Temperature Variations in a Cement Concrete Pavement and the Underlying Subgrade

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This paper presents the results of temperature observations carried out for slightly more than 2 yr on a 6-in. thick portland cement concrete slab at Kharagpur, India. Temperature studies were also made on the water bound macadam base and the natural subgrade beneath the slab. The observed time-temperature variations are compared with existing theories of temperature distribution in a concrete slab. Based on the observed data, an empirical equation to estimate the amplitude of surface temperature variation in the 6-in. slab from the air temperature data is given.

•DESIGN OF cement concrete pavements has not appreciably advanced from the prevailing empirical methods in spite of the immense development in concrete design and technology. The main reason for this is that from the standpoint of stress analysis the concrete pavement, a long and thin slab resting on a shallow foundation, is a highly complex structure. Any study of pavement stresses must take into account the varying characteristics of the subgrade on which the slab rests. Of the many factors that induce stresses in a concrete pavement, the wheel loads and the temperature variations in the slab are important. Because the effects of moisture differential counteract the more harmful effects of temperature differential, the effect of moisture as a stress producer in a pavement slab is generally neglected. Also, no simple and satisfactory method of precisely measuring the moisture gradient in a slab has been evolved. Extensive observations by the U. S. Corps of Engineers (1) have revealed that the dynamic effect of wheel loads can be handled by a coefficient of impact. Therefore, it is comparatively easy to fairly accurately estimate the wheel load stresses using Westergaard's or Pickett's analysis. These wheel load stresses by themselves may be well within the permissible stresses. However, it is quite possible that the wheel load stresses combined with temperature stresses may lead to slab failures.

The effect of temperature on a cement concrete pavement can be divided into two parts (a) the daily variation of the slab temperature, the top surface being hotter or cooler than the bottom and (b) the yearly or seasonal variation in the average concrete temperature. The former variation causes the slab to curl, thereby creating "curling stresses." The latter gives rise to friction forces between the slab and the base. Generally, the slab will adjust itself to the slowly changing seasonal temperature conditions without causing excessive stresses. Of the two, the effect of daily variation in temperature with its consequent curling is more serious. Apart from the development of curling stresses, it leads to a partial loss of the subgrade support at the corners and edges (critical areas as far as the wheel load dispositions are concerned).

The temperature variation in a concrete slab depends on the meteorological characteristics of the area. Published data on temperature distribution in a concrete road slab has, so far, been confined to subtropical countries. No temperature data appear to be available for concrete roads in humid tropical areas. To gather such data, temperature observations were carried out on a 6-in.-thick cement concrete slab 5 by 4 ft

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at the Indian Institute of Technology, Kharagpur, India for the past 3 yr. The test area was 72 mi southeast of Calcutta, and its geographical location is given as 87.5° East longitude and 22° North Latitude. To simulate the common practice of stage construction generally adopted in India, the 6-in. slab was cast on a 4-in.-thick water bound macadam base laid over a 6-in.-thick laterite stone subbase. The subgrade of sandy clay loam, the stone subbase, and the macadam base were thoroughly rolled before each succeeding layer was laid. The concrete used for the test slab had an average 28-day cube strength of 5,550 psi, modulus of elasticity in flexure of 2.95×10^6 psi, and a modulus of rupture of 533 psi. When laying the concrete, copper-constantan thermocouples were installed at the surface of the concrete at depths of 1, 2, 4, and 6 in. Prior to laying the concrete slab, the subgrade and the interior of the macadam base were carefully exposed in two places. Thermocouples were placed 2 in. inside the base (8 in. from the top of the slab) and 4.5 in. inside the subgrade (20.5 in. from the top of the slab).

No automatic temperature recorders of the continuous type were available except at a prohibitive cost; therefore, a mirror galvanometer was used to measure the e.m.f. set up by the thermocouple junctions. The observations were usually started at 7 A.M. in the summer and 8 A.M. in the winter. Readings were taken at 2-hr intervals. However, between 11 A.M. and 2 P.M., and 4 and 7 A.M., the readings were recorded at 1-hr intervals so the maximum and minimum surface and air temperatures could be obtained. The temperature readings are not continuous, but were planned so as to develop full information covering both daily and yearly temperature cycles. The average temperature of the slab was obtained by averaging the temperatures measured at the different points along its depth. Figures 1 and 2 show the prevailing weather conditions of the test slab area.

From the data obtained, it was possible to find the critical temperature conditions for each of the days; and because the observations were made during all the months of the different seasons, it was possible to get a reasonably accurate picture regarding the daily as well as yearly concrete temperature variations. Table 1 gives a summary of the data obtained in this manner. On a careful study of the table, the following observations appear evident. The average slab temperature varies about 33.7 C (60 F) during the year. This variation controls the magnitude of yearly change in the pavement length caused by temperature changes. The maximum recorded surface temperature of the slab was 51.0 C (124 F). This occurred on May 17, 1961, a clear rainless day.

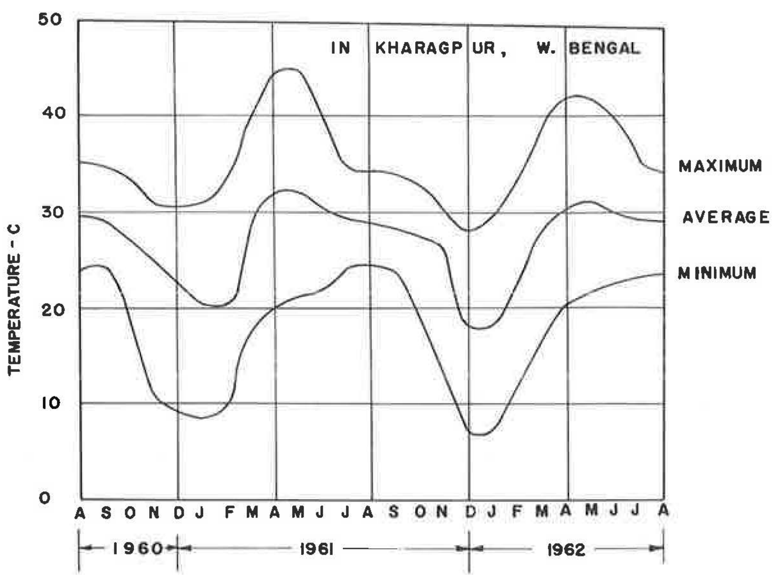

Figure 1. Annual air temperature variation.

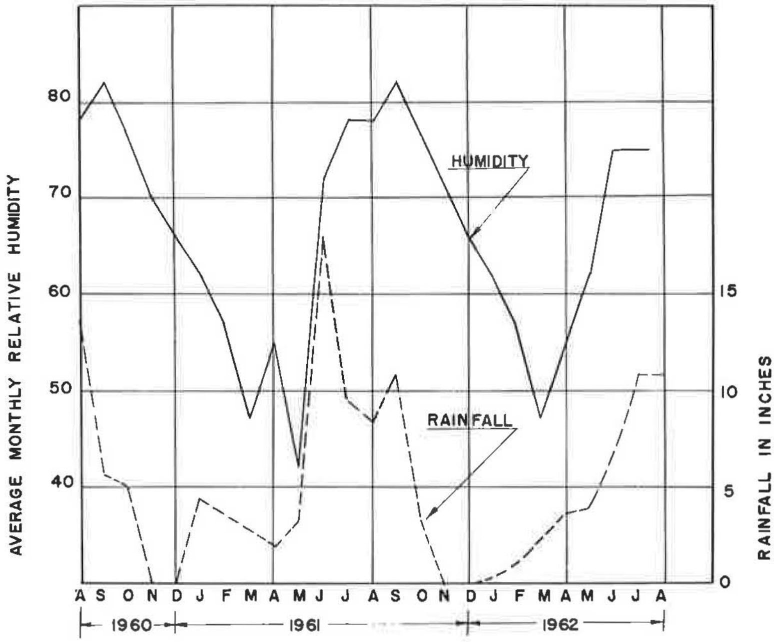

Figure 2. Annual variations in relative humidity and rainfall.

The maximum positive gradient was 12.0 C (21.6 F) on April 11, 1961; and the maximum negative gradient of 6.3 C (11.3 F) on May 2, 1961. This high negative gradient was caused by heavy freak thunderstorms that occurred on the evenings of May 1, 2, 1961. This negative gradient occurred at about 8 P.M. on May 2; it was transient in nature, and rapidly disappeared restoring normal conditions in about 6 hr.

On the same day, the surface temperature of the slab dropped from 44.5 C at 3 P.M. to 27.5 C at 8 P.M. The maximum negative gradient of 5.0 C, due to seasonal variation, occurred at about 5 A.M. on November 29, 1960. It is interesting to recall that the maximum surface temperature recorded by Teller and Sutherland (2) was 112.5 F (44.5 C) and 31.0 C by Bergstrom (3). Swanberg (4) has reported a maximum surface temperature of 122 F for a 7-in. slab in the Minneapolis area. Also the Arlington tests by Teller and Sutherland indicate that the maximum value of the day temperature differential is about three times the maximum value of the night differential. The present observations indicate that under humid tropical conditions the day differential is only slightly more than thice the night differential value. Further more, the observed night temperature differential varies within very narrow limits between winter and summer. Based on the Arlington tests, for purposes of design computations, Kelly (5) recommends a maximum positive temperature differential of 3 F per in. slab thickness. From

TABLE 1

SUMMARY OF OBSERVED TEMPERATURES IN A 6-INCH-THICK CONCRETE SLAB, I. I. T., KHARAGPUR, WEST BENGAL

Date	Avg. Temp. (°C)		Max. Temp. (°C)		
			Day		Night
	Max.	Min.	Surface	Gradient (+)	Gradient (-)
Aug. 31, 1960	34.7	25.8	38.0	7.7	2.8
Sept. 7, 1960	35.5	27.0	37.5	4.1	3.0
Sept. 22, 1960	40.0	28.9	39.3	7.2	4.0
Oct. 26, 1960	36.5	24.1	39.5	7.2	2.3
Nov. 2, 1960	33.6	25.4	36.5	7.1	3.2
Mar. 8, 1961	37.6	23.4	42.0	10.0	4.6
Mar. 24, 1961	39.9	28.4	46.3	10.4	4.7
Apr. 5, 1961	42.4	28.7	47.2	11.5	4.1
Apr. 11, 1961	43.3	28.0	48.0	12.0	4.8
Apr. 17, 1961	45.3	29.2	49.5	10.3	4.5
May 2, 1961	42.4	26.8	45.5	8.0	6.3
May 17, 1961	46.2	32.1	51.0	11.9	4.8
June 4, 1961	42.9	31.5	46.8	9.6	4.5
Feb. 15, 1962	33.3	19.2	37.0	9.5	4.5
Feb. 27, 1962	35.6	23.1	39.2	8.7	3.7

the data available for the 6-in. slab in this study, the maximum positive temperature differential may be assumed to be 2.0 C (4 F) per in. slab thickness and the maximum negative gradient of 1 C (2 F) per in. slab thickness.

Figures 3 to 8 plot the daily temperature variations at different depths for the different yearly seasons. From these graphs, the temperature gradients for six time periods are interpolated and plotted in Figures 9 to 14. A study of these curves reveals

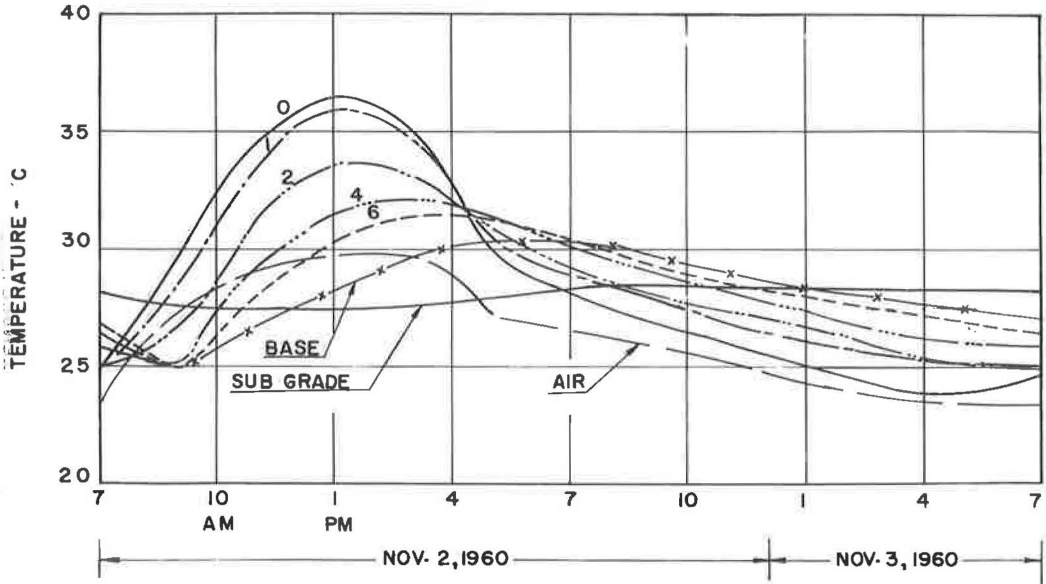

Figure 3. Variation of temperature with time at various depths.

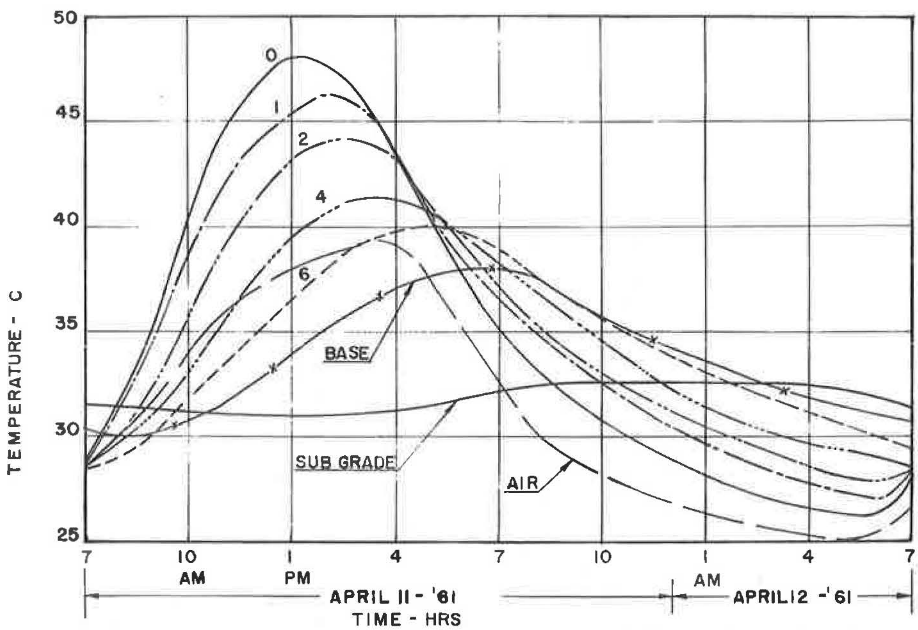

Figure 4. Variation of temperature with time at various depths.

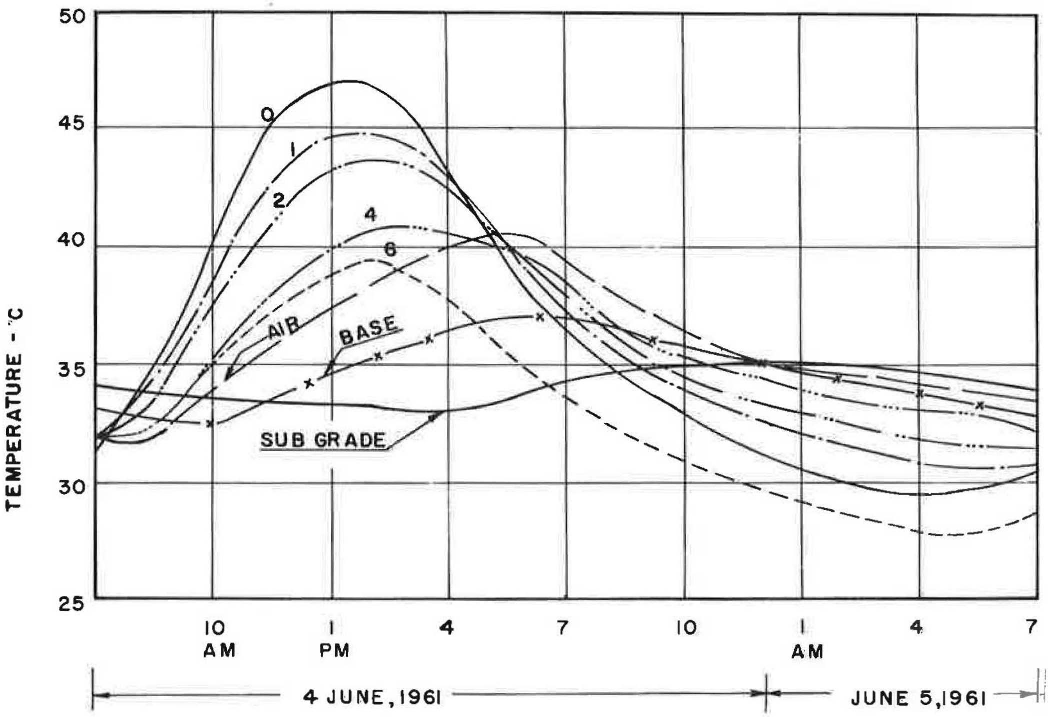

Figure 5. Variation of temperature with time at various depths.

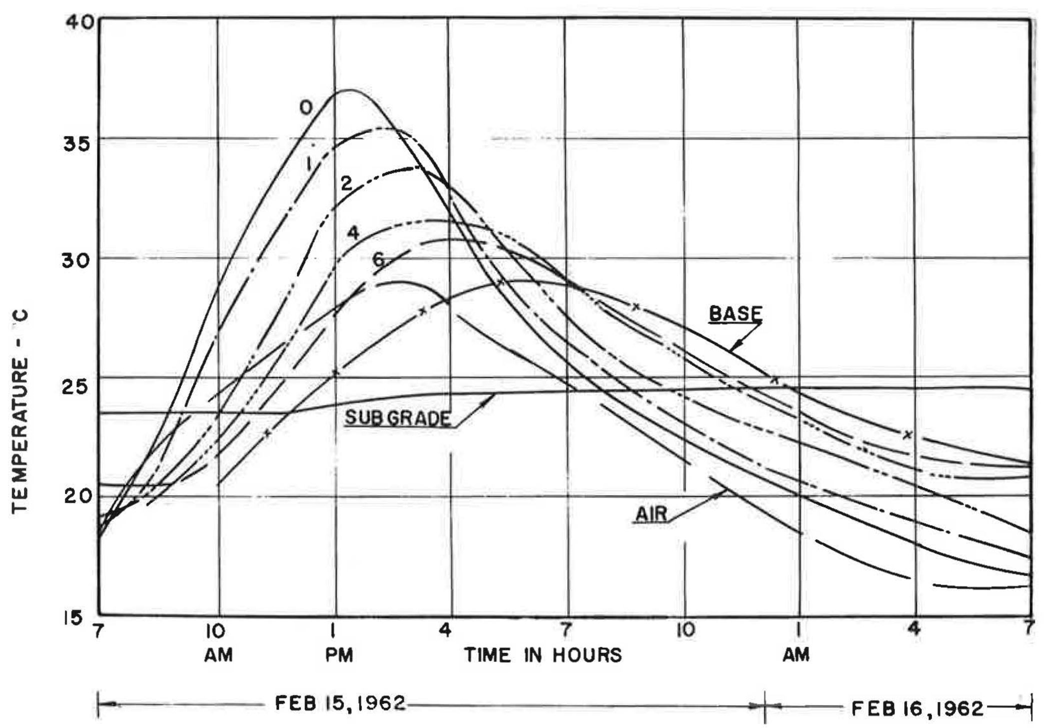

Figure 6. Variation of temperature with time at various depths.

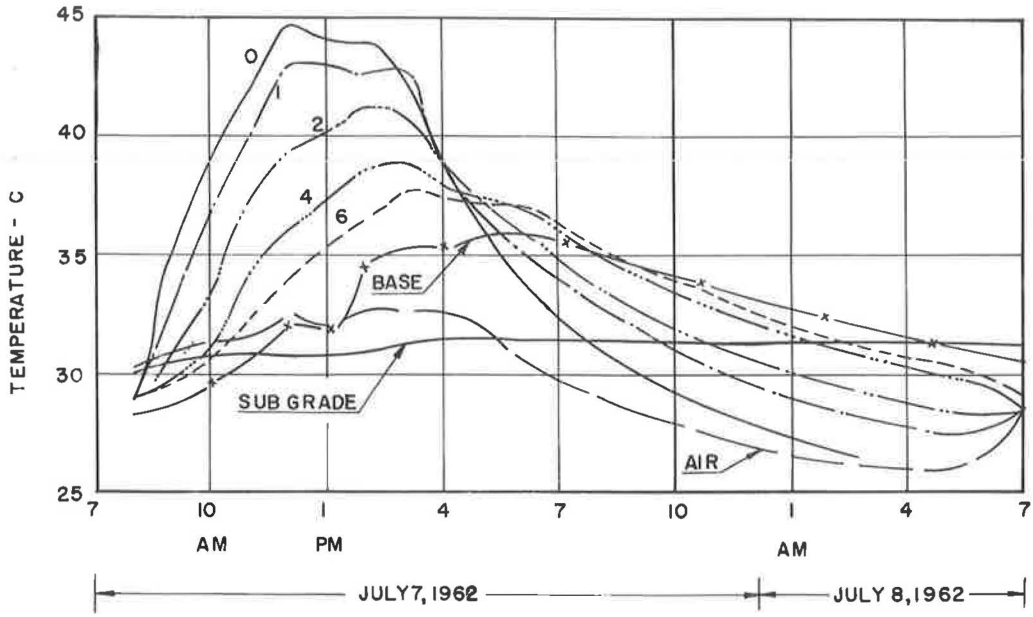

Figure 7. Variation of temperature with time at various depths.

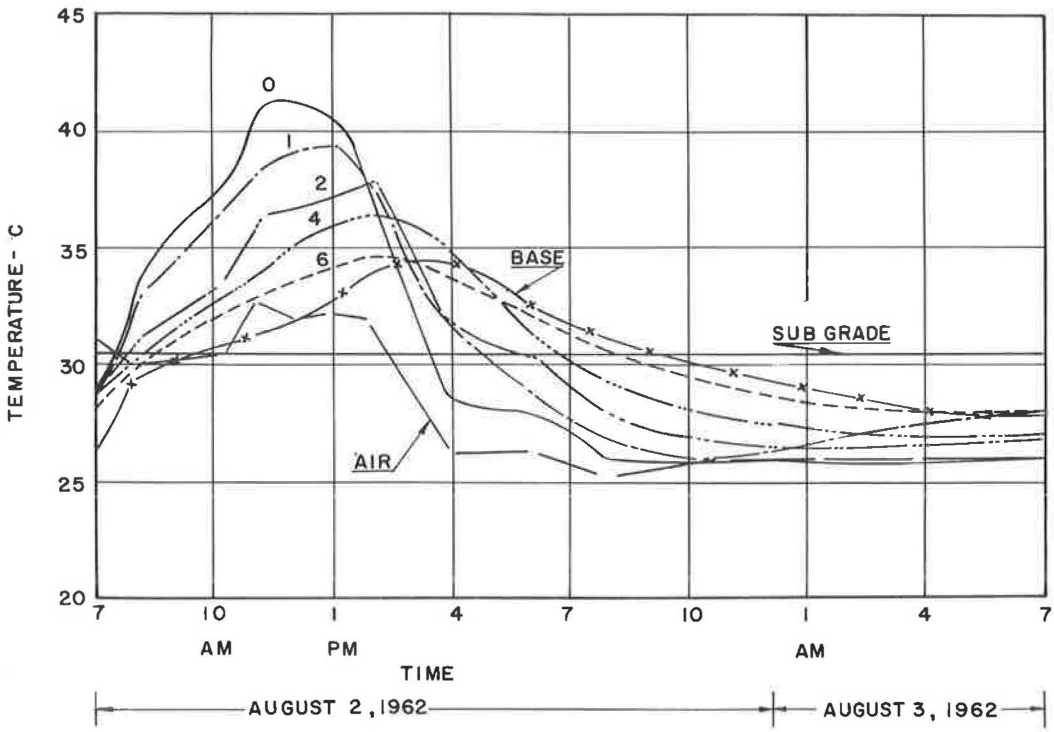

Figure 8. Variation of temperature with time at various depths.

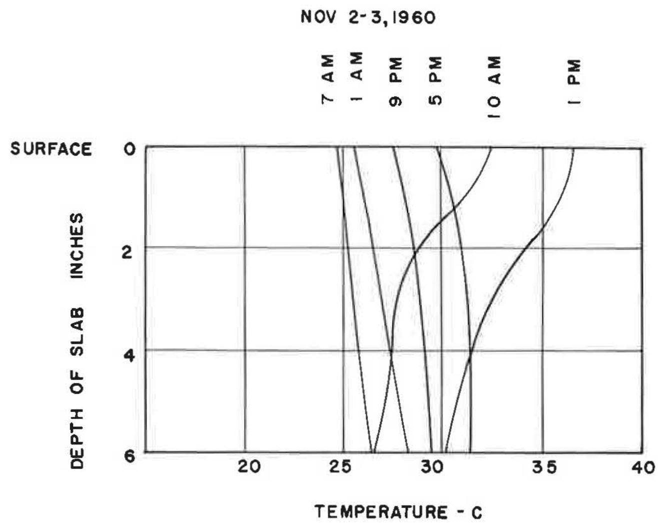

Figure 9. Variation of temperature with depths at various times.

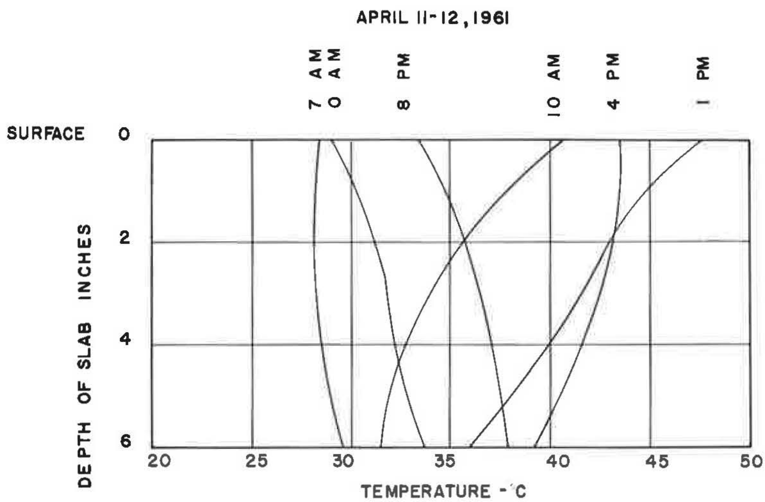

Figure 10. Variation of temperature with depths at various times.

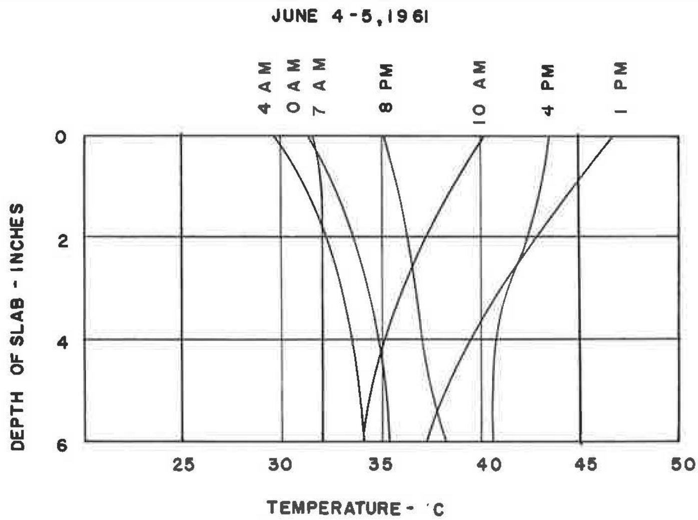

Figure 11. Variation of temperature with depths at various times.

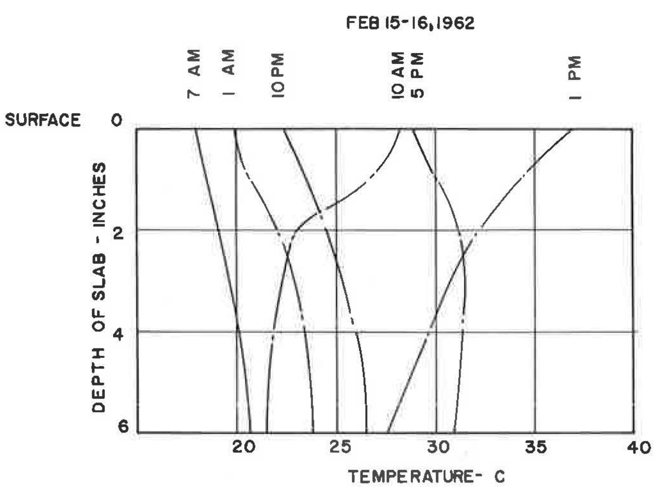

Figure 12. Variation of temperature with depths at various times.

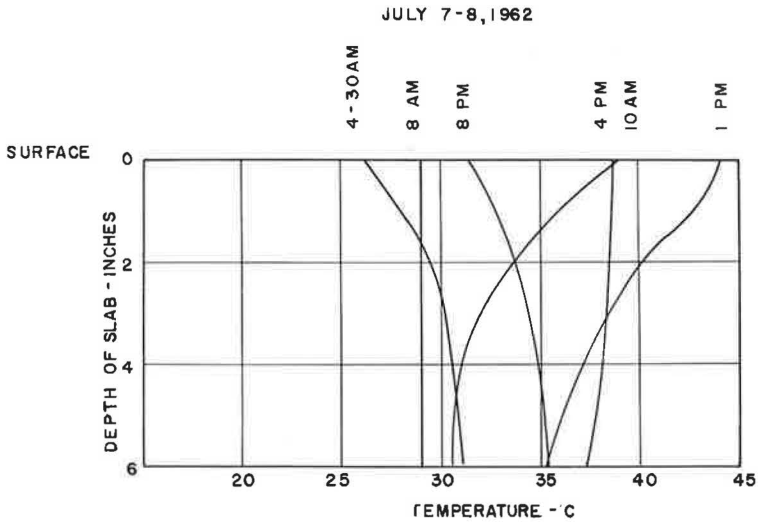

Figure 13. Variation of temperatures with depths at various times.

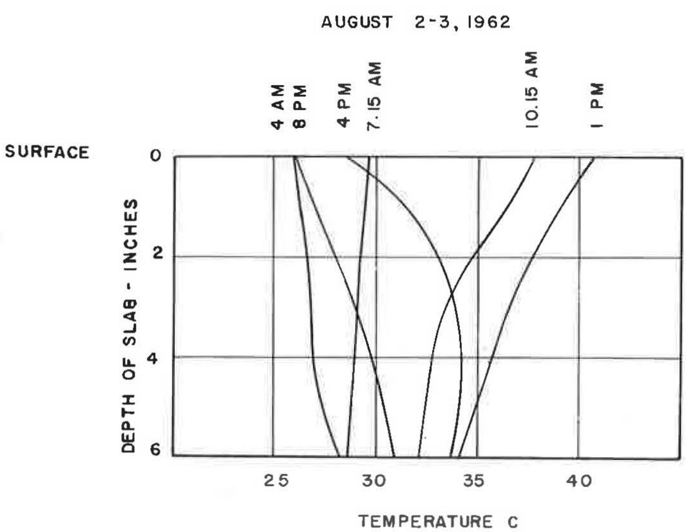

Figure 14. Variation of temperature with depths at various times.

that the daily variation curves approximate a wave form only during the nonmonsoon months. During the monsoon months, July and to September, the curves appear to be very erratic. During these months the sky is rarely clear and direct solar radiation on the slab is not continuous; also, the subgrade and the slab are very wet, if not saturated. Under such circumstances it is safe to assume that the temperature curling stresses will not be critical. The prevailing temperature conditions during the monsoon months also can be disregarded without much error in the development of design criteria for concrete slab temperature stresses in humid tropic areas.

The steepest positive temperature gradient occurs at the time of maximum surface temperature (about 1 P.M.), and the maximum negative gradient occurs between 4 and 5 A.M. Also the maximum gradient curves causing the maximum curling stresses are very nearly linear justifying Westergaard's assumption. Thus, Westergaard's concept of a linear temperature gradient, while it is not valid for the general case, is true for the critical condition in which the designer is interested. These findings are in close agreement with the Arlington test results.

The maximum and minimum observed values of subgrade temperatures underneath the slab are given in Table 2. The daily variation of subgrade temperature is almost negligible, but there is appreciable seasonable variation. The temperature of the subgrade by itself may not be important, but a study of Figures 3-8 referred to previously indicates that in the early hours of the morning when there is no direct solar radiation on the slab and when the temperature gradient in the concrete slab is negative, the subgrade temperature is always higher than the temperatures at the bottom face of the slab, and the stone subbase. Being in contact with them, the subgrade is able to transmit heat in the reverse direction. This phenonemon may be partly responsible for the difference between the observed and theoretical temperature distribution within the slab.

At present there are two elastic theories available for the estimation of curling stresses in a concrete road slab due to temperature variation. Both the theories depend on the coefficients of restraint for their ultimate use. These are very difficult to evaluate precisely during the service behavior of the slab. As such, from a practical point of view, one theory is not superior to the other. However, the variation limits of the curling stresses can be set down from the temperature distribution data. Westergaard's theory, developed as early as 1927, assumes a linear temperature gradient through the slab (6). The other theory was presented by Thomlinson of the Road Research Laboratory, U. K. in 1938 (7). Thomlinson's theory is favored on the continent. He assumes the surface temperature of the slab to vary according to a simple harmonic law. The temperature θ at any given depth x below the surface at any time t is given by the relation:

$$\theta = \theta_o e - \frac{x}{h}\sqrt{\frac{\pi}{T}} \sin\left(\frac{2\pi}{T} t - \frac{x}{h}\sqrt{\frac{\pi}{T}}\right) \quad (1)$$

in which

θ_o = amplitude of the temperature cycle at the free surface of the slab
e = the base of the Naperian system of logarithms
h^2 = diffusivity of the concrete in sq in. per hour $= \frac{\text{thermal conductivity}}{\text{heat capacity per unit volume}}$
T = periodic time of the temperature cycle (24 hours for the daily cycle)

It should be noted that Bergstrom (3) also accepts the above relationship, but assumes θ_o to be a constant, and determines its value so as to insure close agreement between the maximum values of the theoretical and observed temperature gradients. Sparkes (8) and Bergstrom (3) state that close agreement exists between the observed and com-

TABLE 2

EXTREME SUBGRADE TEMPERATURES

Date	Subgrade Temp. (°C)	
	Max.	Min.
Aug. 31, 1960	29.5	28.0
Sept. 7, 1960	31.3	29.0
Sept. 15, 1960	30.7	29.0
Sept. 22, 1960	33.7	29.0
Oct. 26, 1960	30.2	28.2
Nov. 2, 1960	28.7	27.5
Mar. 8, 1961	29.0	27.5
Mar. 24, 1961	33.0	31.4
Apr. 5, 1961	33.5	31.4
Apr. 11, 1961	32.6	30.6
Apr. 17, 1961	35.0	33.8
May 2, 1961	33.8	31.4
May 17, 1961	36.0	33.8
June 4, 1961	35.0	33.5
Feb. 15, 1962	24.5	22.8
Feb. 27, 1962	27.5	26.0

puted temperature distribution in concrete pavements. As already mentioned, the temperature variation at the surface approximates a simple harmonic law only during the dry months of the year and furthermore, this approximation is valid in the morning before the surface temperature has reached its peak value. In the afternoon deviation from the sinusoidal variation is more prominent. The result being that during the day the measured positive temperature differential is always greater than the computed differential, and during the night the maximum measured differential is always less than the computed value. This is clearly shown in Table 3. However, in the evaluation of the curling stresses, this discrepancy can be accounted for by harmonic analysis as suggested by Champion (9). Therefore, it appears that if one is able to establish a reasonably accurate and simple method to estimate the amplitude of the surface temperature variation in a slab, Thomlinson's theory can be used to evaluate the curling stresses expected in the slab.

In most of the developed areas, the meteorological data like the maximum and minimum daily air temperature and daily rainfall will be available. Therefore, if an experimental relationship can be established between the amplitudes of the daily variations of the concrete's surface temperature, and the prevailing air temperature variation in that area, the surface temperature amplitude at a similar locality can be easily estimated. An attempt has been made in this direction for the 6-in. slab under study, and the results are given in Table 4, and Figure 15. It can be seen that for design purposes, the maximum value of the surface temperature for the 6-in. slab can be taken as 1.5 times the maximum value of the air temperature recorded that day. Also the minimum value of the surface temperature is almost equal to the minimum air temperature recorded. It is suggested, therefore, that the amplitude of the surface temperature variation θ_o can be given by the empirical relationship:

$$\theta_o = \frac{1.5\ \theta_{a_{max}} - \theta_{a_{min}}}{2} \qquad (2)$$

in which

$\theta_{a_{max}}$ and $\theta_{a_{min}}$ are the maximum and minimum air temperature values on a particular day on which the amplitude of the surface temperature variation for a 6-in.

TABLE 3

COMPARISON BETWEEN MAXIMUM MEASURED AND CALCULATED TEMPERATURE GRADIENTS

Diffusivity of concrete = h^2 = 6.48 sq in./hr[a]

Date	Max. Temp. Gradient			
	Measured		Calculated	
	Day (+ve)	Night (-ve)	Day (+ve)	Night (-ve)
Nov. 2, 1960	6.3	2.7	4.5	4.5
Feb. 15, 1962	9.5	3.8	7.5	7.5
Apr. 15, 1962	12.0	4.5	8.0	8.0
June 4, 1962	9.6	4.0	6.3	6.3

[a] "Thermal Properties of Concrete." Bull. 1, Boulder Canyon Project Final Reports, U. S. Bureau of Reclamation.

TABLE 4

RATIOS OF EXTREME VALUES OF SURFACE AND AIR TEMPERATURES

Date	Maximum Air Temp. θ_{amax}	Maximum Surface Temp. θ_{omax}	$\theta_{omax}/\theta_{amax}$	Minimum Air Temp. θ_{amin}	Minimum Surface Temp. θ_{omin}	$\theta_{omin}/\theta_{amin}$
Aug. 31, 1960	31.8	38.0	1.19	25.5	27.0	1.06
Sept. 2, 1960	32.0	39.0	1.21	27.0	25.7	0.95
Sept. 8, 1960	32.0	41.4	1.29	25.8	25.5	1.00
Sept. 14, 1960	32.0	38.5	1.20	25.5	25.5	1.00
Sept. 15, 1960	33.0	42.8	1.28	26.5	25.5	0.96
Sept. 22, 1960	34.0	43.0	1.27	27.0	28.0	1.04
Oct. 26, 1960	32.0	39.5	1.23	22.5	22.5	1.00
Nov. 2, 1960	29.8	36.5	1.22	23.5	24.0	1.02
Mar. 8, 1961	34.0	42.0	1.23	21.0	21.5	1.02
Mar. 24, 1961	37.5	46.3	1.23	25.2	26.5	1.05
Apr. 5, 1961	39.0	46.3	1.19	24.8	26.5	1.07
Apr. 11, 1961	39.2	47.5	1.21	25.0	26.3	1.05
Apr. 17, 1961	39.8	49.5	1.24	24.6	27.0	1.10
May 2, 1961	36.0	45.5	1.27	23.8	25.0	1.05
May 17, 1961	41.6	51.0	1.23	28.2	29.8	1.06
June 4, 1961	39.6	46.8	1.18	27.7	29.5	1.06
Feb. 15, 1962	29.0	37.0	1.27	16.2	17.0	1.05
Feb. 27, 1962	31.8	39.2	1.23	20.5	22.3	1.09
July 7, 1962	32.8	44.8	1.36	26.2	26.2	1.00
Aug. 2, 1962	32.6	41.3	1.27	25.2	26.0	1.03
Nov. 15, 1962	29.2	32.0	1.10	18.2	16.0	0.88
Dec. 13, 1962	25.5	28.8	1.13	14.0	14.0	1.00

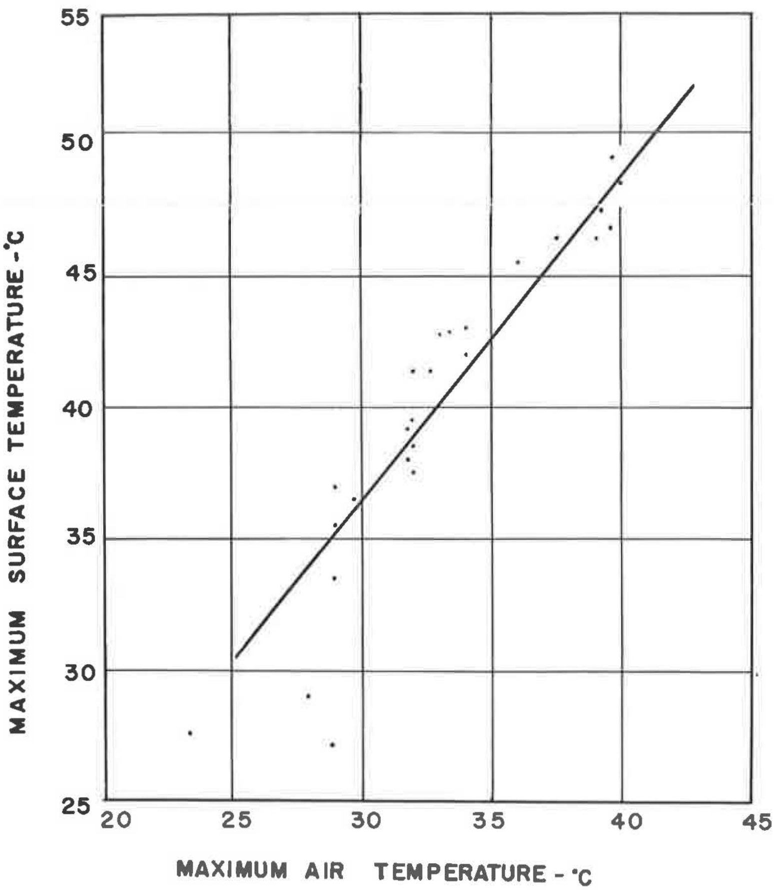

Figure 15. Maximum surface temperature vs maximum air temperature.

slab will be θ_0. It must be noted that there is a phase different between the times at which the peak values occur. Furthermore, this relationship is applicable only to the 6-in. slab laid in the climatic conditions referred to previously. Once the amplitude of the surface temperature variation can be established, the curling stresses can be evaluated from Thomlinson's analysis.

ACKNOWLEDGMENTS

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