TEMPERATURE VARIATIONS IN A CONCRETE PAVEMENT AND THE UNDERLYING SUBGRADE

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SYNOPSIS

This report shows the variations in temperature in a concrete pavement and its underlying subgrade in a northern climate over a period of 5 years. Temperatures were recorded at six places in the 7-in. slab, at five places in the loamy fine sand subgrade, and in the air above the slab at 6-min. intervals from November 1940 through October 1945 Variations in moisture content were measured for 1 year and reported in the progress report on this work in *Proceedings*, Highway Research Board, Vol. 21, 1941, pages 260–271.

The data have been arranged to show the following· monthly maximum and minimum air and corresponding maximum and minimum concrete temperatures at the center of the slab; the depth of frost penetration compared with degree days from 32 deg. F for each of the 5 years and for an average of the 5 years, the number of freezing and thawing cycles at various depths by monthly intervals over the 5-year period and a 5-year average; minimum monthly temperatures at various depths in the subgrade for the winter months, temperature gradient at various depths in the subgrades for the winter months; the cumulative number of drops per year in average slab temperature of a given or greater magnitude based on the 5-year average; average daily range of center-of-slab temperature for a given daily range in air temperature and frequency of daily ranges in air temperature; the percentage of time in the 5-year period that the temperature of the top and bottom of the slab differed for each 1 deg. of difference; percentage of annual time, based on 5-year average, at which various slab temperature differences occurred at various hours of the day and at various months of the year.

Some significant data of interest to engineers in northern States are presented: the average annual range in air temperature was 112 7 deg F. while the average annual range in temperature at the center of the slab was 114 3 deg. F. with a midpoint at 50 4 deg. F.; frost penetrated 5 ft. below the slab by January 14 and departed from the subgrade by March 23 in an average year; the top of slab underwent 48 cycles of freezing and thawing per year, the bottom underwent 24 cycles and the subgrade 1 ft. below the slab 2 cycles; the lowest temperatures recorded in the subgrade were 10 deg. F. at 2 ft. below the slab and 25 deg. F. at 5 ft. below the slab.

The work reported herein was undertaken for the purpose of obtaining factual data regarding the temperatures within a concrete slab and the underlying subgrade and to observe the seasonal and daily changes therein. This information may be of value in calculating contraction and warping stresses in a concrete pavement and in fixing the duration and time of occurrence of these stresses so that they may be combined with load stresses, as affected by traffic distribution, and computations made for the number of repetitions of maximum stress. The data may also be of value in estimating durability of concrete on the basis of freezing and thawing cycles and for anticipating depths required for frost heave treatment. The data were obtained over a 5-yr. period between November 1940 and November 1945. The records of the U. S. weather Bureau reveal that the average of the mean annual temperatures during the 5-yr. period studied was only $\frac{3}{4}$ deg. F. higher than the average for the 44 year history of the U. S. Weather Bureau.

DESCRIPTION OF PROJECT

An experimental concrete slab was constructed in the driveway adjacent to the Minnesota Department of Highways laboratory at the University of Minnesota. The slab was 7 in. thick and 16½ by 17 ft. in area. It was placed on a well drained subgrade of loamy fine sand. The slab was kept clear of snow.

Temperatures were measured by means of eleven thermocouples carefully located in the slab and in the subgrade The layout of the test slab and the location of the thermocouple points within the slab and subgrade are shown in Figure 1. One thermocouple was located at the top surface of the slab, four at intermediate points in the slab, one at the bottom surface of the slab, and five in the underlying subgrade down to a depth of 5 ft. below the bottom of the slab. The twelfth thermocouple was located in air, shielded from the sun so as to show the outside air temperature.

intervals, it is obvious that a great deal of painstaking and tedious work was required to tabulate and summarize the data. A progress report on this work consisting of data from the first year of readings may be found in *Proceedings*, Highway Research Board, Vol 21, 1941, pages 260-271. The 1941 progress report also contained some data on the moisture content of the slab determined by means of Bouyoucos moisture blocks. No additional moisture readings could be obtained

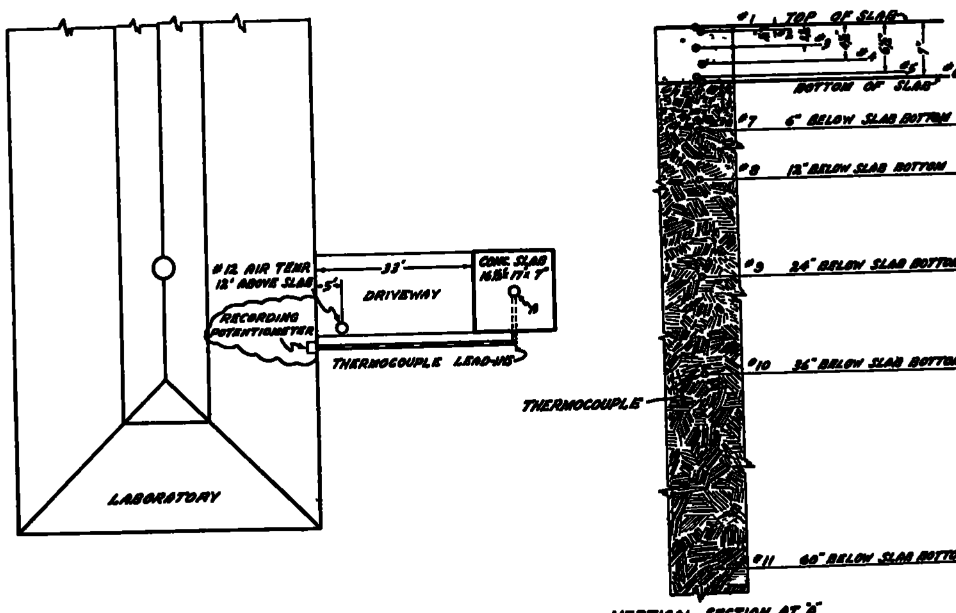

Figure 1. Minneapolis Laboratory Temperature Observation Station

The thermocouples were connected to a recording potentiometer so controlled that each temperature was printed every 6 min on a continous chart. Temperatures could be read to the nearest 1 deg F. A given chart contained the record for all 12 thermocouples for two months Six different colors of ink and two different symbols were used in order to distinguish between the 12 thermocouples.

Readings were taken throughout a 5-yr. period extending from November 1940 to November 1945. During this time, 5,256,000 readings were recorded While all of the readings were not used directly, since most of the data are based on hourly or half hourly

because of the subsequent failure of the installation to function properly.

MAXIMUM AND MINIMUM AIR AND CONCRETE TEMPERATURES

The monthly maximum and minimum air and concrete temperatures are shown in Figure 2 for the 5-yr. period. The concrete temperature used was the average of thermocouple points 3 and 4 which were located 1 in. above and 1 in. below the center of the slab Note that for the minimum temperature, the concrete is always warmer than the air For the maximum temperature, the concrete is warmer than the air in summer because of its greater absorption of the sun's radiant heat but colder than the air in the winter due to the cooling effect of the underlying subgrade. The maximum center of slab temperature recorded was 111 5 F. and was reached on July 23, 1945 Center ,of slab temperatures of 111 F. were recorded on June 21, 1943 and on July 24, 1945 The maximum temperature for the top surface of the slab was 122 F. and was recorded June 21, 1943 and on July 24, 1945. The maximum air temperature recorded was 97 5 F. reached on August 3, 1941. The lowest center of slab temperature recorded was −15 5 F. and was reached on January 7, 1942. The lowest air temperature recorded was −23 F. and was reached on January 19, 1943.

The annual ranges of center of slab temperature and air temperature are shown in Table 1 for the 5-yr. period covered.

It may be seen that the average annual range in center of slab temperature (114.3 F) is just slightly more than the average annual range in air temperature (112.7 F.) The midpoint of the average annual range of concrete temperature would be 50.4 F.

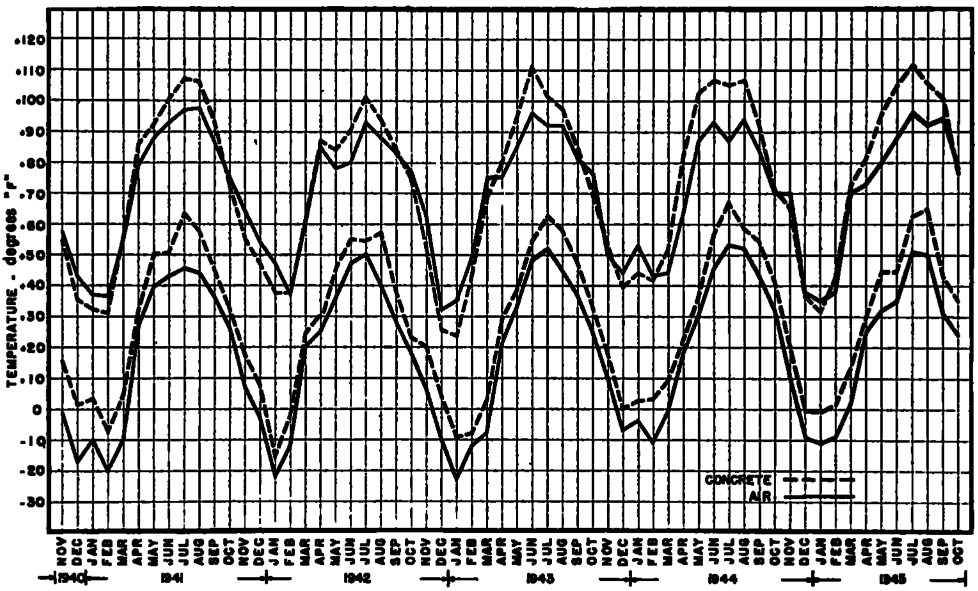

Figure 2. Monthly Maximum and Minimum Air and Concrete Temperatures

TABLE 1
ANNUAL RANGE IN AIR AND CONCRETE TEMPERATURE

	Air			Center of Slab		
	Max deg F.	Min deg F	Range deg F	Max deg F	Min deg F	Range deg F.
1941	97 5	−20	117 5	107	−7 5	114 5
1942	93	−22	115	101	−15 5	116 5
1943	96	−23	119	111	−9 5	120 5
1944	94	−11	105	107	−0 5	107 5
1945	96	−11	107	111 5	−1 0	112 5
Avg	95 3	−17 4	112 7	107 5	−6 8	114 3

FROST PENETRATION

The penetration of frost into the subgrade is shown in Figure 3 for each of the five years together with an average curve for the 5-yr. period. Just above each plotting of frost penetration, the degree-days measured from 32 F. have been plotted These are calculated by summing up the number of degrees that the average daily air temperature is below 32 F for each day starting November 1. Note that these degree-days differ from those used in computing heating seasons in that these are based on 32 F., a more desirable base when studying frost penetration. It may be seen that the severity of the winters varied considerably for the various years. The mildest winter 1941-42 had only 871 9 degree-days while the most severe 1942-43 had 2126 8. Frost reached a depth of 5 ft. below the slab during the month of January each year with the exception of 1942 when frost reached that depth on December 25.

It may be seen that when the degree-days curve is steep the frost penetration is rapid and when the degree-days curve is horizontal, a thaw or upward movement of the frost line occurs. There is, however, very little relation between the cumulated degree-days for the various years at the time the frost reaches a depth of 5 ft. below the slab A partial explanation of this disagreement may be in the given month varies greatly from year to year. The number of cycles at the top surface of the slab for a given winter varies from the average by amounts between + 56 and —53.5 per cent. The number of cycles falls off rapidly as the depth increases. The average number of cycles per winter for the top surface of the slab is 48, while that for the bottom surface is only half that amount. Just 6 in. deeper in the subgrade the number of cycles falls off to one tenth that for the slab

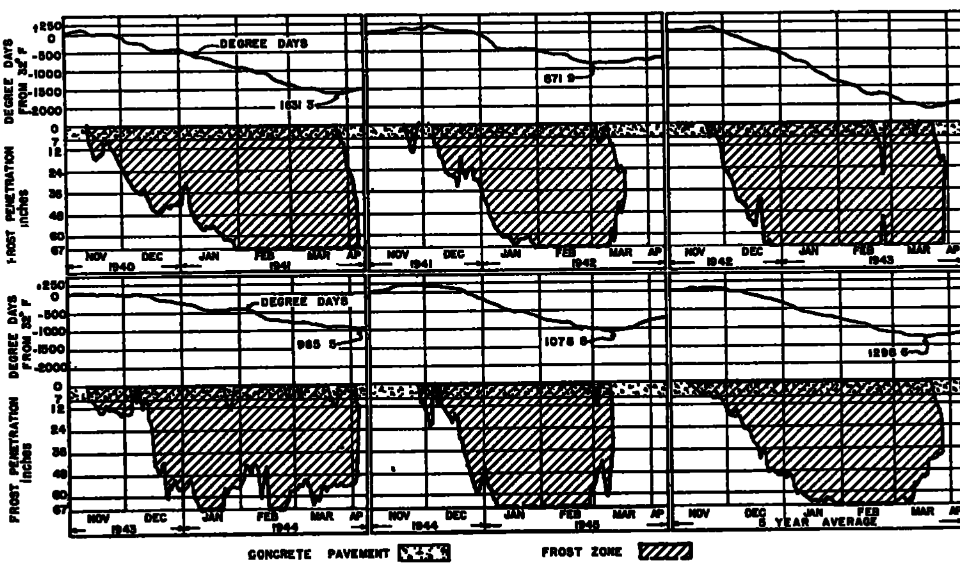

Fig. 3. Frost Penetration as Related to Degree Days.

fact that no account is taken of whether the weather be cloudy or clear with a resulting great difference in the radiant heat absorbed by slab and subgrade.

Thaws, where the average temperature of slab or subgrade remains above 32 F. for more than 24 hr., have been plotted in Figure 3. Of course many more thaws of short duration occurred in the slab It may be noted that in February 1943 and in January and February 1944 thaws proceeded up from below. The frost usually leaves the subgrade during the month of March the average date being March 23. It may be seen that the final thawing proceeds from both the bottom and top.

Table 2 shows the number of freezing and thawing cycles at various depths by monthly intervals over the 5-yr. period together with a 5-yr. average. The number of cycles for a surface At a depth of 24 in. below the slab only one or two cycles of freezing and thawing are to be expected each season. Attention is called to the fact that in certain instances more cycles were measured at 36 in. below the slab than at 24 in. below. This is explained by the fact that the 36-in. depth was thawed out by a thaw progressing slowly upward from the bottom followed by a heavy freeze before the thaw reached the 24-in. depth

Some information regarding the rate of freezing and thawing is desirable for the purpose of correlating laboratory freezing and thawing tests with actual weather. During the winter of 1940-1941, a study was made of the time required for frost to penetrate $2\frac{1}{2}$ in. into the slab. This time was found to vary from 6 min. to $3\frac{3}{4}$ hr. with an average of 1 hr. and 55 min. The time for thawing this $2\frac{1}{2}$-in.

TABLE 2
NUMBER OF FREEZING AND THAWING CYCLES
Investigation no 132

Location of Point	November						December						January					
	1940	1941	1942	1943	1944	Average	1940	1941	1942	1943	1944	Average	1941	1942	1943	1944	1945	Average
No 1—Top of slab	6	12	16	7	0	8 2	6	10	0	11	8	7 0	2	12	0	13	2	5 8
No 2—½ below top of slab	6	12	18	7	0	8 6	6	10	0	11	8	7 0	2	12	0	12	2	5 6
No 3—2½ below top of slab	5	11	12	7	0	7 0	5	8	0	10	7	6 0	1	8	0	10	1	4 0
No 4—4½ below top of slab	4	8	14	5	0	6 2	4	7	0	9	8	5 6	0	7	0	8	0	3 0
No 5—6½ below top of slab	4	8	11	5	0	5 6	0	5	0	10	6	4 2	0	7	0	6	0	2 6
No 6—Between slab and subgrade	3	6	7	5	0	4 2	0	5	0	11	6	4 4	0	4	0	6	0	2 0
No 7—6 below bottom of slab	1	1	0	3	0	1 0	0	1	0	4	5	2 0	0	0	0	3	0	0 6
No 8—12	0	0	0	0	0	0 0	0	1	0	2	4	1 4	0	0	0	0	0	0 0
No 9—24	0	0	0	0	0	0 0	1	1	0	0	0	0 4	0	0	0	0	0	0 0
No 10—36	0	0	0	0	0	0 0	1	0	0	0	1	0 2	0	0	0	0	0	0 0
No 11—60"	0	0	0	0	0	0 0	0	0	0	0	0	0 0	0	1	0	1	1	0 6
No 12—Air temperature	6	15	15	12	6	10 8	9	7	1	13	8	7 6	4	17	2	12	4	7 8

Location of Point	February						March						April						Total					
	1941	1942	1943	1944	1945	Average	1941	1942	1943	1944	1945	Average	1941	1942	1943	1944	1945	Average	1941	1942	1943	1944	1945	Average
No 1—Top of slab	4	8	7	11	5	7 0	23	29	10	12	6	16 0	2	3	4	7	1	3 4	43	74	37	61	22	47 4
No 2—½ below top of slab	4	8	10	11	5	7 6	23	30	11	12	7	16 6	2	3	2	6	1	2 8	43	75	41	59	23	48 2
No 3—2½ below top of slab	0	6	9	10	5	6 0	21	23	10	11	6	14 2	2	1	3	6	1	2 6	34	57	34	54	20	39 8
No 4—4½ below top of slab	0	4	7	10	4	5 0	18	22	9	11	4	12 8	0	0	1	6	1	1 6	26	48	31	49	17	34 2
No 5—6½ below top of slab	0	4	7	8	4	4 6	15	17	7	8	3	10 0	0	0	1	6	0	1 4	19	41	26	43	13	28 4
No 6—Between slab and subgrade	0	1	6	7	4	3 6	11	16	7	7	3	8 8	0	0	0	5	0	1 0	14	32	20	41	13	24 0
No 7—6 below bottom of slab	0	0	2	0	0	0 4	1	1	1	0	1	0 8	0	0	0	1	0	0 2	2	3	3	11	6	5 0
No 8—12	0	0	0	0	0	0 0	1	0	1	0	1	0 6	0	0	0	1	0	0 2	1	1	1	3	5	2 2
No 9—24	0	0	0	0	0	0 0	0	1	1	0	1	0 6	1	0	0	1	0	0 4	2	2	1	1	1	1 4
No 10—36	0	0	0	0	0	0 0	0	1	0	0	2	0 6	1	0	1	1	0	0 6	2	1	1	1	3	1 6
No 11—60"	0	0	0	1	1	0 4	0	0	0	0	0	0 0	1	0	1	0	0	0 4	1	1	1	2	2	1 4
No 12—Air temperature	3	5	7	10	9	6 8	26	26	9	10	7	15 6	2	8	7	8	2	5 4	50	78	42	65	36	54 2

depth varied from 6 min. to 1 hr. and 50 min. with an average of 55 min.

WINTERTIME SUBGRADE TEMPERATURES

Temperatures during the winter months at various depths in the subgrade are shown in Figure 4. The minimum monthly temperature for each thermocouple in the subgrade is shown by years together with a 5-yr. average. The information contained in this figure may be useful in studying frost heaves and their correction. Note that at a depth of 5 ft. below the slab, the temperature seldom goes below 25 F. At a depth of 2 ft. below the slab, the minimum temperature was usually 20 F., but in January 1943 a minimum of 10 F. was reached By studying the graphs for a 5 yr average, some indication may be had on the temperature gradients that may exist in the subgrade In January for example this was 1 deg F. per inch in the subsoil immediately under the slab, while it was only 0.2 deg per inch in the subsoil between 36 and 60 in below the slab.

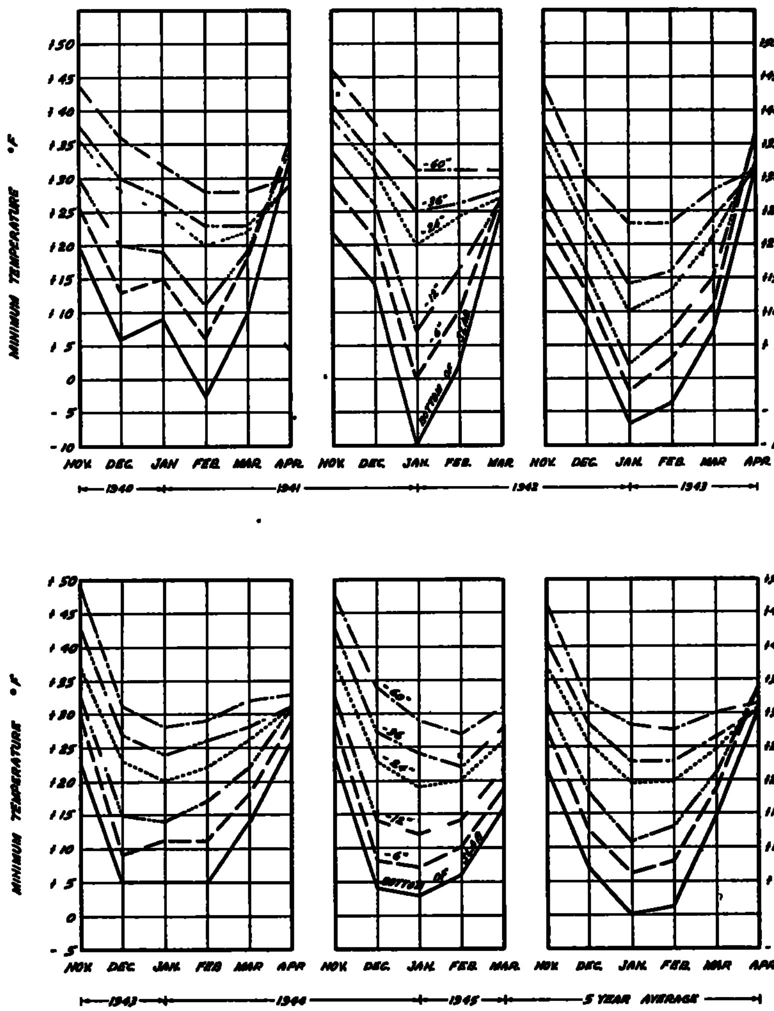

Figure 4. Minimum Temperatures at Various Points in Subgrade Under 7-in. Concrete Slab in Laboratory Driveway.

A further attempt was made in Figure 5 to study subgrade temperature gradient. Since this differential is constantly varying and depends not only on the existing air temperature but also to a large extent on temperatures preceding for a considerable period of time, it was necessary to place very restrictive limits on the readings to be averaged. The readings used were those recorded at 8.00 A.M. for a particular month and for air temperatures between —10 F. and —5 F. The readings used were further limited by the requirement that the bottom of the slab temperature be between —5 F. and +5 F.

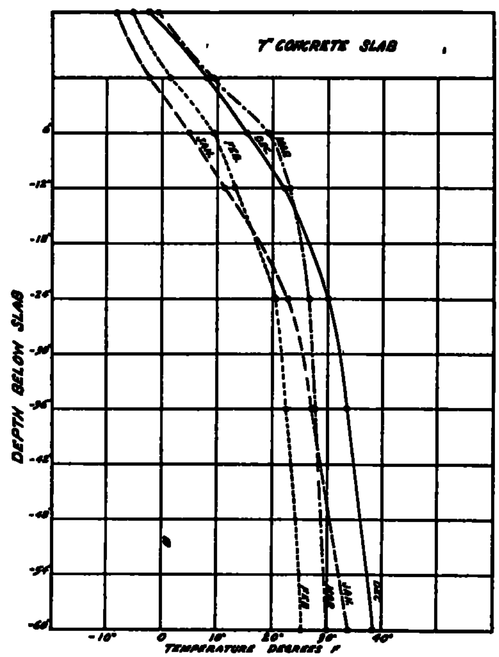

Figure 5. Subgrade Temperature Gradients for Various Winter Months. Air Temperature, —10 F to —5 F. Bottom of Slab Temperature, —5 F to +10 F.

for data in January and February and between 0 F. and +10 F. for data in December and March. The curves in Figure 5 thus represent subgrade temperatures at times of maximum winter temperature differential in the subgrade. Using the data from Figure 5 the maximum temperature gradient in deg F. per inch was calculated for the various depths. These temperature gradients are shown in Table 3. It may be seen that the subgrade temperature gradients are greatest in January except in the region immediately below the slab The temperature gradient at depths exceeding 2 ft is seldon more than ½ deg F. per inch.

TEMPERATURE CONTRACTION

Figure 6 shows the cumulative number of drops per year in average slab temperature of a given or greater magnitude. For example

TABLE 3
SUBGRADE TEMPERATURE GRADIENTS
Air Temperature —10 F to —5 F. Bottom of Slab Temperature —5 F to +10 F

Depth Below Slab	Temperature Gradient deg F. per inch			
	Dec	Jan	Feb	Mar.
in.				
0 to 6	1 17	1 17	1 27	1 67
6 to 12	1 17	1 11	67	75
12 to 24	65	95	62	25
24 to 36	29	.36	15	08
36 to 60	20	.27	.15	10

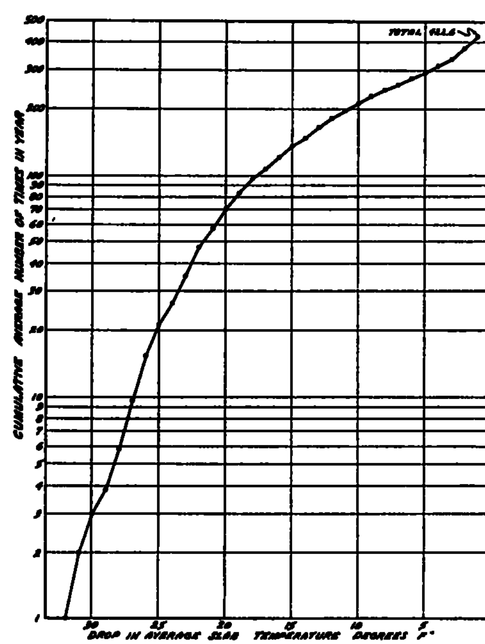

Figure 6. Drops in Average Slab Temperature. Cumulative Number of Drops Per Year of a Given or Greater Magnitude. 5-Year Average Nov. 1, 1940 to Nov. 1, 1945.

there were 70 continuous drops in slab temperature of 20 F. or more There were 300 continuous drops of 5 F. or more. The greatest single continuous drop in average slab temperature was 35 F., and this occurred only once in the 5-yr. period. This information is of value in computing temperature contraction stresses. It was pointed out by Bradbury[1] that the temperature contraction to be used in calculating the average coefficient of subgrade friction is the greatest continuous value of contraction and that it usually occurs within a single day. This is true because each slight reversal of temperature relieves the subgrade frictional forces and releases previously accumulated contraction stress.

A study was made of the daily range in temperature for the center of the slab as related to the daily range in air temperature. On the average, the daily range in center of slab temperature is slightly less than the corresponding daily range in air temperature. Figure 7b shows the frequency of occurrence of various daily ranges in air temperature. Daily ranges greater than 30 F. occurred on the average only 6 times per year. The data in Figure 7 may be useful in estimating the range in slab temperature which may be anticipated in cases where the daily range in air temperature only is known

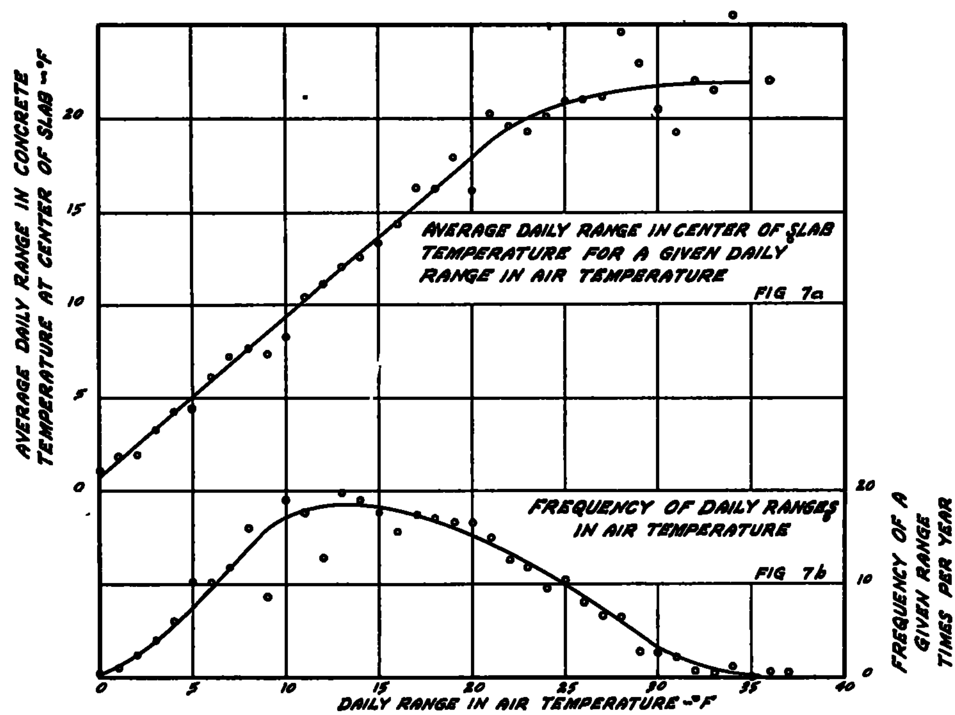

Figure 7

The maximum daily range in center of slab temperature was 40.5 F. and occurred only twice in the 5 year period. A daily range in slab temperature of 38 F. occurred on the average about once a year. The maximum daily range in air temperature was 41 F. and occurred May 21, 1943; the corresponding range in center of slab temperature was 40 5 F. Figure 7a shows the average daily range in center of slab temperature for a given range in air temperature. It may be seen that on the

[1] Discussion of "Structural Design of Concrete Pavements" by E. F. Kelley, *Journal*, A. C. I., Vol. 35, Supplement September, 1939.

TEMPERATURE DIFFERENTIAL BETWEEN TOP AND BOTTOM OF SLAB

Figure 8 presents the duration of various temperature differentials between top and bottom of the slab. The duration is expressed as a percentage of the annual time for each 1 deg. F difference in temperature between top and bottom of the slab. The data represents an average for the 5-yr period. This information is extremely useful in the calculation of temperature warping stresses By knowing the duration of the various temperature differentials, one is able to estimate the number of annual load repetitions to combine

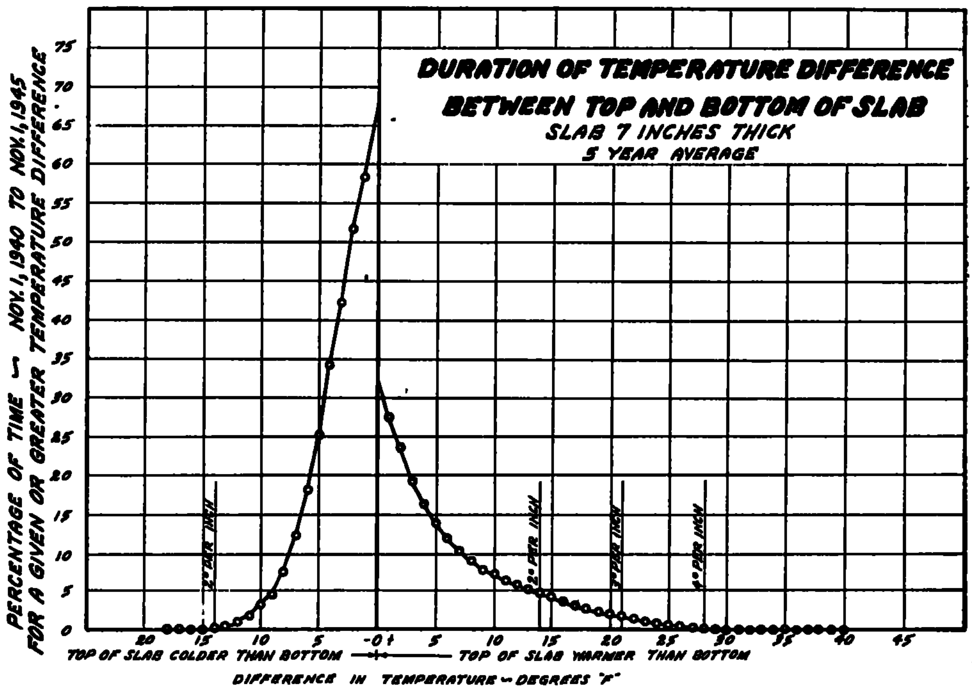

Figure 8. Duration of Temperature Difference Between Top and Bottom of Slab

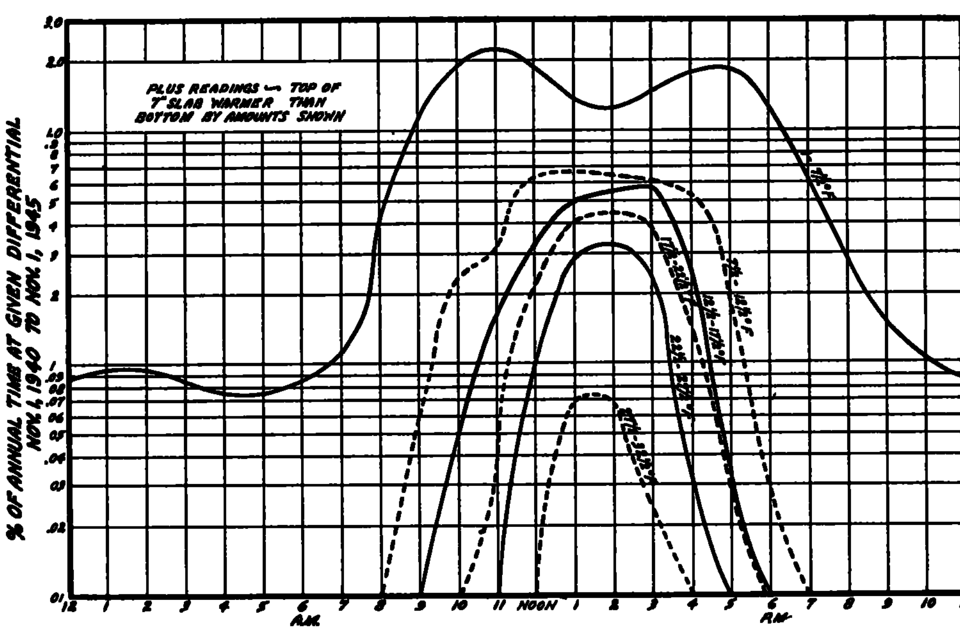

Figure 9. Percentage of Annual Time at Which Various Slab Temperature Differentials Occurred at Various Hours of the Day.

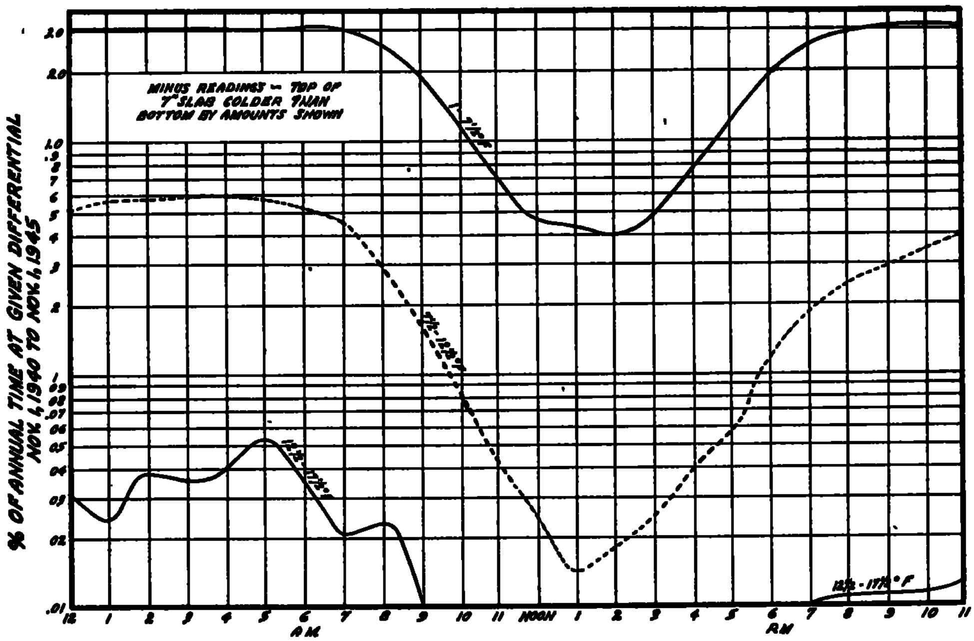

Figure 10. Percentage of Annual Time at Which Various Slab Temperature Differentials Occurred at Various Hours of the Day.

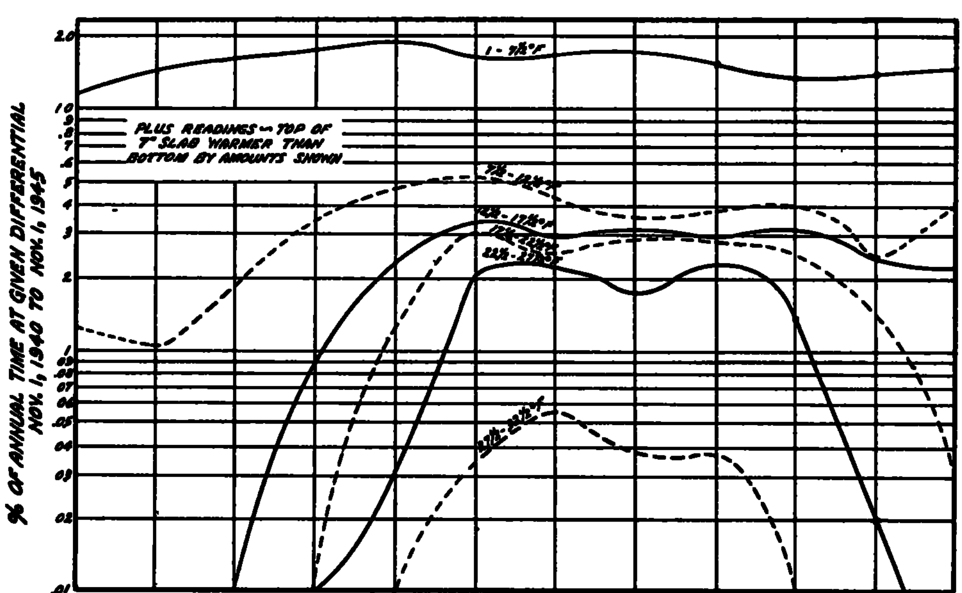

Figure 11. Percentage of Annual Time at Which Various Slab Temperature Differentials Occurred at Various Months of the Year.

with the maximum warping stress and thus compute probable pavement life by means of fatigue curves. Note that during 67.8 per cent of the annual time the top of slab is colder than the bottom although the percentage of the time for any marked temperature differential is small. The temperature differential may conveniently be expressed as degrees per inch of slab thickness. Thus the top of slab is colder than the bottom by 1 or more deg. F. per inch during 12.49 per cent of the time. The top of slab is colder than the bottom by 2 or more deg F. per inch during only 0 20 per cent of the time. The top of slab is warmer than the bottom by 3 or more deg. F. per inch during only 1.73 per cent of the time. The percentages of the time for the top 2 or more deg. F. per inch warmer and for 1 or more deg. F. per inch warmer are 4 69 and 10.42 respectively.

Some information is desirable regarding the daily and seasonal variation in slab temperature differentials, in order that warping stress calculations may be coordinated with seasonal or daily peaks in traffic volume. Figures 9 and 10 show the percentage of the annual time at which various slab temperature differentials occurred at various hours of the day The values shown were obtained from a 5-yr. average. Figure 9 shows differentials when the top of slab is warmer and Figure 10 shows differentials with top of slab colder. The summation of the percentage ordinates at each hour of the day on Figures 9 and 10, together with the 13.9 per cent of the time when slab temperature differentials were less than 1 deg F, totals 100 per cent. As might be expected, the curves for top of slab warmer are peaked about the line representing 2:00 P M., while the curves for top of slab colder are dipped down at that time of day

Figures 11 and 12 show the percentages of the annual time at which various slab temperature differentials occurred at various months of the year. Figure 11 shows differentials when the top of slab is warmer, and Figure 12 shows differentials when the top of slab is colder. As in Figures 9 and 10, the summation of the

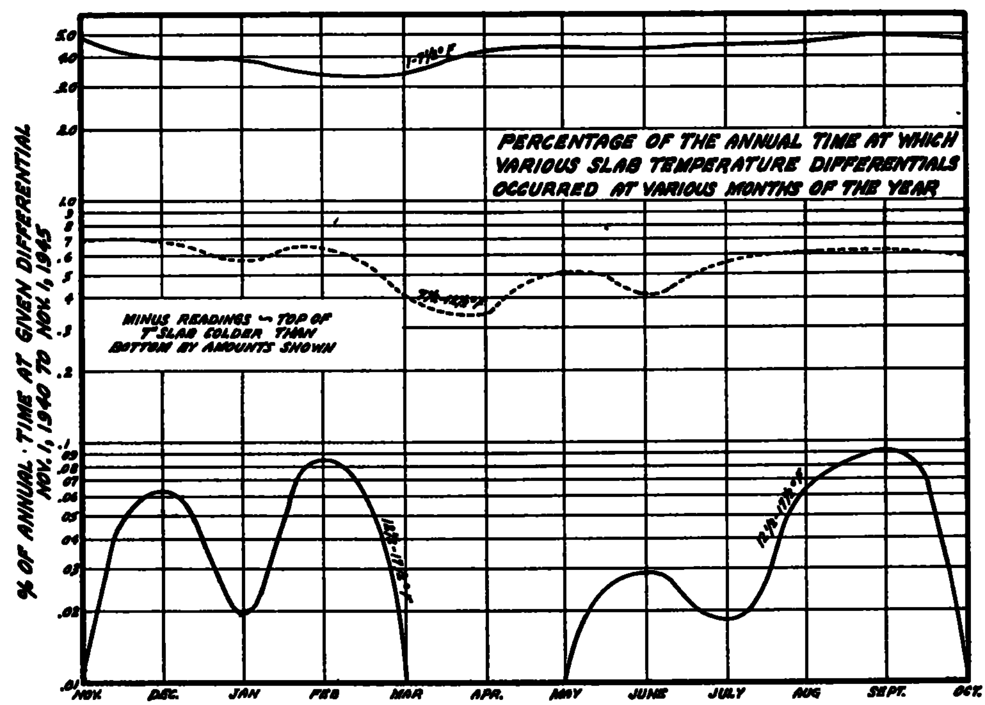

Figure 12. Percentage of Annual Time at which Various Slab Temperature Differentials Occurred at Various Months of the Year.

monthly percentage ordinates for the two figures, plus the additional 13.9 per cent for differentials less than 1 deg. F., results in a total of 100 per cent. It may be seen that the principal durations of the larger differentials with top of slab warmer are during the spring and summer months. It may be seen that the time intervals with the top of slab colder are rather well distributed throughout the year, except for the intervals where the differential is more than 12½ deg. F. These latter represent only 0.40 per cent of the annual time.

SUMMARY OF DATA

Maximum temperature surface of slab	122 F.
Maximum temperature center of slab	111.5 F.
Average annual range in air temperature	112 7 F.
Average annual range in center of slab temperature	114.3 F.
Midpoint in average annual range in center of slab temperature	50.4 F
Average date for frost to penetrate 5 ft. below slab	Jan. 14
Average date for frost departure in spring	Mar. 23
Average number of freezing and thawing cycles per year:	
Top of slab	48
Bottom of slab	24
One foot below slab	2
Minimum subgrade temperatures:	
Two feet below slab	+10 F.
Five feet below slab	+23 F.
Maximum continuous drop in average slab temperature	35 F.
Duration of slab temperature differentials in percentage of the annual time:	
Top of slab colder: (67.83 per cent of time)	
1 deg. F. per inch	12.49%
2 deg. F. per inch	0.20%
Top of slab warmer. (32.17 per cent of time)	
1 deg. F. per inch	10.42%
2 deg. F. per inch	4.69%
3 deg. F. per inch	1.73%

DEPARTMENT OF MAINTENANCE

W. H. Root, *Chairman*

REPORT OF COMMITTEE ON MAINTENANCE OF JOINTS IN CONCRETE PAVEMENTS AS RELATED TO THE PUMPING ACTION OF THE SLABS

Harold Allen, *Chairman, Principal Materials Engineer, Public Roads Administration*

C. W. Allen
A. A Anderson
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SYNOPSIS

The pumping committee has completed three major projects during 1945: (1) A survey of the pumping of concrete pavements in North Carolina; (2) A survey of the pumping of concrete pavements in Kansas; and (3) The preparation of recommendations on the design of rigid pavements as requested by the Project Committee on Rigid Pavement Design.

The North Carolina and Kansas surveys were made on a cooperative basis by the respective State highway departments and the Portland Cement Association. Abstracts of these reports are included as a part of this report. The full text of the reports will be published as a special Research Report supplementing the reports issued in 1945.[1] The conclusions presented in these reports are those of the authors and do not necessarily represent those of the committee.

[1] "Special Papers on The Pumping Action of Concrete Pavements," *Research Reports* No. 1-D, Highway Research Board, 1945