TEMPERATURE DISTRIBUTIONS IN ASPHALTIC CONCRETE PAVEMENTS

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The straight-line relationship derived from Maryland data between temperatures at a given depth and the surface temperatures plus 5-day average air temperatures is as valid for upper New York State and Arizona as for Maryland. The main differences were in the annual ranges and annual mean temperatures. The concept for estimating pavement temperature distributions appears to be valid and may be used with confidence for estimating pavement temperatures at all latitudes and longitudes.

ASPHALTS are susceptible to temperature change. Similarly, the structural responses of bituminous concrete pavement systems to traffic loadings vary with temperature fluctuations. Surface deflection or rebound is a readily measurable response of a pavement system to a load. The correlations between loads and deflections may be improved by adjusting measured deflections to an equivalent deflection at a common (or base) temperature to reduce the effect of the temperature variable. Under normal conditions of measuring surface deflection, only the surface temperature at the time of measurement can be conveniently determined. Previous analyses indicated that the long-term influences on pavement temperature could be reasonably accounted for by using a 5-day air temperature history. Accordingly, a technique (1) for adjusting pavement deflection measurements to a reference mean pavement temperature was developed. Mean pavement temperatures were estimated from the measured pavement surface temperature at the time of the deflection measurement and the mean daily air temperatures for the previous 5 days as an indication of the air temperature history. This method was simplified by the Asphalt Institute (2).

The method of estimating pavement temperatures at depths raised several questions:

1. What is the effect on the accuracy of the temperature estimating system of such variables as altitude, latitude, longitude, and solar exposure?
2. Does the straight-line relationship (1) based on Maryland data (3) hold true for data from other locations?
3. If other data sets are combined with the Maryland data, does the accuracy of the estimate increase?
4. Can graphs developed from the Maryland data set be used with confidence for other locations?

To answer these questions required that additional data sets be acquired and analyzed. Straub (4) of Clarkson College in upper New York and Jimenez (5) of the University of Arizona, Tucson, supplied data sets for this analysis. Their cooperation is greatly appreciated.

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Table 1. Temperature distributions in asphaltic concrete pavements at 8:00 a.m.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-3.6	0.533	0.985	3.0
	New York	-0.5	0.520	0.985	2.8
	Arizona	-1.9	0.525	0.995	2.0
	Combined	-2.2	0.527	0.988	2.9
	Adjusted	-2.3	0.527	0.988	3.0
4	Maryland	-1.4	0.528	0.987	2.8
	New York	0.3	0.523	0.986	2.8
	Arizona	2.3	0.504	0.994	2.0
	Combined	0.0	0.520	0.989	2.7
	Adjusted	0.5	0.516	0.990	2.7
6	Maryland	0.3	0.531	0.988	2.7
	New York	1.0	0.530	0.986	2.8
	Arizona	5.2	0.497	0.994	1.9
	Combined	1.5	0.523	0.990	2.7
	Adjusted	1.7	0.519	0.989	2.7
8	Maryland	1.6	0.535	0.987	2.9
	New York	1.4	0.537	0.986	2.9
	Arizona	7.9	0.494	0.994	2.0
	Combined	2.5	0.529	0.989	2.8
	Adjusted	2.9	0.523	0.990	2.7
10	Maryland	2.7	0.536	0.985	3.1
	New York	2.0	0.540	0.985	2.9
	Arizona	10.5	0.489	0.992	2.2
	Combined	3.4	0.532	0.987	3.0
	Adjusted	3.8	0.526	0.988	2.9
12	Maryland	4.3	0.532	0.983	3.3
	New York	3.8	0.532	0.982	3.2
	Arizona	11.3	0.486	0.992	2.2
	Combined	5.1	0.526	0.985	3.2
	Adjusted	5.5	0.520	0.986	3.1

Note: 1 in. = 25 mm.

Table 2. Temperature distributions in asphaltic concrete pavements at 10:00 a.m.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-3.5	0.532	0.987	3.1
	New York	-1.1	0.531	0.984	3.3
	Arizona	-6.4	0.540	0.995	2.2
	Combined	-1.8	0.522	0.988	3.3
	Adjusted	-2.1	0.527	0.988	3.3
4	Maryland	-2.2	0.501	0.978	3.8
	New York	1.3	0.489	0.979	3.5
	Arizona	-4.2	0.502	0.991	2.8
	Combined	0.0	0.485	0.982	3.7
	Adjusted	0.2	0.486	0.984	3.6
6	Maryland	-1.0	0.488	0.970	4.3
	New York	3.0	0.467	0.968	4.3
	Arizona	-1.9	0.485	0.988	3.0
	Combined	1.2	0.472	0.977	4.1
	Adjusted	1.2	0.473	0.978	4.1
8	Maryland	0.2	0.484	0.967	4.5
	New York	3.8	0.462	0.962	4.6
	Arizona	0.6	0.474	0.987	3.1
	Combined	2.2	0.468	0.975	4.2
	Adjusted	2.8	0.464	0.976	4.2
10	Maryland	1.4	0.482	0.966	4.6
	New York	4.2	0.465	0.963	4.5
	Arizona	3.1	0.463	0.985	3.2
	Combined	3.5	0.465	0.975	4.3
	Adjusted	3.9	0.463	0.975	4.3
12	Maryland	2.8	0.479	0.965	4.6
	New York	5.8	0.456	0.960	4.7
	Arizona	4.7	0.457	0.986	3.1
	Combined	4.9	0.460	0.974	4.3
	Adjusted	5.4	0.457	0.974	4.3

Note: 1 in. = 25 mm.

Table 3. Temperature distributions in asphaltic concrete pavements at noon.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-2.5	0.546	0.989	3.2
	New York	-2.4	0.565	0.986	3.8
	Arizona	-7.4	0.563	0.993	2.7
	Combined	-1.4	0.541	0.988	3.8
	Adjusted	-1.7	0.547	0.988	3.7
4	Maryland	0.1	0.482	0.983	3.6
	New York	1.1	0.493	0.985	3.4
	Arizona	-9.3	0.524	0.986	3.6
	Combined	0.6	0.480	0.982	4.0
	Adjusted	0.1	0.486	0.985	3.8
6	Maryland	1.7	0.447	0.966	4.8
	New York	3.8	0.444	0.969	4.4
	Arizona	-9.1	0.498	0.980	4.2
	Combined	1.9	0.446	0.971	4.8
	Adjusted	1.4	0.453	0.984	4.6
8	Maryland	2.8	0.430	0.952	0.6
	New York	5.3	0.421	0.954	5.1
	Arizona	-6.5	0.473	0.976	4.4
	Combined	3.2	0.427	0.963	5.3
	Adjusted	3.4	0.429	0.965	5.1
10	Maryland	4.0	0.422	0.944	5.8
	New York	6.0	0.415	0.948	5.4
	Arizona	-3.2	0.451	0.972	4.5
	Combined	4.7	0.415	0.958	5.5
	Adjusted	4.4	0.419	0.959	5.4
12	Maryland	5.5	0.413	0.937	6.1
	New York	7.8	0.398	0.937	5.8
	Arizona	-2.3	0.447	0.971	4.5
	Combined	5.8	0.408	0.953	5.7
	Adjusted	5.7	0.411	0.955	5.6

Note: 1 in. = 25 mm.

Table 4. Temperature distributions in asphaltic concrete pavements at 2:00 p.m.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-2.7	0.574	0.986	4.0
	New York	-3.2	0.595	0.984	4.4
	Arizona	-5.6	0.580	0.992	3.1
	Combined	-1.7	0.569	0.987	4.3
	Adjusted	-2.1	0.576	0.987	4.3
4	Maryland	1.1	0.501	0.987	3.5
	New York	1.4	0.514	0.988	3.4
	Arizona	-7.1	0.539	0.987	3.6
	Combined	1.1	0.503	0.986	3.8
	Adjusted	0.4	0.511	0.989	3.5
6	Maryland	3.6	0.451	0.976	4.2
	New York	4.9	0.452	0.977	4.1
	Arizona	-7.4	0.508	0.983	3.9
	Combined	3.0	0.457	0.979	4.4
	Adjusted	2.1	0.467	0.981	4.2
8	Maryland	5.2	0.422	0.962	5.1
	New York	6.8	0.417	0.961	5.0
	Arizona	-6.9	0.484	0.979	4.1
	Combined	4.4	0.428	0.969	5.0
	Adjusted	4.1	0.433	0.972	4.7
10	Maryland	6.3	0.406	0.950	5.6
	New York	7.9	0.400	0.952	5.3
	Arizona	-5.7	0.466	0.974	4.4
	Combined	5.6	0.410	0.961	5.4
	Adjusted	4.8	0.418	0.963	5.3
12	Maryland	7.4	0.392	0.937	6.2
	New York	10.0	0.375	0.935	5.9
	Arizona	-4.5	0.457	0.973	4.5
	Combined	6.4	0.399	0.953	5.8
	Adjusted	6.0	0.405	0.956	5.6

Note: 1 in. = 25 mm.

ANALYSES AND RESULTS

The same computer program was used to separately analyze the New York and Arizona data sets as was used to analyze the Maryland data set (1). The analyses indicated that a straight-line relationship, $y = A + Bx$, was equally valid for all data sets; however, the equations were not identical (Tables 1 through 6). The major differences among the data sets were in the annual temperature ranges and annual mean temperatures. Inspection of the data and least squares fits showed that, for a given hour, depth, and surface temperature plus 5-day average air temperature history, temperatures differed by as much as 10 F (5.6 C) in the upper (extrapolated) ranges (Figure 1). Closer inspection showed that, when the equation was solved for temperatures within the temperature range for the respective sites, the discrepancies were minimal and generally within the limits of scatter of the Maryland data set.

The scatter (standard error of estimate) for the New York and Arizona data sets was generally less than the scatter for the Maryland data for corresponding depths. However, there were fewer observations. Figure 2 shows the data for 1:00 p.m. and a 4-in. (102-mm) depth. Slight rotational and horizontal shifts were observed in the New York and Arizona data as compared to the Maryland data.

From the standpoint of longitudes, the New York site was 8 clock minutes earlier than the Maryland site; the Arizona site was 16 clock minutes behind the equivalent Maryland clock time. To adjust for these longitudinal effects, New York and Arizona clock times were determined for the appropriate Maryland sun times. Interpolated pavement temperatures for those adjusted clock times were plotted. Figure 3 shows the same data as in Figure 2 but adjusted for longitudinal differences. A threefold net effect of the longitudinal adjustment was noted:

1. The rotational shifts in the fitted straight lines were less,
2. The horizontal shifts between the data sets were less, and
3. Longitudinal adjustments for depths from the surface down to the 2-in. (51-mm) depth were very slight and are likely to be unnecessary [longitudinal adjustments appear to begin to be significant for depths equal to and greater than 4 in. (102 mm)].

The adjustments for longitude resulted in a closer grouping of the data, which fell within the outer limits of the Maryland data. The increased number of observations within the same limits reduces the standard error of estimate and increases the correlation coefficient.

Whether the scatter of pavement temperature data could be reduced by analyzing the data on the basis of daytime exposure to solar radiation was investigated. Analyses were made for sunrise, midmorning, midday, midafternoon, and sunset.

Sunrise = SR

Midmorning = SR + 0.25 (SS - SR)

Midday = SR + 0.50 (SS - SR)

Midafternoon = SR + 0.75 (SS - SR)

Sunset = SS

where SR = sunrise clock time and SS = sunset clock time, obtained from tables prepared by the Nautical Almanac Office, U. S. Naval Observatory.

After clock times for these five points in time were determined for each day, pavement temperatures were interpolated, recorded, plotted, and analyzed. The results are given in Tables 7 through 11. The scatter of data decreased for the sunrise, midmorning, and sunset times but increased for midday and midafternoon. The wider

Table 5. Temperature distributions in asphaltic concrete pavements at 4:00 p.m.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-2.7	0.595	0.985	4.4
	New York	-3.7	0.613	0.982	5.0
	Arizona	-0.2	0.577	0.991	3.1
	Combined	-2.1	0.593	0.986	4.5
	Adjusted	-2.8	0.600	0.985	4.6
4	Maryland	2.5	0.526	0.988	3.6
	New York	1.2	0.542	0.987	3.8
	Arizona	0.5	0.544	0.986	3.7
	Combined	1.4	0.537	0.988	3.7
	Adjusted	1.2	0.539	0.989	3.5
6	Maryland	5.8	0.474	0.987	3.4
	New York	4.9	0.482	0.984	3.6
	Arizona	0.0	0.519	0.982	4.1
	Combined	3.8	0.491	0.986	3.7
	Adjusted	3.4	0.496	0.986	3.7
8	Maryland	7.5	0.441	0.981	3.8
	New York	7.1	0.442	0.977	4.0
	Arizona	0.3	0.493	0.978	4.3
	Combined	5.5	0.458	0.980	4.1
	Adjusted	5.3	0.460	0.981	3.9
10	Maryland	8.5	0.420	0.972	4.3
	New York	8.5	0.416	0.970	4.4
	Arizona	1.7	0.468	0.973	4.5
	Combined	6.6	0.434	0.974	4.5
	Adjusted	6.4	0.437	0.973	4.5
12	Maryland	9.9	0.399	0.961	5.0
	New York	10.7	0.386	0.955	5.0
	Arizona	2.6	0.456	0.969	4.7
	Combined	7.7	0.416	0.964	5.1
	Adjusted	7.7	0.417	0.963	5.1

Note: 1 in. = 25 mm.

Table 6. Temperature distributions in asphaltic concrete pavements at 6:00 p.m.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-5.0	0.619	0.984	4.6
	New York	-3.9	0.621	0.979	5.2
	Arizona	-2.7	0.603	0.989	2.9
	Combined	-4.3	0.618	0.982	4.8
	Adjusted	-4.7	0.619	0.982	4.9
4	Maryland	0.6	0.570	0.985	4.1
	New York	0.2	0.577	0.983	4.3
	Arizona	-0.8	0.594	0.984	3.3
	Combined	0.1	0.577	0.984	4.2
	Adjusted	0.3	0.574	0.985	4.0
6	Maryland	4.9	0.523	0.986	3.6
	New York	3.7	0.531	0.986	3.6
	Arizona	0.0	0.576	0.982	3.5
	Combined	3.7	0.534	0.985	3.7
	Adjusted	3.6	0.532	0.986	3.7
8	Maryland	7.4	0.488	0.986	3.3
	New York	6.0	0.492	0.987	3.2
	Arizona	0.5	0.557	0.980	3.6
	Combined	5.9	0.500	0.985	3.5
	Adjusted	5.9	0.498	0.986	3.4
10	Maryland	8.6	0.465	0.985	3.4
	New York	7.6	0.461	0.986	3.1
	Arizona	1.1	0.538	0.976	3.8
	Combined	7.2	0.474	0.982	3.6
	Adjusted	7.4	0.470	0.982	3.6
12	Maryland	10.2	0.439	0.979	3.7
	New York	9.8	0.429	0.980	3.5
	Arizona	2.7	0.518	0.974	3.8
	Combined	9.0	0.448	0.975	4.0
	Adjusted	9.0	0.444	0.976	4.0

Note: 1 in. = 25 mm.

Figure 1. Temperature at 2-in. (51-mm) depth at 11:00 a.m.

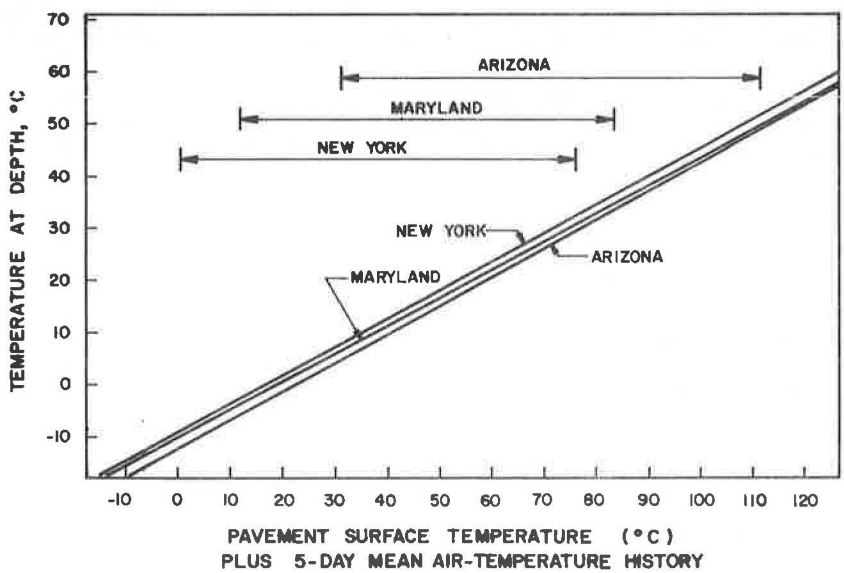

Figure 2. Temperatures at 4-in. (102-mm) depth at 1:00 p.m.

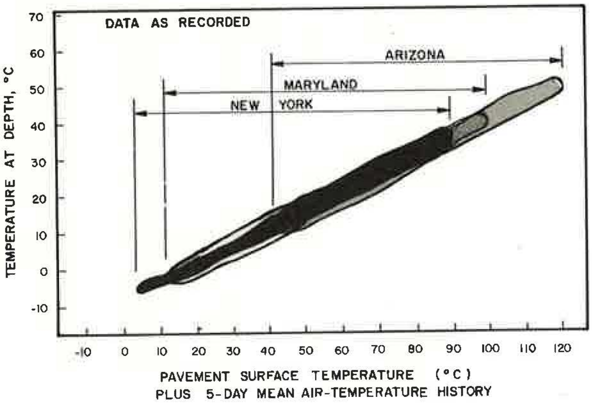

Figure 3. Temperatures at 4-in. (102-mm) depth at 1:00 p.m. adjusted to equivalent Maryland longitude.

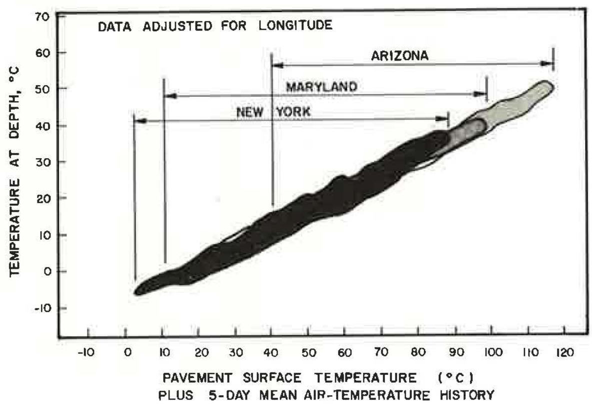

Table 7. Temperature distributions in asphaltic concrete pavements at sunrise.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-5.2	0.561	0.988	2.8
	New York	-0.7	0.532	0.982	3.1
	Arizona	-2.0	0.534	0.993	2.2
	Combined	-3.1	0.547	0.985	3.0
4	Maryland	-2.8	0.573	0.990	2.6
	New York	-0.3	0.555	0.982	3.3
	Arizona	-0.2	0.546	0.996	1.8
	Combined	-1.5	0.563	0.987	2.9
6	Maryland	-1.7	0.579	0.988	2.9
	New York	0.5	0.565	0.981	3.5
	Arizona	1.4	0.554	0.995	1.8
	Combined	-0.5	0.571	0.986	3.1
8	Maryland	-0.3	0.585	0.987	3.1
	New York	1.4	0.565	0.980	3.6
	Arizona	3.3	0.557	0.994	2.1
	Combined	0.6	0.576	0.985	3.2

Note: 1 in. = 25 mm.

Table 8. Temperature distributions in asphaltic concrete pavements during midmorning.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-3.1	0.525	0.980	3.3
	New York	-0.1	0.516	0.983	3.0
	Arizona	-6.0	0.544	0.994	2.1
	Combined	-2.0	0.521	0.985	3.1
4	Maryland	-4.4	0.541	0.983	3.2
	New York	-0.8	0.525	0.983	3.1
	Arizona	-5.2	0.530	0.992	2.4
	Combined	-1.6	0.518	0.983	3.3
6	Maryland	-5.2	0.553	0.982	3.4
	New York	-0.7	0.534	0.982	3.2
	Arizona	-4.3	0.529	0.991	2.5
	Combined	-1.6	0.525	0.982	3.5
8	Maryland	-4.5	0.562	0.984	3.3
	New York	-0.3	0.537	0.983	3.1
	Arizona	-2.1	0.526	0.990	2.6
	Combined	-0.9	0.531	0.984	3.4

Note: 1 in. = 25 mm.

Table 9. Temperature distributions in asphaltic concrete pavements during midday.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-2.4	0.548	0.986	3.7
	New York	-2.7	0.571	0.984	4.0
	Arizona	-6.8	0.563	0.993	2.8
	Combined	-1.3	0.543	0.986	4.0
4	Maryland	0.4	0.482	0.982	3.7
	New York	1.1	0.493	0.984	3.5
	Arizona	-9.9	0.531	0.988	3.5
	Combined	0.4	0.484	0.983	4.0
6	Maryland	1.5	0.451	0.970	4.5
	New York	3.8	0.448	0.972	4.2
	Arizona	-9.7	0.506	0.981	4.1
	Combined	1.7	0.451	0.973	4.7
8	Maryland	2.8	0.434	0.957	5.2
	New York	5.0	0.427	0.960	4.8
	Arizona	-6.1	0.473	0.977	4.3
	Combined	3.4	0.429	0.965	5.1

Note: 1 in. = 25 mm.

Table 10. Temperature distributions in asphaltic concrete pavements during midafternoon.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-4.9	0.603	0.984	4.6
	New York	-4.5	0.618	0.981	5.1
	Arizona	-5.9	0.599	0.992	3.0
	Combined	-3.4	0.595	0.984	4.7
4	Maryland	-1.4	0.536	0.985	4.0
	New York	-0.8	0.548	0.985	3.9
	Arizona	-8.4	0.574	0.987	3.7
	Combined	-1.4	0.540	0.986	4.1
6	Maryland	0.7	0.491	0.982	3.9
	New York	2.7	0.491	0.982	3.8
	Arizona	-9.3	0.547	0.981	4.2
	Combined	0.4	0.497	0.982	4.2
8	Maryland	2.9	0.458	0.975	4.3
	New York	4.8	0.452	0.974	4.4
	Arizona	-8.1	0.514	0.975	4.6
	Combined	2.6	0.460	0.975	4.6

Note: 1 in. = 25 mm.

Table 11. Temperature distributions in asphaltic concrete pavements at sunset.

Depth (in.)	Data Set	A	B	R	S.E.
2	Maryland	-4.4	0.613	0.979	4.7
	New York	-2.6	0.607	0.972	5.3
	Arizona	-2.6	0.596	0.987	2.8
	Combined	-3.4	0.607	0.977	4.8
4	Maryland	-2.4	0.602	0.983	4.0
	New York	-1.9	0.603	0.977	4.8
	Arizona	-5.7	0.616	0.988	2.7
	Combined	-2.1	0.600	0.981	4.3
6	Maryland	-1.2	0.578	0.985	3.7
	New York	-0.1	0.576	0.981	4.1
	Arizona	-8.1	0.622	0.986	3.0
	Combined	-1.0	0.578	0.983	3.9
8	Maryland	0.0	0.557	0.987	3.3
	New York	1.2	0.548	0.984	3.6
	Arizona	-9.7	0.614	0.983	3.2
	Combined	0.2	0.555	0.985	3.5

Note: 1 in. = 25 mm.

variations at midday and midafternoon may be caused by summer afternoon showers and variable cloud covers. Although this last analysis was of interest and needed to be investigated, the system is very awkward to use, does not provide greater accuracy, and is not recommended for general use. It does, however, lend credence to the original system.

DISCUSSION AND IMPLEMENTATION

Air temperature history adequately accounts for differences in latitude and altitude. Adjustments can be made for differences in longitude by interpolating between hourly graphs, which can be prepared from data given in Tables 1 through 6. If the purpose of estimating pavement temperatures is to determine the magnitude of the asphaltic tensile strain, longitudinal adjustments may well be worth the effort. If the objective is to adjust deflection data (1, 2), such refinements may not be justified. The Asphalt Institute (2) has proposed using one graph for estimating temperatures at various depths to calculate an average pavement temperature that can be used to adjust measured deflections to equivalent deflections at a standard temperature. The discrepancies due to use of one temperature distribution graph are greater than those caused by not adjusting for longitude. Furthermore, the choice of adjustment curves for deflection measurements will have a more pronounced effect than making no adjustment for longitude or exposure to solar radiation. Therefore, the set of equations based on Maryland data (1) may be used with confidence for other latitudes and longitudes.

SUMMARY

1. The addition of a 5-day average air temperature history to the surface temperature results in a straight-line correlation with temperature at a given depth. This relationship appears to be equally valid for data sets from upper New York State, Maryland, and Arizona.
2. The equations originally developed from the Maryland data set appear to be reasonably accurate for other locations.
3. The effects of changes in latitude are accounted for in the air temperature history. The net result is a shift up or down the temperature scale, reflecting the annual temperature range at a particular site.
4. Combining data from Maryland, New York, and Arizona resulted in slightly more scatter than the Maryland set alone.
5. Longitudinally adjusting the New York and Arizona data to equivalent Maryland times reduced the scatter and slightly improved the accuracy.
6. Analyzing all data sets in terms of daytime exposure to solar radiation also resulted in a straight-line correlation between surface temperature plus air temperature history and temperature at a given depth. The graphs for sunrise, midmorning, and sunset were more accurate than the Maryland graphs, whereas those for the midday and midafternoon were less accurate.
7. Analysis of the effect of daytime exposure to solar radiation validated the method of analysis used for the Maryland graphs but is too cumbersome.
8. Graphs derived from the Maryland data are recommended for use in other latitudes and longitudes. More accurate results may be obtained if the clock time at any site is adjusted to a longitude within the time zone equivalent to the College Park, Maryland, longitude of 76° 56' within the Eastern Standard Time zone.

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