TEMPERATURE AND MOISTURE VARIATIONS IN CONCRETE PAVEMENTS

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SYNOPSIS

This investigation was started to obtain a record in a northern climate of movements resulting from changes in temperature and moisture in a concrete pavement slab and the underlying subgrade Temperatures were recorded at six places in the 7-in slab and five places in the sandy subgrade every 6 min for one year Moisture content was determined by means of Bouyoucos moisture blocks at center of slab and at three places in the subgrade.

The data have been arranged to show the following · (1) weekly maximum and minimum air temperatures and the corresponding maximum and minimum temperatures in the center of the slab, (2) relation between daily range in air temperature and daily range in center-of-slab temperature, (3) typical hourly differentials in temperature between top and bottom of slab for the period when the difference was a maximum, (4) the duration of the various temperature differentials between top and bottom of slab in percentage of the total time for one year, (5) the number of times during the year that the various temperature differentials occurred; (6) percentage of total annual time that indicated temperature differentials between top and bottom of slab occurred during each month; (7) same as 6, only for the hours of the day; (8) temperature gradient from top to bottom of slab; (9) number of freezing and thawing cycles during one winter and also rates of freezing and thawing, (10) cumulative degree-days air temperature and frost penetration into subgrade; (11) percentage of moisture in concrete.

This information is of value in computing movements of slab or stresses due to average temperature and moisture changes and for warping stresses due to temperature differences within the slab The time factor as to month and time of day makes it possible to correlate these data with traffic survey data and compute the probable combined load and warping stresses that may occur during the expected life of the pavement. The data on freezing and thawing and rates of frost penetration may aid in determining which laboratory cycle to adopt and also the relationship between the number of laboratory cycles and the number of years outside exposure

Concrete pavements, particularly in the northern states, are subjected to stresses from climatic changes which not only affect the load carrying capacity of the slab, but also the life expectancy or the durability of the structure. It was for the purpose of securing additional data to use in computing total stresses under load, and to determine durability that this investigation was started. Measurements have been taken over a twelve-month period. The method of taking measurements, and a summary of the data obtained are shown graphically.

SLAB LAYOUT

The experimental concrete slab was constructed in the driveway leading into the highway laboratory. It is 16½ ft. by 17 ft. in area and 7 in. thick and was laid on a subgrade of loamy fine sand. The slab is so located that it has good drainage. It has been kept free of snow and ice. It is not shaded from early morning to late afternoon.

The vertical location and numerical designation, from 1 to 11 inclusive, of the thermocouples in the concrete and the underlying soil, are shown on the right of the sectional diagram of Figure 1. It will be noted that Thermocouple No. 1 is placed at the top of the slab, No 2, ½ in. below the top of the slab, No. 3, 2½ in. below the top of the slab, No. 4, 4½ in. below the top, No. 5, ½ in. from the bottom and No 6 at the bottom of the concrete. Thermo-

couples 7, 8, 9, 10 and 11 were placed in the subgrade at the points shown, No. 11 being 60 in. below the slab. Thermocouple No. 12 recording air temperature was placed 5 ft. from the laboratory building and approximately 12 ft. above ground level. The thermocouples as shown on the plan are located at Point A which is at the center of the slab. The thermocouples lead into the laboratory where an electric potentiometer records the temperature at each point every 6 min.

On the left of the sectional diagram are shown the vertical locations of the Bouyoucos[1] moisture blocks. One block was placed in the center of the slab at location A. One block was placed 3 in. below the slab and the other 27 in. below the slab.

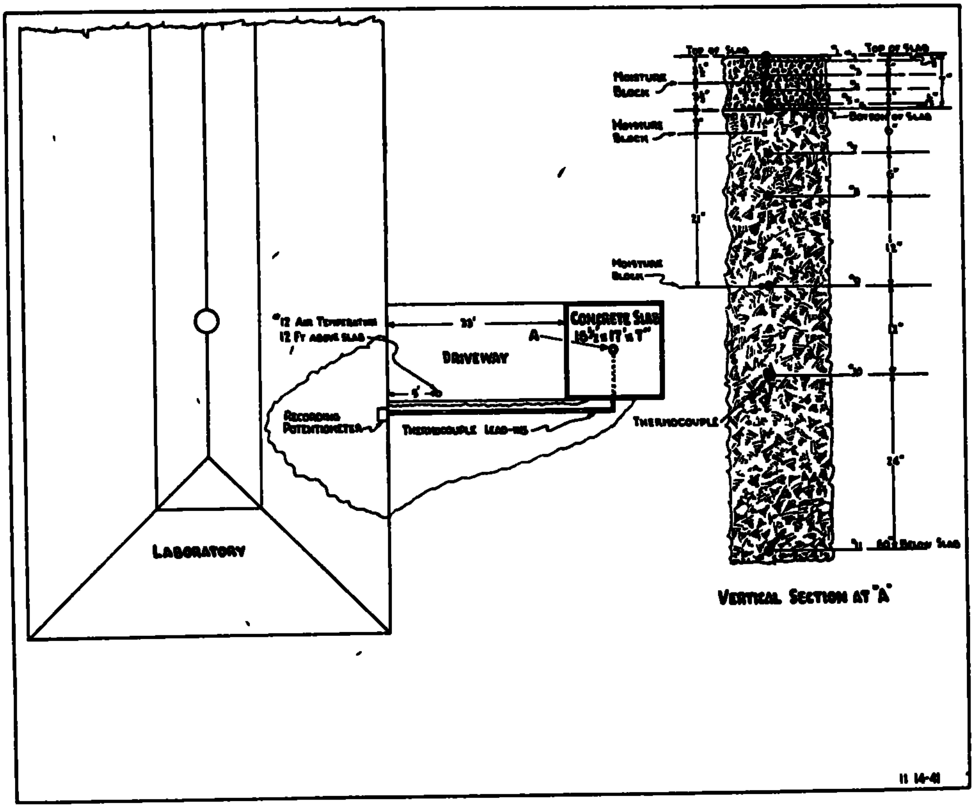

Figure 1. Minneapolis Laboratory Temperature and Moisture Observation Station

[1] Technical Bulletin 172, Michigan State College, Agriculture Experiment Station.

POTENTIOMETER RECORD

The manner in which the potentiometer records the temperatures at the thermocouple points is illustrated in Figure 2 The time in hours is plotted on the vertical scale and the temperature in degrees on the horizontal scale. The readings of each of the twelve thermocouple points are shown by a distinctive designation, either a circle or cross in one of six colors.

AIR AND CONCRETE TEMPERATURES

The solid lines in Figure 3 show the weekly maximum and minimum air tem-

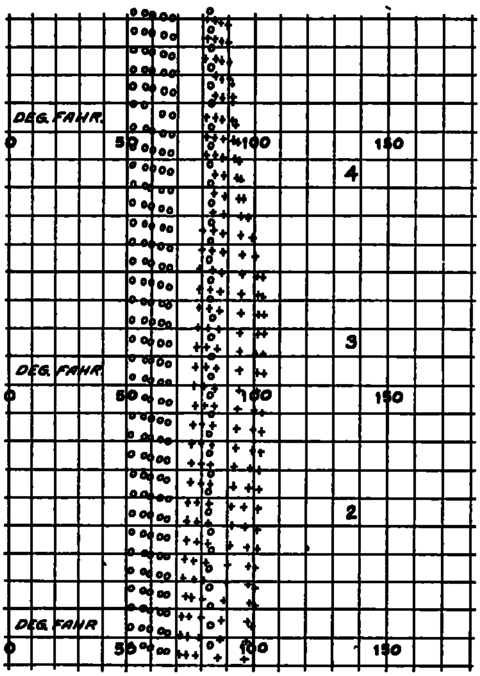

Figure 2. Copy of a Section of a Potentiometer Record

peratures from November 1, 1940, to November 1, 1941. The corresponding maximum and minimum temperatures in the vertical center of the concrete slab are shown by the broken lines. The maximum weekly variation in the concrete temperature was 47° F. and occurred during the month of June. The maximum annual variation in the concrete temperature was 115° F. The maximum temperature of the concrete 108° F. occurred when the air temperature was 96° F, the minimum concrete temperature −8° F occurred when the air temperature was +7° F.

In Minnesota practically all concrete paving construction occurs between May 1 and October 1. On the basis that concrete placed has a temperature of 70° F. then the maximum compressive stress due to increase in temperature for a modulus of elasticity of 4 million was 840 lb. per sq in.

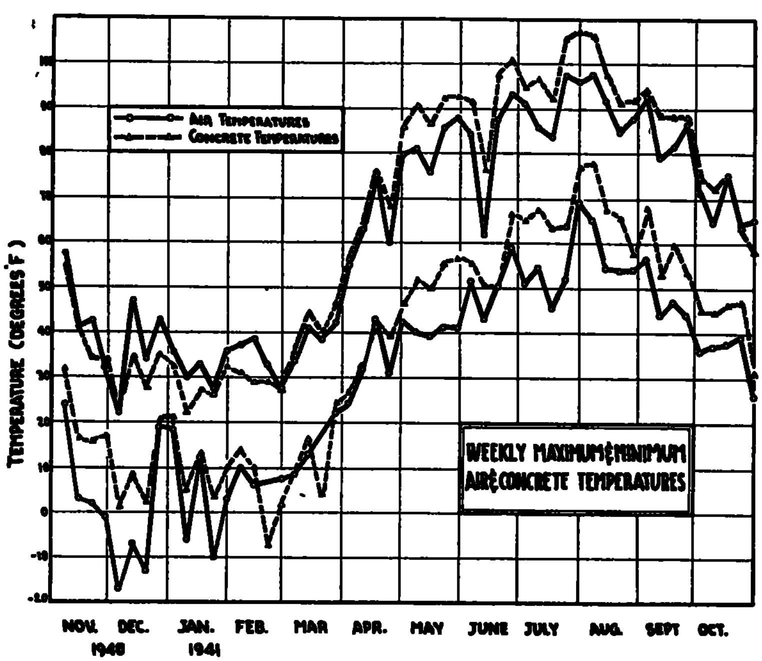

Figure 3

TEMPERATURE RANGE RELATIONSHIP

The relationship between the daily range in air temperature and the daily range of center-of-slab temperatures is shown in Figure 4. It will be noted that this is not a straight line relationship During the period of greatest range in air temperature, the range in average concrete temperature is approximately the same traction stress in a pavement slab is not dependent on the annual change in temperature but on the subgrade resistance that is developed during a single period of continuously falling temperature.

Figure 4 should be useful in predicting fluctuations in concrete temperatures when only air temperature records are available.

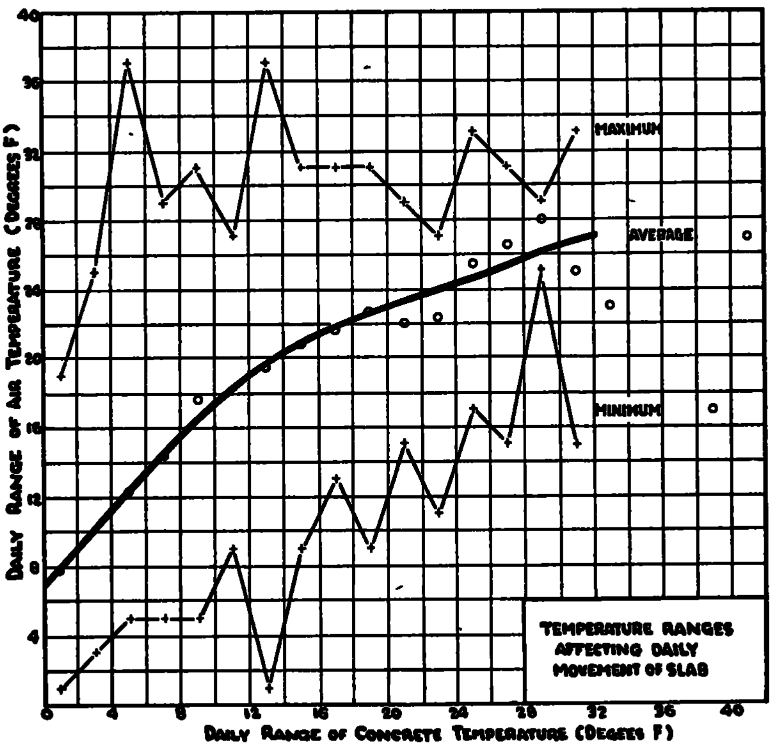

Figure 4

but in the lower ranges of air temperature it is less. This is probably attributable to the fact that during the period of the higher ranges there is greater absorption of solar heat because of the greater angle of incidence of the sun's rays.

The importance of these daily ranges of temperature was pointed out by Bradbury.[2] He showed that the maximum con-

FREQUENCY OF SLAB TEMPERATURE DROPS

The number of times during the year that the average slab temperature dropped continuously for the various increments in temperature is shown in Figure 5. For instance there were 42 times when the temperature dropped continuously for 4° F. Similarly a continuous drop of

[2] Discussion by R D Bradbury of paper by E. F. Kelley, "Application of Results of Research to the Structural Design of Concrete Pavements," p 464-13, Supplement September, 1939, Volume 35 *Journal*, American Concrete Institute

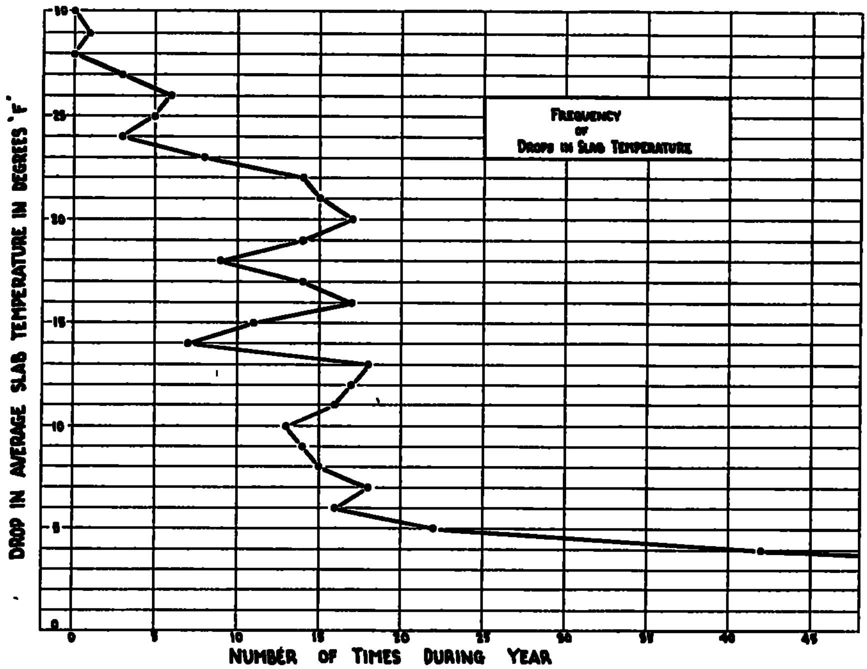

Figure 5

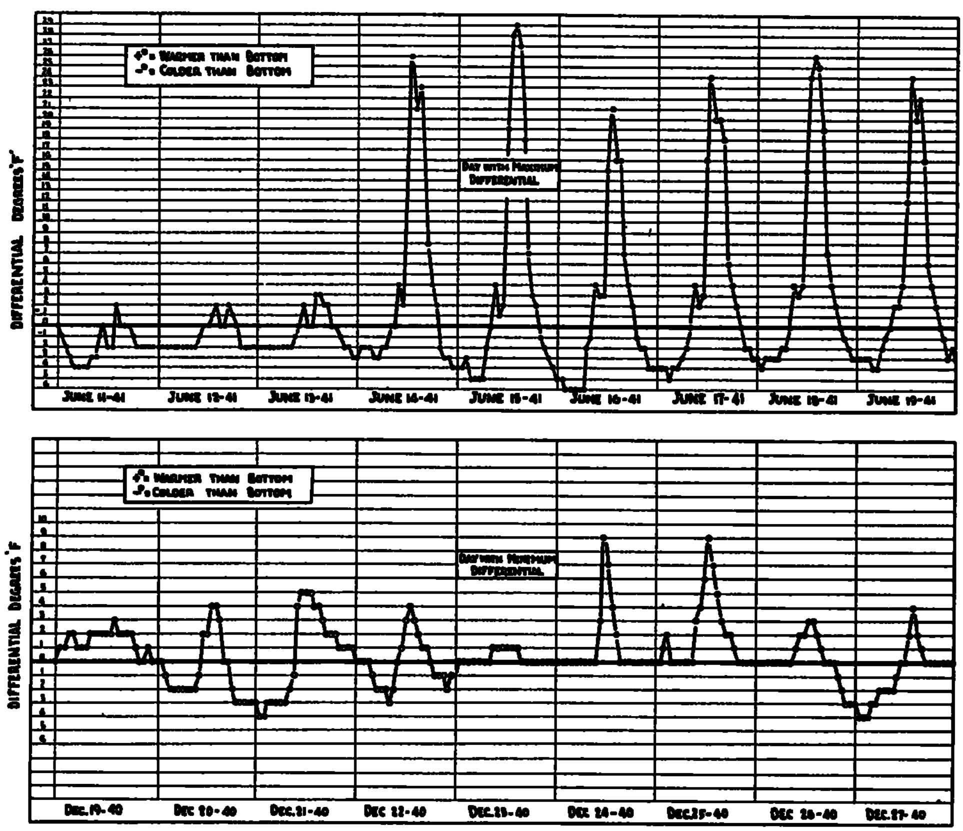

Figure 6. Typical Sections of Temperature Differential Between Top and Bottom of Slab

20° F. occurred 17 times. The maximum continuous drop in temperature was 29° F, and this only occurred once.

TEMPERATURE DIFFERENTIALS

As previously stated, temperatures were recorded for each thermocouple point every 6 min. As thermocouple points were located in the concrete at top and bottom of slab it provided a complete record for one year of the temperature differential between the top and bottom. Figure 6 shows the record for a few days in June 1941, when the maximum variation for any one day occurred and a few days in December 1940, when the minimum variation occurred. The difference in temperature is plotted as a plus ordinate when the top of the slab is warmer than the bottom and as a minus ordinate when the top is colder than the bottom As shown at 2.00 P.M. on June 15, 1941, the top of the slab was 29° F. warmer than the bottom but at 2 00 A M. the following night, the top of the slab was 6° F. colder than the bottom. The minimum differential for a 24-hour period was 1° F. and occurred on December 23, 1940

DURATION OF TEMPERATURE DIFFERENTIALS

The duration of the various temperature differentials between top and bottom of concrete slab in percentage of time of the 12-mo. period from November 1, 1940, to November 1, 1941, is shown in Figure 7. Such temperature differentials produce warping stresses which may be an important factor in the design of concrete pavements. Designers have usually assumed a temperature differential of three or four degrees fahrenheit per vertical inch. A 4-deg. differential per vertical inch for a 7-in. slab would produce a

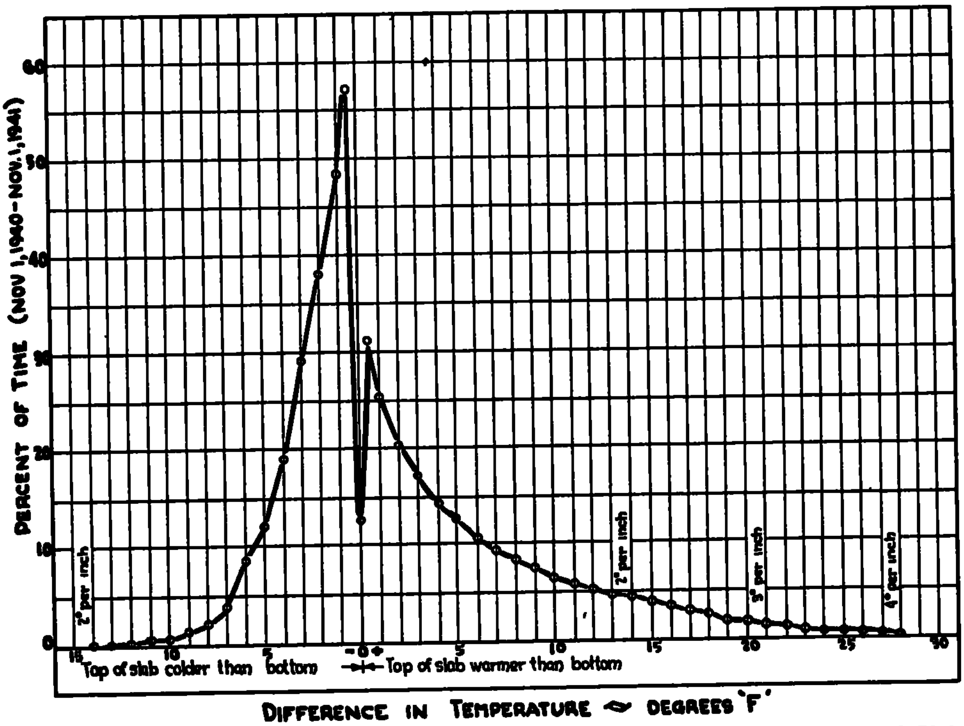

Figure 7. Duration of Temperature Differentials Between Top and Bottom of Slab

tensile warping stress of approximately 308 lb per sq in. for this slab, 16½ by 17 ft. The importance of this stress depends on the percentage of time during which it prevails and the number and magnitude of the wheel loads that the slab is subjected to during that period

It will be noted in this diagram that a warping stresses, Figure 7 shows that for 96 per cent (100−4) of the time the temperature differential between top and bottom of the slab is less than 2 deg. per vertical inch. This temperature differential would produce a tensile stress of approximately 154 lb. per sq. in. for the slab 7 in. by 16½ ft. by 17 ft.

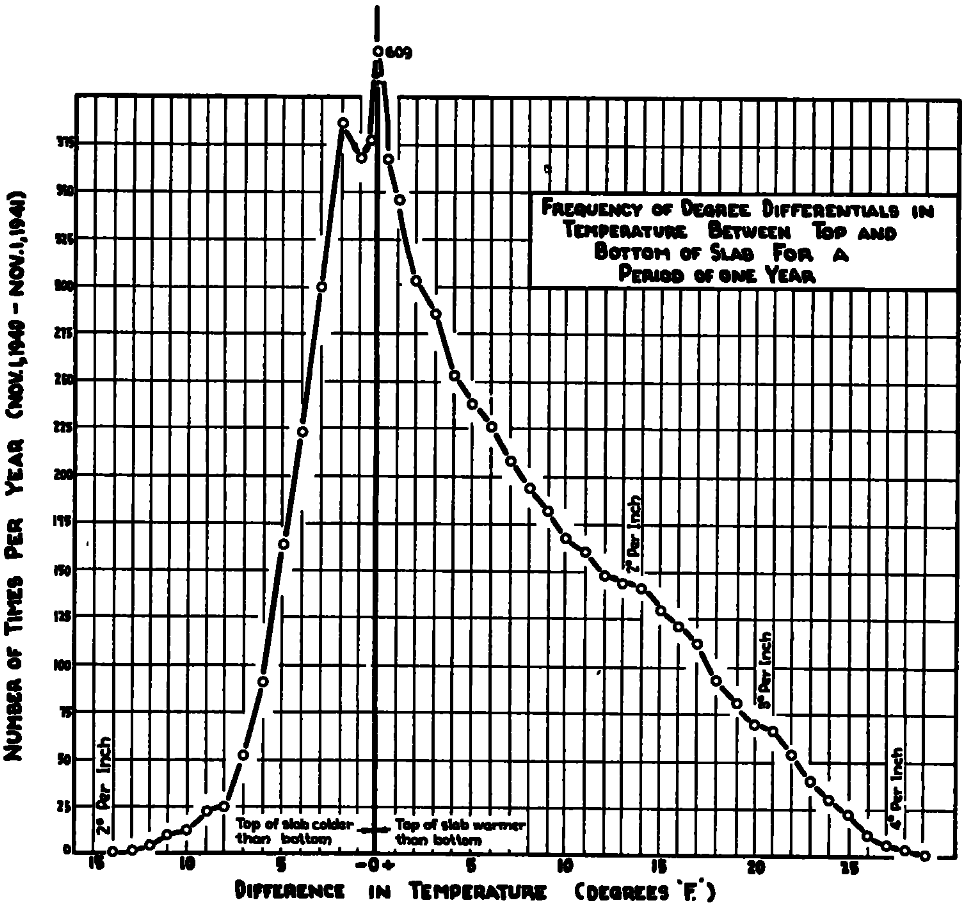

Figure 8

temperature difference between top and bottom of 4° F. per vertical inch occurred less than 1 per cent of the total time. There would not be many repetitions of heavy wheel load stresses in the slab at the time it is subjected to such a high warping stress.

As a further illustration of the effect of

FREQUENCY OF TEMPERATURE DIFFERENTIALS

The number of times during the year that the various temperature differentials between top and bottom of a 7-in slab occurred is shown in Figure 8 The 4-deg. per inch difference discussed previously occurred only three times and the 2-deg.

per inch difference occurred 140 times. As shown in Figure 8, there were 140 minus 65 or 75 times that the temperature differential was more than 2° F. and less than 3° F. per inch.

MONTHLY DISTRIBUTION OF TEMPERATURE DIFFERENTIALS

Figure 9 shows the percentage of total annual time (November 1, 1940, to November 1, 1941) that the indicated temperature differentials between the top and bottom of slab occur during each month. The upper diagram shows the differential when the top of the slab was warmer than the bottom and the lower diagram the differential when the top was colder than the bottom. As an illustration, it can be been in the upper diagram that the 17½-22½-deg. differential which occurred 1 85 per cent of the total annual time was distributed as follows:

From October 1st to March 1st—0 0
For each of the remaining months from 0 2 to 0 3 per cent of the time

A summation of the monthly ordinates shows that the slab was between 7½-12½° F colder at the top than at the bottom for about 50 per cent of the time and was never less than 2 6 per cent of the total time for any one month.

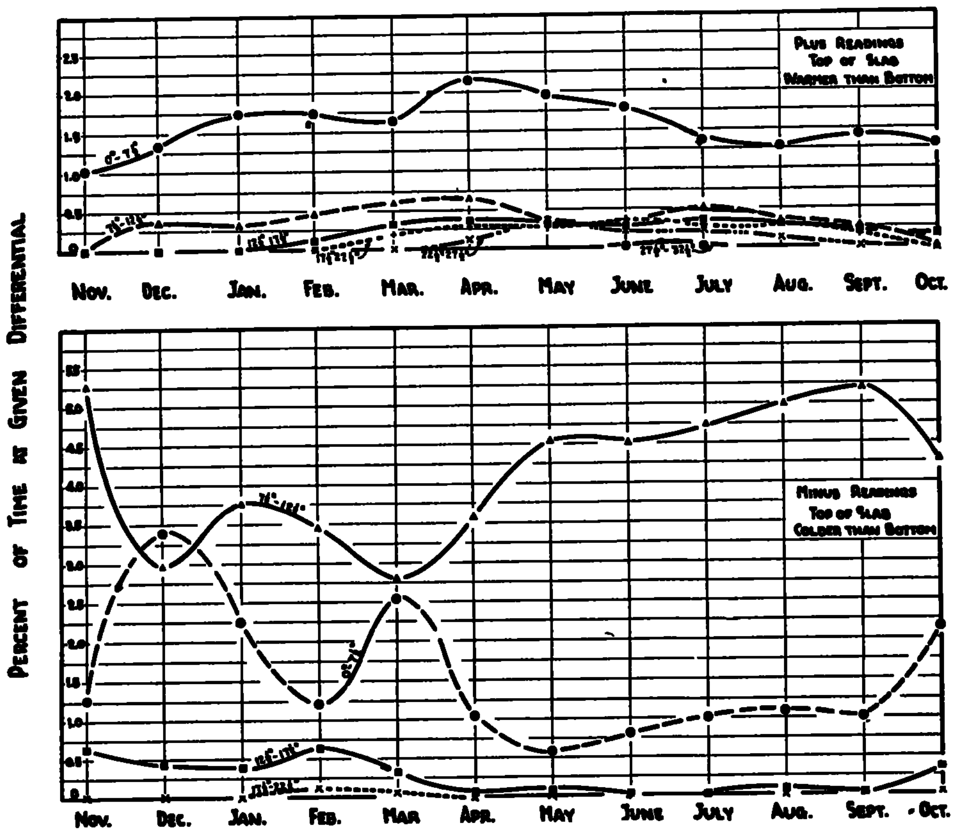

Figure 9

In traffic surveys data are obtained which show the character and volume of traffic for the different months, days of the week, and hours during the day.

The information shown on this diagram plus the hourly frequency shown on Fig-

ure 10 together with the traffic survey data would enable the designer to compute the magnitude and frequency of combined load and warping stresses.

HOURLY DISTRIBUTION OF TEMPERATURE DIFFERENTIALS

The hourly distribution just referred to is shown on Figure 10. As an illustration, it shows in the upper diagram that the temperature differential between top and bottom of slab of 12½-17½° F. or approximately 2° F. per vertical inch occurs a small percentage of the time and only between 10 A M and 5 P. M. reaching a peak between 1 and 2 P. M The percentage of time decreases for the higher differentials becoming less than two hours for the 27½-32½° F. differential As shown in the lower diagram when the top is colder than the bottom, the maximum differential is 12½-17½ deg. and this occurs less than 1 per cent of the total time and between 7 P. M. and 6 A. M. The warping stresses when the top of the slab is colder than the bottom appear to be unimportant.

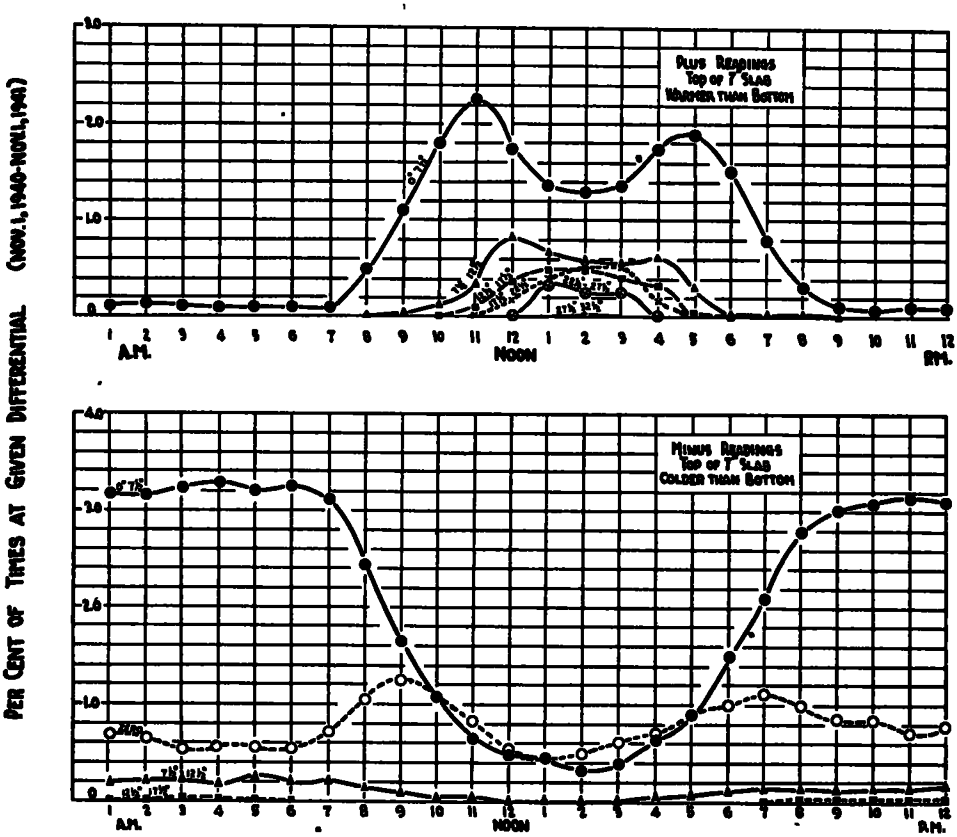

Figure 10. Frequency of Temperature Differential at Various Hours of Day

The data shown on this diagram provides one more reason for doing the heavy trucking at night or early morning.

TEMPERATURE GRADIENTS

The temperature gradient, from top to bottom of slab, has been assumed in most calculations as a straight line.

Figure 11 shows the difference in tem-

perature for various ranges between top of slab and the different vertical locations of the thermocouple points. Each of the curves shown represents an average taken from ten separate days at which time the given differential occurred In Figures 9 and 10 it was shown that major temperature differentials occurred during the summer and during the middle of the day. tance of warping stress, it appears that the small variations from the straight line relationship are not important.

NUMBER OF FREEZING AND THAWING CYCLES

Figure 12 shows the total number of freezing and thawing cycles which occurred during the 1940-41 winter at each

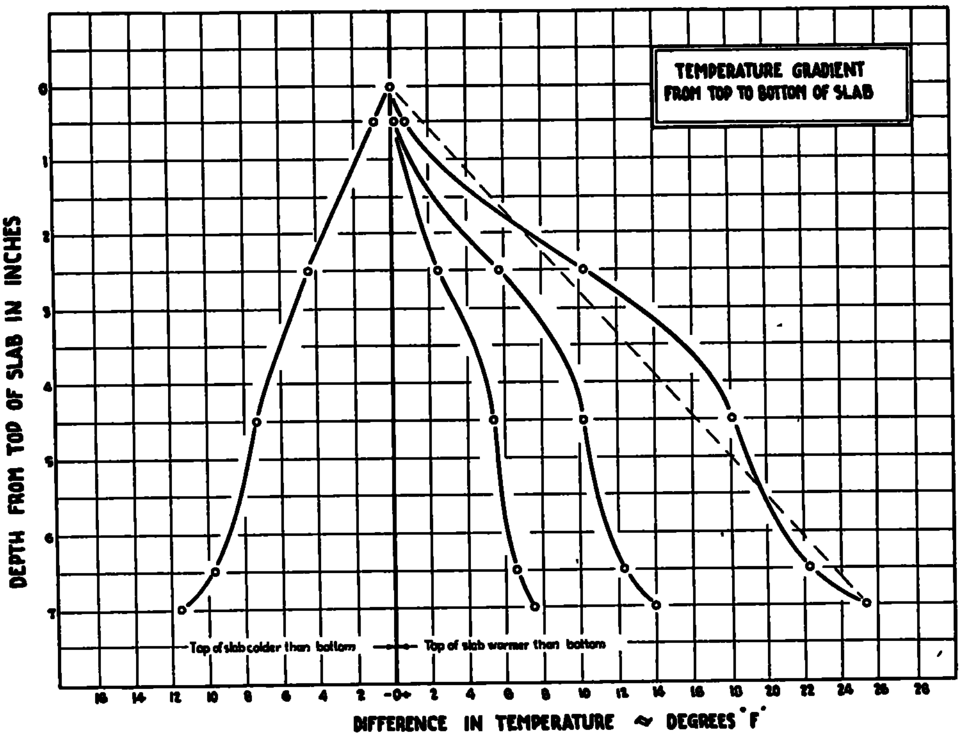

Figure 11

At that time the subgrade was colder than the top of the slab and as shown it affected the gradient.

The difference between a straight line relation from top to bottom of the slab for the maximum or a 25-deg differential and the temperature for both 2½ and 4½ in. below surface was less than 2° F At ½ and 6¼ in. depths there was a difference of about 1° F in the opposite direction. Taking into consideration the many variables encountered in design and the impor- of the thermocouple points. The location of each point and its numerical designation are tabulated in the figure No. 1 and No. 2 were placed at the surface and ½ in from the surface of the concrete. No 6 was placed at the bottom of the concrete No. 7, No 8, No. 9, No. 10 and No. 11 were placed at various depths in the subgrade, the last being 60 in. below the slab. The total number of annual cycles in the concrete varied between 43 for the upper half inch to 14 at the bottom of the slab

It is of interest to note that the maximum number of freezing and thawing cycles at any point in the subgrade was two, although the total frost penetration was more than 5 ft

In laboratory researches on the durability of concrete, different rates of frost penetration and thawing have been used It has not been possible, however, to calculate the life expectancy so far as durability is concerned for concrete when exposed to the elements as in a concrete pavement This involves the number of freezing and thawing cycles as well as the rate of freezing and of thawing. During the past winter the rate of frost penetration in the upper 2½ in. of this slab varied from less than 6 min. to 3¾ hr. with an average of 1 hr. and 55 min The rate of thawing varied from less than 6 min to 1 hr and 50 min., with an average of 55 min.

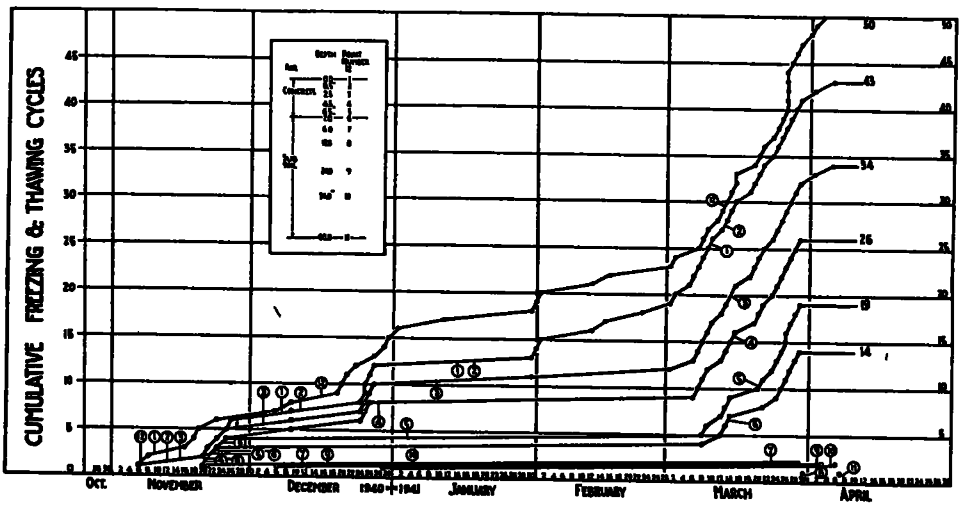

Figure 12

CUMULATIVE DEGREE-DAYS AND FROST PENETRATION

The upper curve in Figure 13 shows the cumulative degree-days (air temperature), above and below 32° F. between October 25, 1940, and April 10, 1941. The lower diagram shows the frost penetration into the subgrade for corresponding days. Any reversal in the direction of the upper line from the horizontal indicates a change from freezing to thawing, or from thawing to freezing The first drop in temperature occurred on November 11, 1940, and as shown on the lower diagram the frost penetrated into the concrete and the subgrade It is of interest to note that on November 22, 1940, January 3, 1941, and at other times when the temperature became milder the subgrade thawed from the bottom From January 30 to April 6, 1941, the subgrade was frozen below the lowest thermocouple, which was located 5 ft. below the slab.

MOISTURE VARIATION IN THE CONCRETE

The percentage of moisture in the slab was determined by means of Bouyoucos plaster of paris moisture blocks placed in the vertical center of the concrete slab The solid circles show the results obtained in the slab located in the driveway near the laboratory and the solid squares the results obtained about 200 miles distant in the Worthington test pavement. No readings could be taken during the winter months when the concrete was frozen.

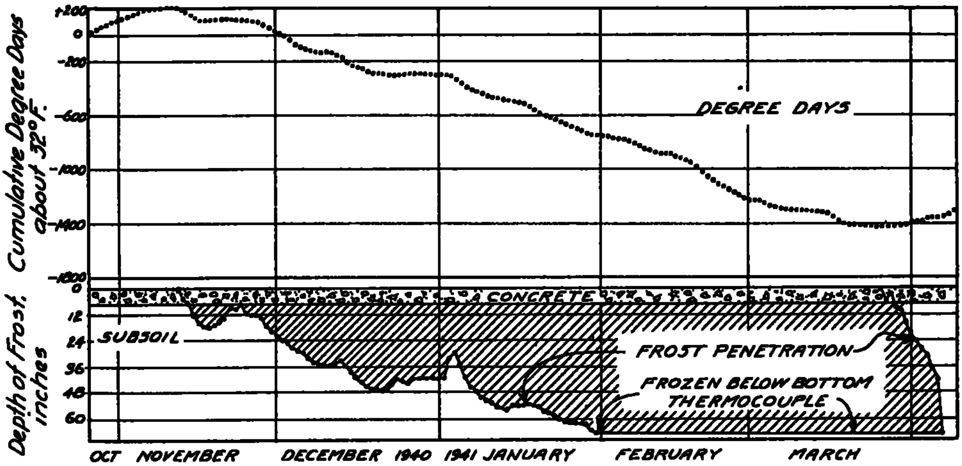

Figure 13

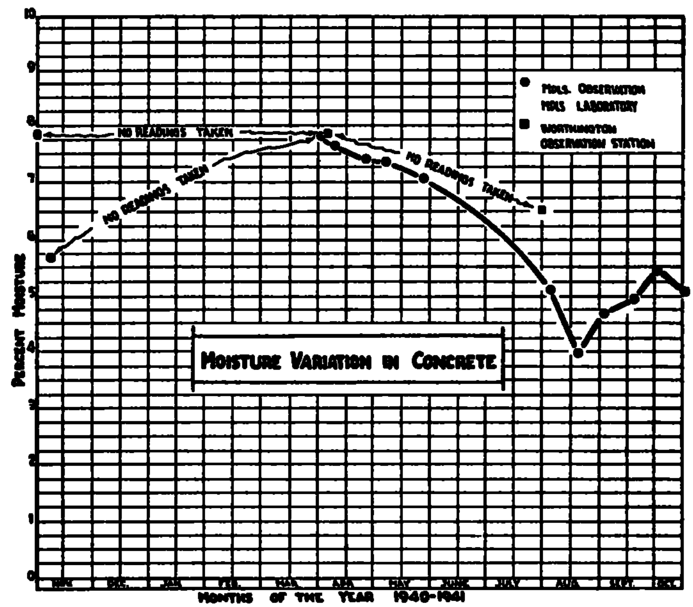

Figure 14

The greatest variation in the moisture content is slightly less than 4 per cent. The decrease in moisture which would cause tensile stresses in the concrete occurred during the season when the temperature of the concrete was increasing. The tensile stresses in the concrete caused by a decrease in moisture would therefore tend to decrease the compressive stresses resulting from increase in concrete temperature. Unfortunately, no data were obtained on variations in moisture content vertically which could be used in computing warping stresses.

The above data were obtained during the first year of a proposed five-year study and are presented at this time with the thought that they may be of value in the computation of stresses and durability of concrete resulting from temperature and moisture changes.