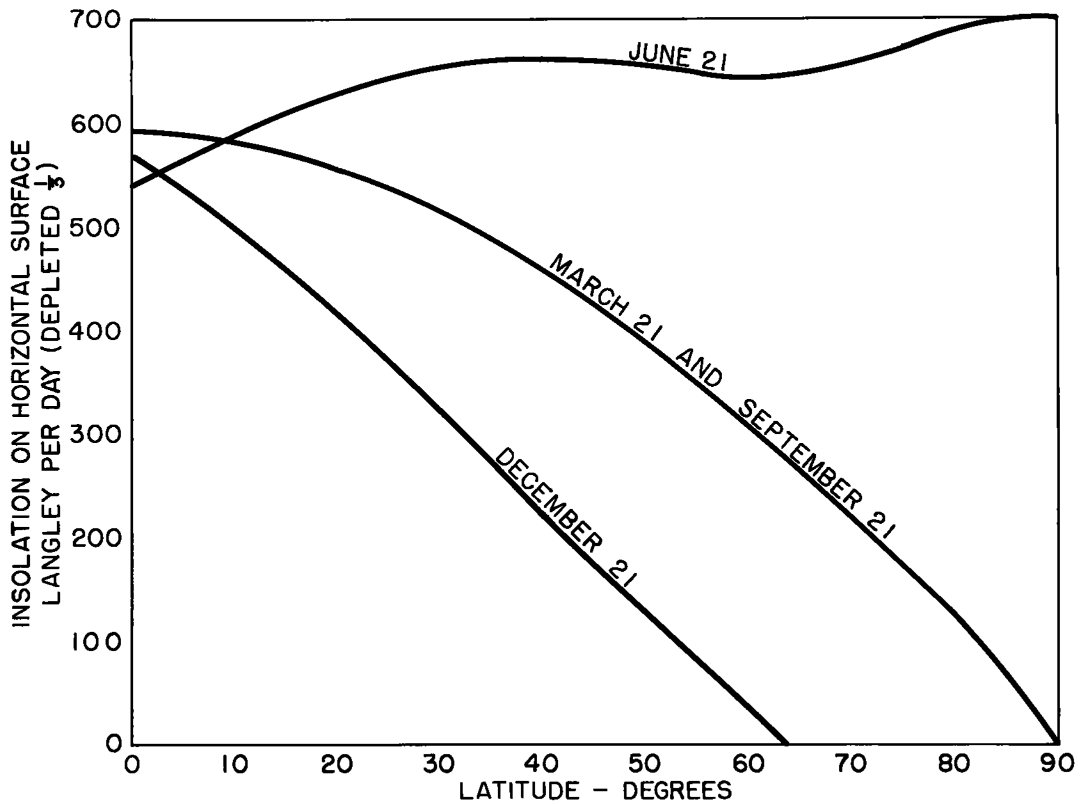

Figure 7. Insolation vs latitude.

TABLE 5

CALCULATED TEMPERATURE 1 INCH BELOW CONCRETE SURFACE IN KANSAS

Date 1940	T_A	T_R	L	Temp 1 in Below Surface, F Observed	Calculated
	F	F	Lang		
July 30	89	22	750	126	126
Sept 20	74	18	540	105	101
Oct 17	58	26	420	83	82
Apr 27	63	22	690	96	97
June 26	83	18	790	120	120

CONCLUSIONS

The foregoing calculations indicate the possibility of roughly correlating surface temperatures with values reported by the Weather Bureau so that means are available to extrapolate field observed temperatures to other times and places. To calculate exact temperatures for a given structure, exact values of its thermal properties and the ambient conditions must be known.

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