PAVEMENT TEMPERATURES IN THE SOUTHWEST

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A study was conducted on a test section of asphalt pavement to produce needed temperature data from the desert portions of the Southwest. Solar radiation data were recorded concurrently for comparison with the temperature data. Typical temperature patterns for each month of the test period are presented and explained with the aid of heat transfer theory. Presentations of the data show the average minimum and maximum temperatures throughout the test period as well as the temperature durations at various levels. Evaluation of the statistics has led the authors to suggest possible additions to the present methods of testing asphaltic concrete for use in desert areas. Comparison between solar radiation and temperature substantiates the theory that shallow depths are greatly influenced by the sun's energy. Analysis of the data shows that prediction of pavement temperatures is possible with the use of information from weather reports of air temperature and solar radiation.

•THE DESIGN of asphaltic pavement has developed from an art, depending primarily on experience, to procedures based on analytical methods attempting to balance stress and strength. The return to the use of thick layers or many layers of asphaltic concrete in pavements has required that knowledge of surface and subsurface temperatures be known. The knowledge of temperature existing in the asphaltic structure is required because the stresses developed and strength of the asphaltic system are both temperature dependent.

In recognition of the need for the knowledge of temperature distribution in asphalt pavements, The Asphalt Institute has sponsored research to obtain such data. Kallas (5) and Straub et al. (12) have reported on measurements obtained from installations that served as guides for the present work. The Kallas data were obtained in Maryland and are assumed to represent average climatic conditions in the United States. The Straub measurements were made in Potsdam, New York, and represent conditions in a colder climate. It follows that data on pavement temperatures from the desert Southwest were required, and arrangements were made to obtain comparable measurements in Tucson, Arizona.

COLLECTION OF DATA

Temperature

The temperature data were recorded with the use of a Leeds and Northrup Speedomax G-12 point recorder on loan from The Asphalt Institute. The recorder printed temperatures from 0 to 200 F on a continuous roll of graph paper. Printing one temperature every 24 seconds, the recorder completed the 12-point cycle once every 4 minutes and 48 seconds or approximately every 5 minutes. The hourly temperatures at every depth and the maximum surface temperature for the day were taken from the printed sheets and recorded on prepared data sheets. A copy of a completed data sheet is shown in Figure 1.

The wires from the recorder and the wires from the thermocouples were joined together by a system of dual-point plugs. This system facilitated removal of the re-

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PERIOD: 15 June 1969 THRU 21 June 1969
* INDICATES APPROXIMATE AVERAGE RATE AT THAT TIME
DATA RECORDED AS $Btu/ft^2/hr$ AT THAT TIME

MONTH	June						
DAY	15	16	17X	18X	19X	20X	21X
TIME 0500	0	0	0	0	0	0	0
0600	22	18	22	22	25	22	25
0700	90	54*	88	88	90	88	92
0800	166	101*	157	157	160	160	164
0900	214*	124*	223	223	220	225	227
1000	286	214*	272	274	272	274	277
1100	319	180*	304	306	301	304	308
1200	326	326	322	324	319	322	331
1300	324	322*	324	322	319	324	333
1400	236*	306*	304	306	299	308	313
1500	292*	295*	268	268	265	274	277
1600	225*	70	218	218	216	223	225
1700	90*	216	146	151	148	155	155
1800	52	40	74	76	79	83	70
1900	11	16	16	16	16	16	18
MAX	328	360	326	324	324	328	335
TIME	1220	1130	1230	1230	1230	1245	1245

COMMENTS: X indicates a clear day

Figure 1. Temperature test data sheet.

corder from the test site whenever nevessary. Shortly after the pad was instrumented, the wires extending to the recorder were covered with a plastic sheath, and this proved to be a mistake. The purpose of the plastic was to protect the wires from the weather and keep them dry. Instead, condensation collected inside the shield, and the moisture on the wires seemed to affect the temperature readings. Forcing air through the protective shield might have solved this problem if air had been available. Because forced air was not available, experience showed that leaving the wires unprotected in the normally low relative humidity of southern Arizona gave the best results. Backing the low relative humdity is the fact that rainstorms in southern Arizona are rather infrequent and short-lived.

The temperature recording was started on June 30, 1969, and the recorder was turned on and off manually. As a trial, the recorder was run from approximately 8:00 a.m. to 5:00 p.m. daily with an additional 24-hour run once each week. It was not felt necessary to run the recorder 24 hours every day because the temperatures did not fluctuate greatly during the night and showed fairly uniform patterns from night to night. Therefore, it was decided to record for 24 hours once each week, and this proved to be quite sufficient. The 8:00 a.m. to 5:00 p.m. recording was barely sufficient and also very tiring to perform manually, so a 24-hour clock was used to turn the recorder on and off automatically. The timing sequence was set to turn the recorder on at 6:45 a.m. and off at 5:15 p.m. during the winter months. This sequence seemed optimum to record the minimum temperatures in the morning, the rise and fall patterns during the day, and the maximum temperatures during the afternoon. This time interval had to be lengthened as the days became longer.

Solar Radiation

The Institute of Atmospheric Physics at the University of Arizona keeps a continuous record of the solar radiation rate on a horizontal surface. The measuring equipment is on top of the Physics, Mathematics, and Meteorology Building on the campus. The measuring device is an Eppley Pyranometer, Model 50, made by Eppley Laboratories of Newport, Rhode Island, and consists of alternating black and white concentric circles mounted inside a glass bulb. The recording device, a Brown Electronik Model Y153XLLV-X-27V made by Honeywell, determines the radiation rate by interpreting the temperature difference between the 2 colored surfaces. The recorder prints a graph on a continuous roll of paper with radiation rates from 0 to 2 langleys. Besides printing the rate, the recorder is equipped with an integrating device to give the cumulative solar radiation received. The plotted graphs were read to give on-the-hour

Date: 5 August 1969

TC #	1	2	3	4	5	6	7	8	9	10	11	12
Loc	AIR	12"	10"	8"	6"	4"	2"	SUR	6"	4"	2"	SUR
0100	86	110	110	110	108	106	102	96	109	107	102	97
0200	84	109	109	108	106	104	100	95	107	105	101	96
0300	83	108	108	107	106	103	99	93	106	103	99	94
0400	82	108	107	106	104	102	98	92	105	102	98	93
0500	82	107	106	104	103	100	96	91	104	100	96	92
0600	82	106	106	104	102	99	96	91	103	99	96	92
0700	86	106	106	104	102	100	96	96	102	99	96	95
0800	92	106	106	104	102	100	102	106	104	102	101	105
0900	96	106	106	104	104	103	108	118	104	104	107	114
1000	100	106	106	105	106	107	115	130	106	108	114	127
1100	103	105	106	105	107	110	121	139	107	113	122	137
1200	106	105	106	106	110	116	128	148	110	118	130	145
1300	108	106	108	108	114	121	133	153	113	123	136	150
1400	110	108	109	110	118	126	138	157	116	127	140	155
1500	110	109	111	114	120	128	140	155	119	130	142	153
1600	104	109	111	114	121	128	138	143	120	130	140	143
1700	104	109	112	115	122	127	131	130	121	128	132	131
1800	102	109	112	115	121	124	127	125	120	126	130	130
1900	100	110	112	116	120	122	124	120	120	124	124	122
2000	91	111	113	116	119	120	117	108	119	121	119	110
2100	90	111	113	115	116	116	112	104	117	117	113	106
2200	88	111	112	114	113	113	109	102	114	114	110	104
2300	87	111	112	112	112	110	106	100	112	111	107	101
2400	86	110	111	111	109	108	104	98	110	109	104	99

Figure 2. Solar radiation data sheet.

rates and also the maximum rate for the day. The values in langleys were converted and recorded as Btu's per square foot-hour on prepared data sheets. Data have been taken daily from sunrise to sunset. A sample, completed data sheet is shown in Figure 2.

TEMPERATURE

Surface

Figure 3 shows temperature patterns for a typical July day. The surface experiences the greatest temperature variation by far. During the early morning hours, the temperature decreases slowly and reaches its minimum around 6:00 a.m. The surface temperature at night depends to a great extent on atmospheric conditions and usually averages about 5 F above the air temperature. After 6:00 a.m., the surface temperature increases very rapidly as the heating effects of solar radiation win over the cooling effects of the air. The increase in temperature tapers off around 12:00 noon, and the temperature remains fairly stable until about 3:00 p.m. during which time the maximum surface temperature usually occurs. After 3:00 p.m., the cooling effects of the air win over the radiation effects, and the temperature falls rather rapidly until around 7:00 p.m. when it again approaches the range of night air temperatures. From

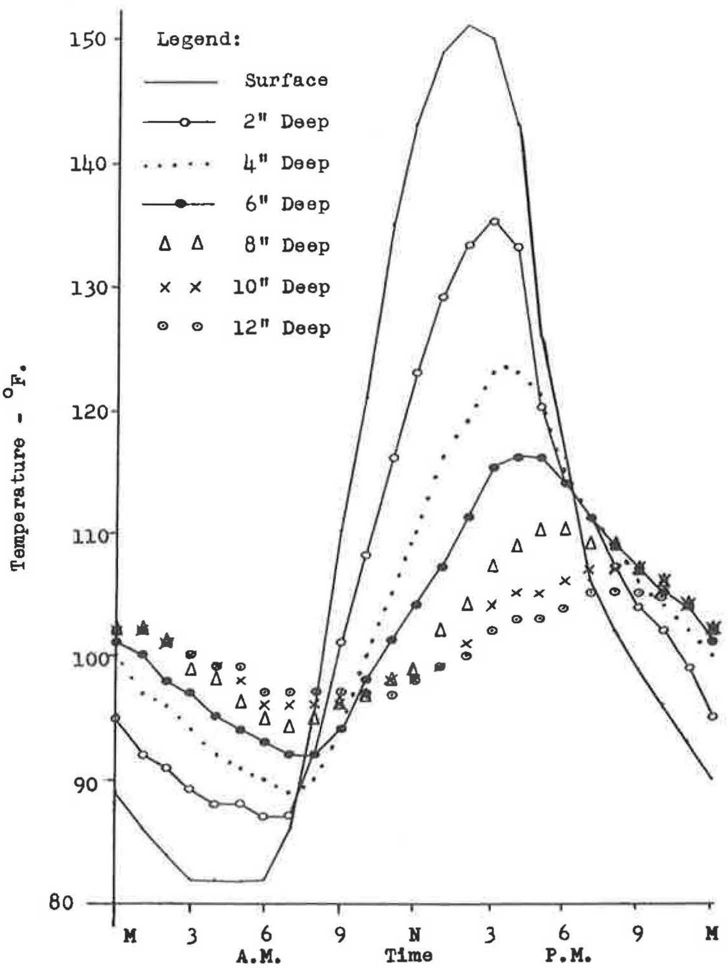

Figure 3. Typical pavement temperature patterns in July.

then until midnight, the surface temperature decreases slowly, still approaching the air temperature but remaining slightly above it.

The WASHO Road Test (13) and Galloway (4) both indicate that the surface temperature of asphaltic concrete is below the air temperature in the winter. In southern Arizona, the surface temperature did not fall below the air temperature. It is not expected that it would unless there happens to be a sudden, rare, large increase of air temperature during the night. The surface is kept warm by residual heat in the lower layers, and the pavement establishes a dynamic thermal equilibrium in the heat flow out of the warm underlayers.

Two-Inch Level

The 2-in. level follows much the same pattern as the surface except that the temperature differential is not so extreme. The 2-in. level cools during the early morning hours but stays warmer than the surface, taking its position in the thermal equilibrium. Normally between 7:00 and 9:00 a.m., the surface temperature surpasses the 2-in. level temperature as they both start their rapid increases almost simultaneously. The 2-in. level reaches its upper plateau slightly after the surface but holds it for a short period of time after the surface starts its decline. The surface temperature falls below that of the 2-in. level between 5:00 and 7:00 p.m. The temperature at the 2-in. level continues its decline into the night but stays above the surface temperature.

Deeper Levels

The deeper layers follow much the same pattern except that their respective daily differentials are much less severe. As depth increases, the extreme temperatures are delayed slightly from the layer just above. For example, the minimum of 6 in. occurs after the minimum at 4 in., and the maximum at 6 in. occurs after the maximum at 4 in.

Differentials

Knowledge of minimum temperatures is desired in design because asphaltic concrete loses flexibility with decreasing temperature. As opposed to this, knowledge of maximum temperatures is desired because asphalt loses stability with increasing temperature. Information on the daily temperature differentials is desired because of their effect on the physical properties of the asphaltic cement. Temperature differential may also be important because of the warping stresses it might induce in the pavement. However, warping stresses may not be important in asphaltic concrete because of its relatively low modulus of elasticity.

Table 1 gives surface temperature data. Before they are discussed, the column headings should be clarified.

1. The time period over which the averages were taken include the months from June through December, 1969, and January through May, 1970. Normally the time period is one calendar week in duration. One particular period covers 2 weeks, and a 4-week period is missing because of power failure problems in the area of the test site. Several other periods may have statistics for fewer than 7 days because of various small problems encountered with the recorder.
2. Minimum temperature indicates the lowest temperature recorded at each particular level during the specified time period. An idea of the time of day of these minimums can be obtained from the typical temperature plots discussed earlier.
3. Average minimum indicates the average of the daily minimum temperatures that occurred at each level during each week. These averages give a better understanding of the lower boundary of the temperature range than the minimum temperature.
4. Minimum peak is the lowest daily high temperature of each particular level for each time period.
5. Maximum peak is the maximum high temperature occurring at each level during the time period.

TABLE 1
SURFACE TEMPERATURE STATISTICS

Time Period	Minimum	Avg Minimum	Minimum Peak	Maximum Peak	Avg Peak	Avg Spread
6-30 to 7-15	—	—	149	160	155	—
7-6 to 7-12	87	88	134	160	148	60
7-13 to 7-19	84	86	183	158	146	60
7-20 to 7-26	82	83	139	151	146	63
7-27 to 8-2	85	87	142	158	152	65
8-3 to 8-9	91	93	146	156	151	58
8-10 to 8-16	82	83	115	155	142	59
8-17 to 8-23	82	83	147	149	148	65
8-24 to 8-30	85	87	136	146	143	56
8-31 to 9-13	84	84	121	145	132	48
9-14 to 9-20	72	76	116	135	130	54
9-21 to 9-27	70	76	128	131	130	54
9-28 to 10-4	74	74	116	132	125	51
10-5 to 10-11	62	68	117	125	119	51
10-12 to 10-18	56	59	109	116	113	54
10-19 to 10-25	54	59	90	110	103	44
10-26 to 11-1	52	55	101	108	104	49
12-7 to 12-13	41	45	71	88	81	36
12-14 to 12-20	42	43	82	88	86	43
12-21 to 12-27	45	46	80	88	85	39
12-28 to 1-3	31	39	64	78	73	34
1-4 to 1-10	34	38	72	81	75	37
1-11 to 1-17	42	47	81	89	84	37
1-18 to 1-24	44	46	85	93	87	41
1-25 to 1-31	34	49	81	91	87	38
2-1 to 2-7	38	44	80	94	88	44
2-8 to 2-14	50	54	96	109	102	48
2-15 to 2-21	44	51	92	105	98	47
2-22 to 2-28	50	53	98	104	102	49
3-1 to 3-7	49	54	58	106	92	38
3-8 to 3-14	47	52	95	112	106	54
3-15 to 3-21	45	52	100	114	108	56
3-22 to 3-28	52	55	108	117	114	59
3-29 to 4-4	51	60	98	118	112	52
4-5 to 4-11	62	67	105	122	114	47
4-12 to 4-18	55	67	76	126	106	39
4-19 to 4-25	58	63	107	117	112	49
4-26 to 5-2	55	61	102	126	110	49
5-3 to 5-9	58	67	100	134	120	53
5-10 to 5-16	70	81	126	138	130	49
5-17 to 5-23	80	84	123	138	131	47
5-24 to 5-30	76	80	119	127	121	41

6. Average peak designates the average of the daily peak temperatures at each level occurring during the time period. During periods in which the day-to-day weather was fairly constant, the minimum peak and the maximum peak close in on the average peak temperature.

7. Average spread is the numerical difference between the average peak temperature and the average minimum temperature during the time period. This number represents the average rise and fall in temperature that each level experienced during the course of one day.

For the surface and the 2-, 4-, 6-, 8-, 10-, and 12-in. levels, the minimum temperatures were 31, 37, 40, 42, 42, 42, and 43 F respectively. The temperatures all occurred within the same week and further demonstrate the upward transfer of heat as discussed earlier. Arena (1) presents tables showing that the binder course experienced lower temperatures than the wearing courses. In this study the surface minimum was always the lowest temperature. However, the minimum temperatures reported by Arena (1) in Louisiana are in the same range as those from this study. Minimum temperatures in the cooler climate of Maryland, reported by Kallas (5), were about 15 F less than those in Arizona. Straub, Schenck, and Przybycien (12) reported minimum temperatures from northern New York that were about 20 F below those in Arizona.

The maximum temperatures experienced at the surface and the 2-, 4-, 6-, 8-, 10-, and 12-in. levels were 160, 142, 132, 123, 116, 113, and 111 respectively. From the 2 sets of extremes, the pavement levels experienced long-term differentials of 129, 105, 92, 81, 74, 71, and 68 respectively. Fortunately these differentials occurred over a period of approximately 6 months as opposed to the average daily spread in which the heating and cooling cycles take approximately 6 hours and 18 hours respectively. Kallas (5) and Straub, Schenck, and Przybycien (12) reported maximum temperatures below those of Arizona, but these could be expected in the cooler climates.

Because of the maximum peaks that occurred in August and through July, it might be suspected that higher maximum temperatures were experienced before the recording started. This has been neither proved nor disproved, but later evidence will substantiate the possibility.

Daily temperature differentials decrease with depth as observed earlier on the typical monthly temperature plots. The data also show that the daily temperature differential decreased during the colder months.

Level Duration

Data were obtained that give the relative amount of time during which the temperatures at the 7 depths were equal to or above a given temperature. The temperatures in the 6- and 12-in. sections were essentially the same and, therefore, the data are valid for both cases. Because the recording took place primarily in the daytime when higher temperatures were recorded in the shallow depths, the warmer temperature durations could be obtained with each, and a 10 F interval was used. Because the data collection was limited to one 24-hour run each week, the availability of data for lower temperature patterns was rather limited, and the interval was expanded to 20 F. This procedure may be justified by the fact that the desired temperature durations were in the upper layers with the warmer, more critical levels.

Table 2 gives data from the surface. The surface temperature stayed above 70 F 100 percent and above 90 F roughly 70 percent of the time during July, August, and September. During July and August, the surface remained above 110 F about 40 percent of the time, above 130 F roughly 25 percent, and above 140 F from 7 to 22 percent. The temperature stayed above 150 F from 3 to 8.5 percent of the time and reached 160 F on several days but did not remain there for any appreciable amount of time. The time that was spent above 160 F during June, if any, still remains a question here.

Also during July and August, the 2-in. level reached the 140 F mark on several instances but did not spend much time above this level. The durations above 130 F do indicate that the 140 F range was approached quite frequently. At any rate, it can be concluded that the asphaltic concrete between the 2-in. level and the surface does experience a significant amount of time above 140 F.

The asphalt between the 2- and 4-in. level approaches the 140 F temperature range; below the 4-in. level, it approaches the value of 130 F. Below the 6-in. depth, the asphalt pavement was above 110 F but did not exceed 120 F. In turn, below the 10-in. level, the asphaltic concrete occasionally did reach 110 F.

In many parts of the United States, pavement temperatures do not reach the levels recorded in Tucson, Arizona. Tests on asphaltic concrete have been developed in which the testing temperature is 140 F. The observations in Arizona raise questions concerning the use of only 140 F for stability testing in hot, desert regions. Upper layers of the pavement exceed this level, and lower layers never reach it. Before any changes are suggested, consideration must be given to the present, widespread acceptance and use of conventional test procedures. It is doubtful that it would be fair or necessary to change the entire test for a relatively small portion of the country.

On the basis of the data reported in this paper, the authors believe that minor modifications to test procedures might be an improvement for use in the Southwest. For asphaltic concrete to be placed above the 2-in. level, the standard 140 F stability test could be performed and several extra samples could be made and tested at 160 F. The mix would be considered acceptable if the 160 F stability did not fall below a specified

TABLE 2

PERCENTAGE OF TIME PERIOD WHEN SURFACE LEVEL TEMPERATURE WAS ABOVE GIVEN TEMPERATURE

Time Period	30 F	40 F	50 F	60 F	70 F	80 F	90 F	100 F	110 F	120 F	130 F	140 F	150 F
6-30 to 7-5	—	—	—	—	100	—	60	—	42	—	28	22	8.5
7-6 to 7-12	—	—	—	—	100	—	79	—	38	—	17	9	2
7-13 to 7-19	—	—	—	—	100	—	71	—	37	—	15	11	3
7-20 to 7-26	—	—	—	—	100	—	67	—	29	—	16	8	2
7-27 to 8-2	—	—	—	—	100	—	75	—	39	—	33	17	6
8-3 to 8-9	—	—	—	—	100	—	100	—	45	—	29	21	7
8-10 to 8-16	—	—	—	—	100	—	67	—	29	—	15	11	3
8-17 to 8-23	—	—	—	—	100	—	78	—	37	—	14	7	0
8-24 to 8-30	—	—	—	—	100	—	71	—	34	—	14	7	0
8-31 to 9-13	—	—	—	—	100	—	75	—	25	—	9	5	0
9-14 to 9-20	—	—	—	—	100	—	42	—	25	18	7	0	—
9-21 to 9-27	—	—	—	—	100	—	54	—	23	18	6	0	—
9-28 to 10-4	—	—	—	—	100	—	40	—	24	12	4	0	—
10-5 to 10-11	—	—	100	—	75	—	35	—	15	6	0	—	—
10-12 to 10-18	—	—	100	—	46	—	32	21	9	0	—	—	—
10-19 to 10-25	—	—	100	—	40	—	17	10	2	0	—	—	—
10-26 to 11-1	—	—	100	—	54	—	20	13	0	—	—	—	—
12-7 to 12-13	—	100	85	34	19	9	0	—	—	—	—	—	—
12-14 to 12-20	—	100	67	38	24	16	0	—	—	—	—	—	—
12-21 to 12-27	—	100	71	39	23	14	0	—	—	—	—	—	—
12-28 to 1-3	100	67	32	21	10	0	—	—	—	—	—	—	—
1-4 to 1-10	100	89	37	23	11	1	0	—	—	—	—	—	—
1-11 to 1-17	100	100	77	32	21	10	0	—	—	—	—	—	—
1-18 to 1-24	100	100	70	40	26	15	3	0	—	—	—	—	—
1-25 to 1-31	100	96	83	42	36	16	3	0	0	—	—	—	—
2-1 to 2-7	100	97	70	37	25	14	4	0	—	—	—	—	—
2-8 to 2-14	—	100	100	57	36	24	10	2	0	—	—	—	—
2-15 to 2-21	—	100	96	50	36	27	17	5	0	—	—	—	—
2-22 to 2-28	—	—	100	75	39	30	21	7	0	—	—	—	—
3-1 to 3-7	—	100	95	65	27	18	12	4	0	—	—	—	—
3-8 to 3-14	—	100	100	—	38	31	19	9	1	0	—	—	—
3-15 to 3-21	—	100	95	—	41	33	26	17	3	0	—	—	—
3-22 to 3-28	—	100	100	—	52	38	31	23	10	0	—	—	—
3-29 to 4-4	—	—	100	71	48	34	26	17	8	0	—	—	—
4-5 to 5-11	—	—	—	100	60	42	34	21	13	1	0	—	—
4-12 to 4-18	—	—	100	82	50	33	23	15	8	3	0	—	—
4-19 to 4-25	—	—	—	100	68	40	31	23	7	0	—	—	—
4-26 to 5-2	—	—	100	92	59	41	30	18	7	3	0	—	—
5-3 to 5-9	—	—	100	98	78	58	39	27	20	10	1	0	—
5-10 to 5-16	—	—	—	—	100	70	51	39	29	20	5	0	—
5-17 to 5-23	—	—	—	—	100	96	55	39	27	21	6	0	—
5-24 to 5-30	—	—	—	—	100	92	39	25	17	4	0	—	—

percentage of the 140 F value. For pavement between the 2- and 6-in. levels, the present 140 F testing temperature simulates the actual conditions experienced in the field. Asphaltic concrete below the 6-in. level could also be tested by the conventional procedure with extra samples molded for testing at 120 F. If the 120 F stability exceeded the 140 F stability by more than a specified amount, a weaker mixture might be justified for use at this level.

If these suggestions are followed, years of conventional testing procedure would not be thrown out; instead, the method would be modified to evaluate better the stability of mixes in southwestern desert regions. At the same time, problems may be avoided by eliminating a mixture that loses stability rapidly above 140 F. The majority of mixes probably would not weaken too much, but some might if the viscosity of the asphalt cement used was very sensitive to temperature in the 140 to 160 F range. On the other hand, for the pavement that will never experience in situ temperatures above 120 F, a substantial savings might arise by developing a less expensive mixture with adequate stability. Asphalt pavements are expected to have a certain degree of flexibility, and a pavement with too much stability may prove to be as harmful as one with inadequate stability.

SOLAR RADIATION AFFECTING TEMPERATURE

Solar radiation has a great deal of influence on the temperatures in asphaltic concrete. In his paper on pavement temperatures in Australia, Richards (9) states that the net radiation has a greater influence than air temperature on pavement temperatures. Straub, Schenck, and Przybycien (12) also reached the same conclusion and substantiated it by the use of graphs. One graph showed surface temperature plots for 2 days with similar radiation rates and different air temperatures with only a small effect on the surface. The other graph showed one clear and one cloudy day with similar air temperatures that produced a large difference in surface temperature. This section presents a new method of showing that solar radiation is more influential than air temperature on the upper layers of a pavement system. Figure 4 shows plots of solar radiation, air temperature, and pavement temperature against time.

Surface Temperature

For a typical clear July day, the first appreciable solar radiation is recorded at about 6:00 a.m. The rate increases steadily and rapidly until about 11:00 a.m., when it starts to level off. Between 11:00 a.m. and 1:00 p.m., the rate reaches its maximum, and about 2:00 p.m. it begins to decrease as rapidly as it increased during the morning hours. The radiation becomes hardly noticeable by 7:00 p.m. and completely nil by 8:00 p.m. For the scale at which the figure is drawn, the slope of the surface

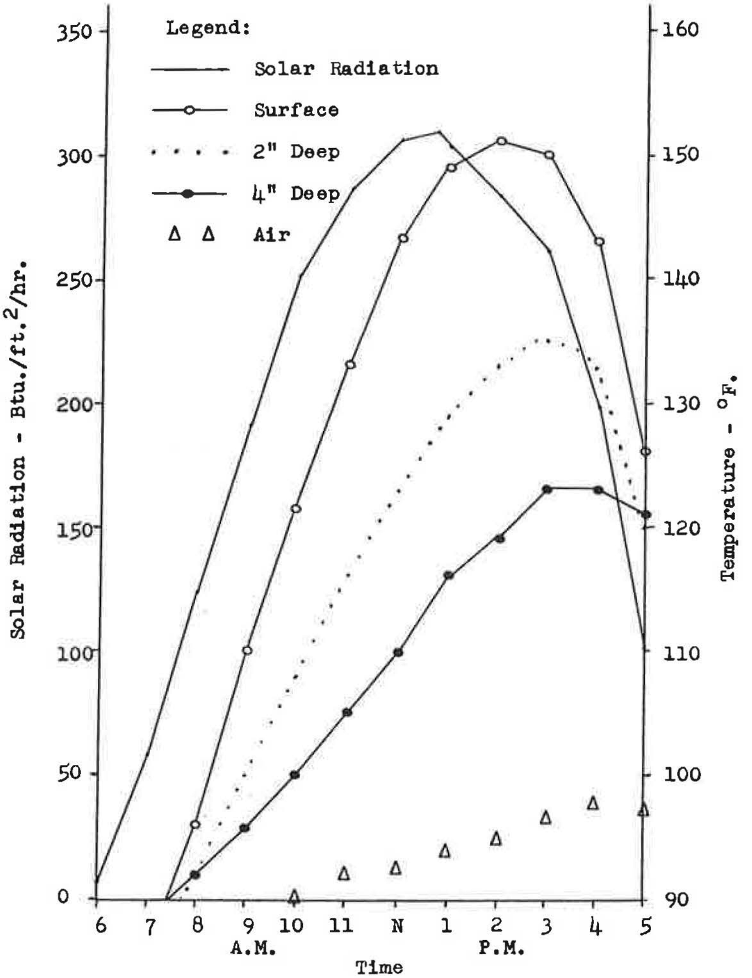

Figure 4. Solar radiation and temperature versus time for typical July day.

temperature curve is very similar to that of radiation curve in the morning hours. The surface temperature continues to increase while the solar rate passes through its upper plateau. As the radiation begins to taper off, the temperature peaks and then begins to fall as the cooling effects of the air win over the heating effects of the sun. The temperature falls with the decreasing radiation until it reaches the range of the air temperature where it remains until the next day.

Trying to correlate the air temperature curve with surface temperature is not nearly so successful. The air temperature curve increases slowly throughout the morning and early afternoon and usually reaches its maximum around 4:00 or 5:00 p.m. or 2 to 4 hours after the surface reaches its maximum. The peak temperature at the surface may be as much as 70 F above the air temperature at that time and, therefore, it becomes quite clear that, although surface temperatures may be dictated by air temperatures at night, they are definitely affected more heavily by solar radiation during the critical peak temperature periods.

Lower Level Temperatures

Temperatures for the 2- and 4-in. levels are also shown on the figures, and their correspondence with radiation is similar to that for the surface temperature. Their temperature increases are delayed by the time required for the heat conduction to their respective levels. Therefore, these temperatures could best be explained by the solar radiation effect and the heat transfer theory suggested earlier. The 2- and 4-in. level temperatures rise well above the air temperature, and this indicates that they are influenced to a great extent by the solar radiation.

Lower levels do not experience large spreads in temperatures as do the upper layers, but their temperature increases are an indirect effect of the solar radiation rates. However, the mean temperatures at the deepest layers do seem to follow the average daily maximum temperatures throughout the year.

PREDICTION OF UPPER LAYER PEAKS

The critical temperatures in southern Arizona are the peak temperatures in the upper layers of the pavements. A simple method of predicting the peak temperatures might be a valuable asset. Barber (2) presented an equation for calculating pavement temperatures from weather reports and several properties of the bituminous material. The large number of variables makes his equation rather cumbersome, but it does yield temperatures with reasonable accuracy. Also, Southgate (11) presented 2 sets of figures for predicting temperatures. The first set gives temperatures at depths of less than 2 in. from the surface temperature for different hours of the day. The other set predicts temperatures for various hours of the day at depths up to 12 in. from the surface temperature and the air temperatures from the 5 previous days. This method may give approximate results, but difficulty may be encountered in measuring the true surface temperature. Temperatures given by simple thermometers resting on the surface do not compare well with thermocouples implanted at the surface. Southgate's method was developed primarily for prediction of temperatures to be used in deflection analysis. The method of predicting upper layer peaks from air temperatures and solar radiation data presented in this section gives the critical peak temperatures that are quite important.

Figures 5, 6, and 7 are used for the surface, the 2-in. depth, and the 4-in. depth respectively. The maximum air temperature for the day should be selected on the abscissa scale. The average of the solar radiation rates at 11:00 a.m., noon, and 1:00 p.m. and the maximum for the day should be selected on the ordinate scale. The intersection of these lines should fall in the range of the given curves. Interpolating between the curves should give a good approximation of the temperature peak that can be expected at that level. The maximum air temperature supplied by the U.S. Weather Bureau should give the best results because the curves were constructed from its temperature data.

The curves were constructed solely on the basis of recorded data and, therefore, are purely empirical in nature. Their validity cannot be checked by data recorded at

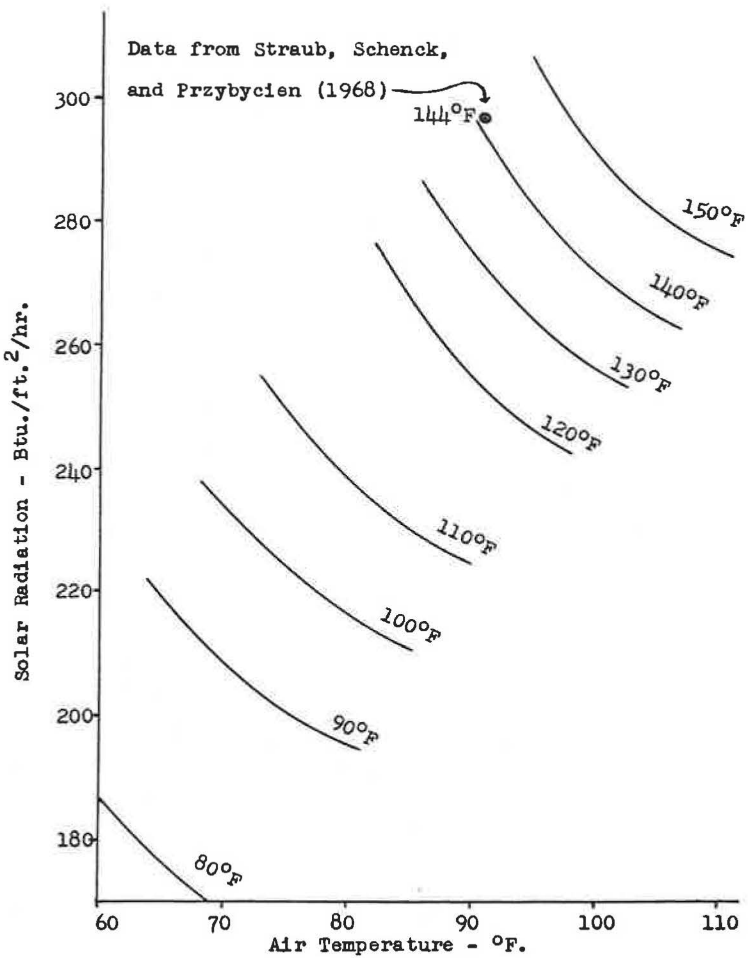

Figure 5. Prediction of surface temperature on clear days from solar radiation rate and air temperature.

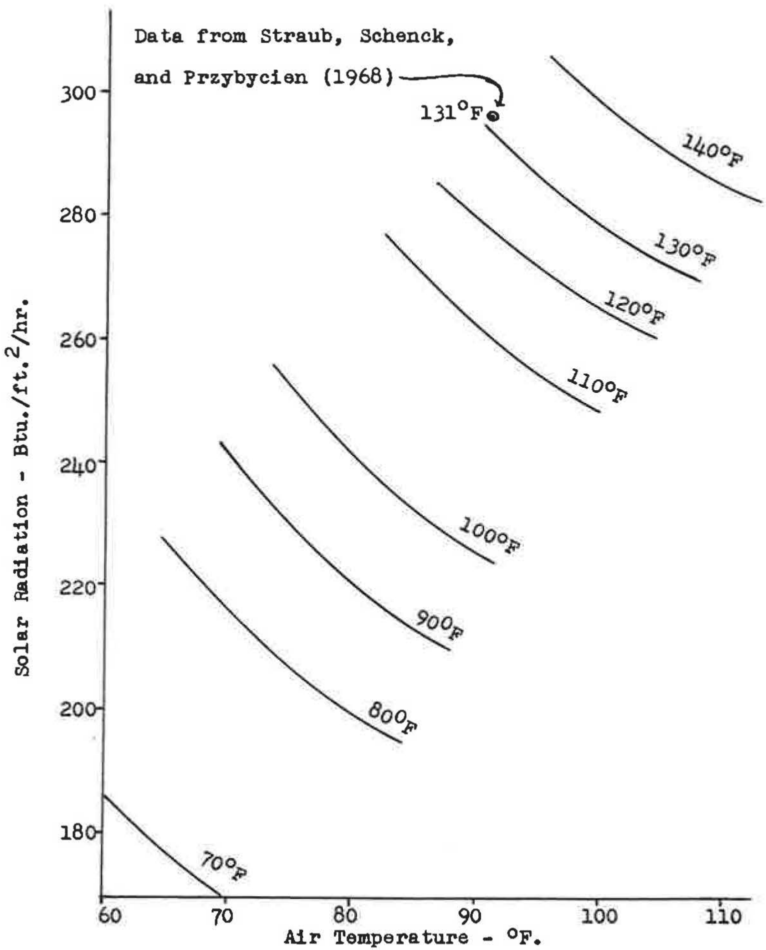

Figure 6. Prediction of 2-in. level temperature on clear days from solar radiation rate and air temperature.

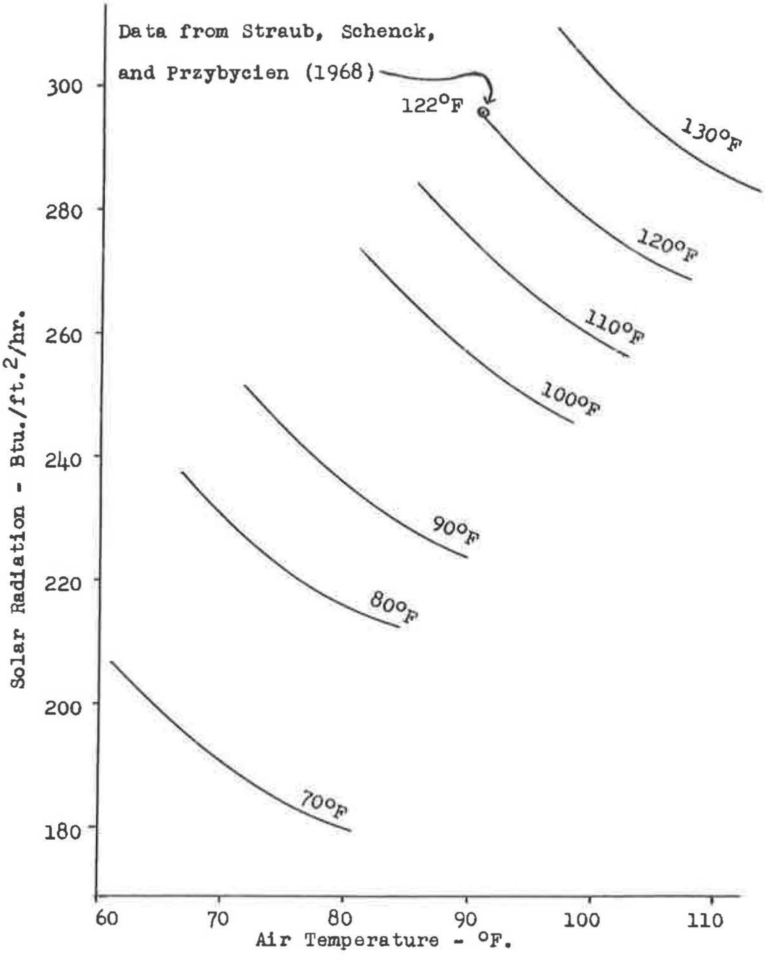

Figure 7. Prediction of 4-in. level temperature on clear days from solar radiation rate and air temperature.

the time of this report. However, compared with solar radiation values and the maximum air temperature from the report by Straub, Schenck, and Przybycien (12), these figures give their maximum temperatures to within 2 F. The points plotted on the figures give their maximum temperatures and show the close correlation. Because of the number of variables involved in predicting temperatures, it is doubtful that this accuracy is possible in all cases, and a standard error of ±5 F would probably be much more realistic.

Values for air temperature were taken from the U.S. Weather Bureau because it records under more standardized conditions with continuously moving air. The air temperature recorded at the test site varied from the Weather Bureau temperature primarily because of the effects of solar radiation.

Several values from the solar radiation data were tried on the ordinate scale before the average of 11:00, 12:00, and 1:00 and the maximum was chosen. The values tried included the maximum rate, different hourly rates taken singularly, and other averages; but the average mentioned earlier was the best for constructing the curves.

As mentioned earlier, a question arises as to whether higher temperatures occurred during June than were mentioned in July. Entering air temperatures as high as 105 F or more and computed solar radiation values as high as 320 Btu/ft^2/hr or more would cause the predicted temperature to be above the present range of the curves. The feeling of the authors is that higher pavement temperatures did occur before recording commenced.

CONCLUSIONS

The data included in this report cover the recording period from June 30, 1969, through May 30, 1970. The authors strongly recommend that the recording be continued to cover at least one full year.

The maximum temperatures recorded at the surface and at 2-, 4-, 6-, 8-, 10-, and 12-in. levels were 160, 142, 132, 123, 116, 113, and 111 F while the minimum temperatures were 31, 37, 40, 42, 42, 42, and 43 F respectively.

A statistical analysis has been run to determine the average minimum and maximum temperatures encountered throughout the testing period. This coupled with an analysis of the time durations at various temperature levels has led to suggestions for modifying conventional test procedures in hot, desert regions. Solar radiation data have been coupled with temperature data to support the theory that the former are much more influential than the latter on upper layer temperatures during daylight hours. A quick and easy method has been presented to predict the maximum upper layer temperatures that can be expected on clear days.

A large amount of data have been collected concerning pavement temperatures in the hot southwest portions of the United States. These data can be made available for further analysis if so desired.

REFERENCES

1. Arena, P. J. Service Temperature Study for Asphaltic Concrete. Louisiana Department of Highways, Baton Rouge, Research Rept. 14, 1964.
2. Barber, E. S. Calculation of Maximum Pavement Temperatures From Weather Reports. HRB Bull. 168, 1957, pp. 1-8.
3. Boen, H. L., and DeMarrais, G. A. Surface and Subsurface Temperature Variations and Comparisons. Public Roads, Vol. 30, No. 12, 1960.
4. Galloway, J. W. Temperature Durations at Various Depths in Bituminous Roads. Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR 138, 1968.
5. Kallas, B. F. Asphalt Pavement Temperatures. Highway Research Record 150, 1966, pp. 1-11.
6. Kingham, R. I. A New Temperature-Correction Procedure for Benkelman-Beam Rebound Deflections. The Asphalt Institute, College Park, Md., Research Rept. 69-1, 1969.
7. Lamb, D. R., Scott, W. G., Gietz, R. H., and Armijo, J. D. Lateral Cracking of Asphaltic Concrete. Wyoming State Highway Department, Cheyenne, Research Pub. H-17, 1967.
8. Manz, G. P. Study of Temperature Variation in Hot-Mix Asphalt Base, Surface Course and Subgrade. Highway Research Record 150, 1966, pp. 12-19.
9. Richards, B. G. Pavement Temperatures and Their Engineering Significance in Australia. HRB Spec. Rept. 103, 1969, pp. 254-266.
10. Roberts, P. K., and Russam, K. Road Temperatures in the Tropics. Road Research Laboratory, Harmondsworth, England, Rept. 29, 1966.
11. Southgate, H. F. An Evaluation of Temperature Distribution Within Asphalt Pavements and Its Relationship to Pavement Deflection. Kentucky Department of Highways, Lexington, Research Rept., 1968.
12. Straub, A. L., Schenck, H. N., Jr., and Przybycien, F. E. Bituminous Pavement Temperature Related to Climate. Highway Research Record 256, 1968, pp. 53-77.
13. The WASHO Road Test—Part 2: Test Data, Analyses, Findings. HRB Spec. Rept. 22, 1955.