Harvard University, Vol. II, pp. 260-262, June, 1936.
64. Fuller, H. U., "Frost Penetration as Affected by Weather and Snow Conditions," Journal, New England Water Works Association, Vol. L, No. 3, pp. 299-301, September, 1936.
65. Ruedy, R., "Soil Temperatures in Canada," National Research Council of Canada," Ottawa, NRC 685, 11 pp., 1937.
66. Arndt, W. J., "Temperature Changes and Duration of High and Low Temperatures in a Concrete Pavement," Proceedings, Highway Research Board, Vol. XXIII; pp. 273-279, 1943.
67. Shannon, W. L., "Frost Investigations at Dow Field, Bangor, Maine," Proceedings, Highway Research Board, Vol. XXIV, pp. 71-86, 1944.
68. Cooling, L. F. and Ward, W. H., "Damage to Cold Stores Due to Frost Heaving," Journal, Institute of Refrigeration, Proc., pp. 41, 37-58, 1944-45.
69. Dill, Robinson and Robinson, "Measurements of Heat Losses from Slab Floors," Report BMS 103, Bldg., Materials and Structures, National Bureau of Standards, March, 1945.
70. White, R. G., "Installations for Noting the Water and Thermal Relationships in Soil," Agricultural Engineering, Vol. XXXVII, pp. 21-25, 1946.
71. Bouyoucos, G. J., "A New Electrical Resistance Thermometer for Soils," Soil Science, Vol. LXIII, No. 4, pp. 291, 298, April 1947, Highway Research Board, Abstracts, No. 141, p. 4.
72. Beskow, G., "Scandinavian Soil Frost Research of the Past Decade," Proceedings, 27th Annual Meeting, Highway Research Board, December, 1947.
73. Johnson, A. W., "Frost Action in Highway Subgrades and Bases," Parts 1 and 2, Engineering and Contract Record, Vol. LX, No. 11, pp. 66-68, 70-83, November, 1947. Vol. LXI, No. 4, pp. 74-76, April, 1948.
74. Coleman, J. D., "Soil Thermodynamics and Road Engineering," Nature, Vol. CLXIII, No. 4134, pp. 143-145, January, 1949.
75. Misener, A. D., "Temperature Gradients in the Canadian Shield," Can. Mining and Metallurgical Bulletin, Vol. XLII, No. 446, pp. 280-287, June, 1949.
76. Langbein, W. B., "Computing Soil Temperatures," Transactions, American Geophysical Union, Vol. XXX, No. 4, pp. 543-547, August, 1949.

SOME FIELD MEASUREMENTS OF SOIL TEMPERATURES IN INDIANA

E. J. Yoder, Research Engineer, and C. R. Lowrie, Jr., Research Assistant
Joint Highway Research Project, Purdue University

Synopsis

This report covers the results of field measurements of soil temperatures made under an asphaltic pavement. Temperature gauges which actuated automatic recording instruments were installed at various depths below the pavement.

The progression of heat waves through the soil, the depth of 32 F. (mean temperature), and the depth of minimum temperatures of 32 F. have been plotted against time. During the winter months measurements were made manually of depth of frost penetration, depth of snow cover, ground water fluctuations, and moisture content of the soils.

No definite conclusions have been drawn from the data other than verification of several important facts brought out by previous investigators. It is indicated, however, that more attention should be directed towards considering minimum daily temperatures in a study of this type. Since this type of research is of necessity a long range study, the accumulation of data over a period of years is desirable in order to better correlate the factors affecting soil temperature.

One of the problems remaining largely unanswered in soils engineering is that concerning the rate of heat transfer in natural soil strata and its effect on the soil structure. This is particularly true with regard to frost action and other problems associated with roads built in areas subjected to extended periods of freezing weather. The criteria governing the design of engineering structures are that they have sufficient strength to enable the structure to support the loads put upon it and are durable, i. e., able to withstand loads over a period of time.

It is necessary to design for the worst conditions likely to occur. In areas subjected to freezing temperatures frost action is one of the major factors to be considered. Much work has been done in the laboratory and the field on frost action and its effects on road stability. Laboratory studies by Winn (1) have shown the mechanics of frost action. Further studies in the field have indicated the unfavorable conditions conducive to severe spring breakup (2) (3).

The effects of frost cannot be fully understood until some knowledge is gained regarding heat transfer in natural soils and seasonal variations of soil temperatures. The agriculturalist has been interested for many years in soil temperatures, primarily from the standpoint of plant growth. Studies of this type have been reported by Radcliffe (4), Bouyoucos (5), and others. In recent years engineers have turned their interest to soil temperatures primarily from the standpoint of predicting depth of frost penetration.

It is obvious depth of frost penetration depends to a very large extent on type of cover. From this standpoint the data presented in this paper are incomplete in that only soil temperatures measured under a bituminous surface are presented. Also, a large portion of the data were obtained during the comparatively mild winter months of 1949-1950.

Factors Affecting Soil Temperature

Foremost among the factors affecting soil temperature is source and amount of heat given to the soil. The primary source of heat is the radiation of the sun; heat transferred to the soil by conduction is comparatively less. Latitude of the location has an important bearing on amount of heat absorbed per unit area of surface. Other factors, e. g., dust and water vapor in the atmosphere, also affect the quantities of heat absorbed by the soil.

The movement of heat into or out of a soil depends upon the difference in temperature between the surface and the atmosphere. Heat flows from a warmer object to cooler surroundings. For a given soil condition, soil temperatures depend upon daily and seasonal fluctuations in air temperature and upon the amount of radiant heat reaching the surface from the sun.

Freezing of soil in nature depends upon the duration of low air temperatures to a large extent. It is customary to measure time and temperature by degree-days. One degree-day below freezing represents one day with a mean temperature of 31 F. Casagrande (6) found a good correlation between an accumulative plot of degree-days, depth of frost penetration, and pavement heave due to frost. The Corps of Engineers has made use of degree-days in predicting the depth of frost penetration (7).

The effect of type of cover, both in regard to quantity and color, has been known for some time. Baver (8) brings out that frost penetration is deeper and its disappearance slower under bare ground than under grass cover, since grass acts as an insulating layer to the soil. Baver states that there is "ample evidence that soils in forests with a good surface litter freeze only to a rather shallow depth during the coldest winter."

Schubler and Wollny (8) studied the effect of soil color on temperature. These studies brought out that the temperature of soil under dark objects is higher than the natural soil while that under white objects is lower. Wollny also observed that dark soils are warmer during the warmer seasons and greater fluctuations in temperature occur under dark soils. He further states that the effect of color is less pronounced with depth.

The effect of snow cover has been known for many years, both from the standpoint of the farmer and engineer. Farmers are aware of the beneficial effect of snow cover on winter grains. All data show that unless the air temperatures falls very low, the depth of freezing in soils under a cover of snow is quite limited.

The engineer is concerned with the freezing of soils under and adjacent to highways. In 1944 and 1945 the Corps of Engineers made a very extensive frost investigation to determine means of predicting depth of frost penetration (7). Later a report was made covering a study of the transfer of heat through pavements (9). The later report stated that a correction factor should be applied to the degree-day values used in the prediction procedures - the magnitude of this correction was recommended as 0.75 for asphalt and 0.90 for portland-cement concrete.

Heat transferred from the air to the soil must pass through the pavement. This causes a time lag between changes in air temperature and the corresponding changes in pavement temperatures (as verified by the Army investigation and by data taken at Purdue.) Thus, the temperature of the surface cover must be considered in a study of soil temperatures.

The physical characteristics of the soil itself determine to a large extent its ability to conduct and to absorb heat. A study of the thermal conductivity of soils was made in 1909 by Patten (10). Further studies were made by the Corps of Engineers, both by the New England divisions (11) and by Kersten at the University of Minnesota (12). These studies indicated that the rate of heat transfer depends on soil density, moisture, and texture. Kersten found that the coefficient of thermal conductivity was greater for frozen soils than for unfrozen soils. He also found that at constant moisture contents increases in density resulted in increases in thermal conductivity; likewise, for constant density, increases in moisture result in increases in thermal conductivity.

The specific heat of a material is defined as the quantity of heat (calories) required to raise the temperature of one gram of the material one degree centigrade. The specific heat of water is 1.0, while that of ice is 0.5. In contrast, the specific heat of dry soil as determined by Long and also by Ulrich is approximately 0.25 (8). It can be seen therefore, that the heat capacity of soil is affected by the quantity of moisture in the soil.

Purpose of Soil Temperature Studies at Purdue

In May of 1938 a program was initiated at Purdue by the Joint Highway Research Project to make a study of frost action in soils to clarify some of the factors affecting frost damage to the highway system of Indiana. These initial studies were directed toward a laboratory study of the mechanics of frost action (1). Further, a great amount of work was done in connection with spring break-up (2). In order to better correlate the field and laboratory studies, soil temperature gauges were installed at the Joint Highway Research Project test-road. These data were first reported by Belcher in 1940.

It was the purpose of this study to accumulate seasonal data of soil temperatures in an attempt to find a correlation between these temperatures and rate and depth of frost penetration.

Concurrently with these studies, a laboratory investigation was made of the mechanics of soil freezing and the effect of freezing and near-freezing temperatures on soil strength. A study was also made on the effect of temperature on soil moisture and in turn the effect of soil moisture on stability.

<u>Description of Field Temperature Gauge Installations</u> - The soil temperature gauges were installed under a flexible pavement composed of 1-in. bituminous material on top of 6 in. of stabilized gravel. The subgrade was a silty clay of Wisconsin Drift age. A layer of sand-clay was encountered below a depth of 40 in. at this particular site. (The cross-section of the pavement is shown in Fig. 1). Figure 2 shows the grain-size distribution curves for the various soil layers.

The gauges were initially installed at the surface of the pavement, and at 3-1/2, 7, 12, 18, and 24 in. They were automatic recording three-pen instruments. These temperature gauges were actuated by pressure variations in capillary tubes produced by changing temperatures. The gauges were installed at the edge of the pavement, each gauge extended into the pavement and subgrade approximately 12 in.

In the fall of 1949 these gauges were taken up and new gauges installed in their place, except that they were placed at depths of 3-1/2, 7, 12, 18, 24, and 42 in., measured from the surface of the bituminous pavement. These gauges were similar to those previously used except they were two-pen type. Figure 3 shows the gauge lead-in cables installed in the ground.

Air temperatures, precipitation, and barometric pressures were measured concurrently with soil temperatures. All the gauges were automatic and recorded values continuously, making it necessary to change the chart on the instruments only once each week. These automatic gauges proved quite satisfactory.

During the winter months measurements were also made manually of depth of frost penetration, depth of snow cover, ground water fluctuations, and moisture content of soils as well as any other information that might be pertinent.

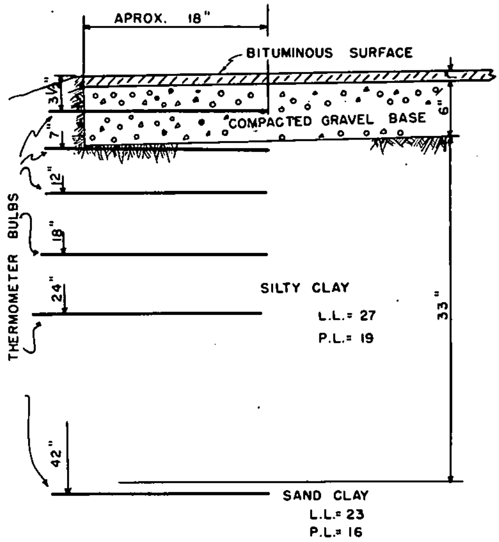

Figure 1. Cross Section Joint Highway Research Project Test Road Showing Depth of Thermometer Bulbs

Soil Temperature Measurements - As was previously mentioned, the soil temperature gauges were first installed in 1940. Up until the fall of 1949, the records concerning ground water fluctuations, moisture content, snow cover, and depth of frost penetration are incomplete. In addition some difficulty was encountered in the clock mechanism of the gauges. Therefore, the data for these years are incomplete, and for periods are entirely lacking. Nevertheless, the data shows some interesting facts.

Figure 4 shows the average results for the winter months of the 3-year period, 1943-1946. On this graph is plotted air and soil temperatures based on weekly mean values, and the accumulated degree-days below 32 F. It will be noted that although the air temperature fell well below 32 F. during the third week in December, the soil temperatures did not fall appreciably below 32 F. Also, the temperature immediately below the base course did not reach 32 F. until a week after temperatures of 32 F. were recorded at 3-1/2 in.

It can be further noticed that, in general, the temperature of the pavement was higher than that of the air. It is to be remembered that this pavement was of asphaltic type; being black in color it would tend to have somewhat higher temperatures than the

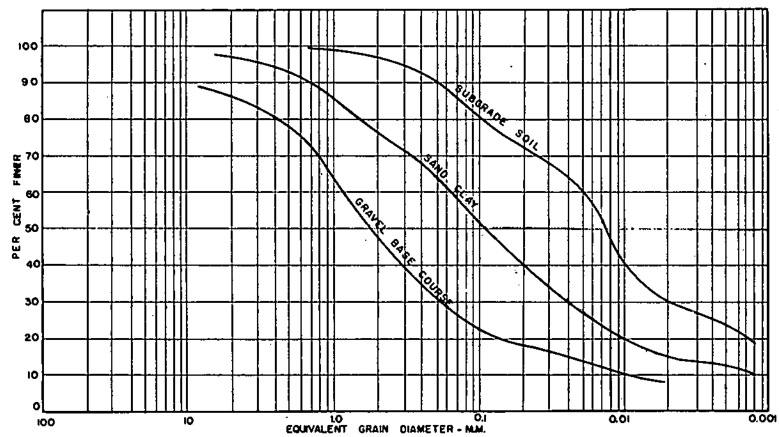

Figure 2. Grain Size Distribution Curves

Figure 3. Close-Up of Soil Temperature Gauge Lead-In Cable

air, due to absorption of heat from the sun's rays; in contrast, the average air temperature was somewhat higher than the pavement in the spring of the year. This demonstrates that in the interpretation of soil temperatures due consideration should be given to surface temperatures, since these are the temperatures affecting soil temperatures at greater depths.

The Corps of Engineers recommends a factor of 0. 75 be applied to degree-day values used in formulas for predicting depth of frost penetration beneath asphaltic pavements (8). For this particular 3-year average, the ratio of maximum degree-days, based on pavement temperature to that based on air temperature was approximately 0. 55.

The curves of Figure 4 illustrate how heat progressed through the soil. This is illustrated by noting that during the later days of December and the early part of January temperatures at 3-1/2 in. increased slightly, as did the air and surface temperatures. However, during this period the temperatures at 7, 12, 18, and 24 in. continued to decrease. The temperatures at 24 in. reached a minimum a short time after maximum degree-days were recorded.

Heat transfer is further illustrated in Figure 5. Here it can be seen that, for the 5-week period shown, a warm layer existed at 12 in. with a cooler layer at 18 in. ,then a warmer layer again at 24 in.

This is further illustrated in Figure 6. Here is shown penetration of 32 F. both daily mean and minimum plotted against time for the winter of 1945-1946. These curves indicate that the rate of decrease in soil temperature during the fall and winter is much slower than the rate of increase in the spring. For example, the temperature at the surface was 32 F. degrees (based on mean values) in the early part of December; then the soil temperatures were gradually lowered until a mean temperature of 32 F. was recorded at 18 in. depth in the later part of February. This time coincides approximately with the time maximum degree-days were recorded. However, the ground soon warmed up as air temperatures rose. That the ground thawed from the bottom as well as the top is illustrated by the slight break in the curve at 3-1/2 and 7 in. during the thawing period.

These curves also indicate the need for considering the daily minimum temperature, as well as the daily mean. It will be noted that a minimum temperature of 32 F. was recorded at 3-1/2 and 7 in. before a mean value of 32 F. was recorded and, also the minimum temperatures progressed deeper and left the soil later than the mean values. The portion of the curve on the right indicates that daily fluctuations in temperatures may cause the soil to freeze during parts of the day and to thaw again the same day. There is ample evidence showing that many times this is the case, i. e. , the soil may freeze at night and thaw during the day although the daily mean temperatures no longer dropped to 32 F. This daily temperature fluctuation also affects moisture conditions.

Figure 7 shows the data obtained during the winter of 1949-1950. These data show trends similar to those shown in Figure 4. The data obtained during this winter are unique in that Indiana experienced a mild, wet winter. Consequently, temperatures below 32 F. were recorded only for short periods of time, and the soil did not freeze to any appreciable depth. This was, however, fortunate in that some very interesting points regarding ground freezing were indicated.

The temperature gauge at 3-1/2 in. registered below-freezing temperatures for only short periods of time. In the early weeks of December, air temperatures fell below freezing. However, freezing temperatures penetrated the ground only to a depth of a little more than 7 in. Figure 8 shows penetration of 32 F. as well as depth of frost. It will be noted that, although freezing temperatures existed at depths of 3-1/2 and 7 in., the ground did not freeze until the middle of January.

During the freezing period in January freezing did occur, although some surface thawing occurred during each day. Of particular note is the unfrozen layer immediately above a frozen layer as shown.

That minimum temperature as well as mean temperatures should be considered in a study of this type is further indicated by the curves on the extreme right. During this period the mean temperatures did not reach 32 F. However, daily minimum temperatures went below 32 F. with the result that the ground alternately froze and thawed with daily temperature fluctuations.

To help correlate soil temperatures with depth of frost penetration, laboratory freezing and thawing tests were performed on both the base material and the subgrade.

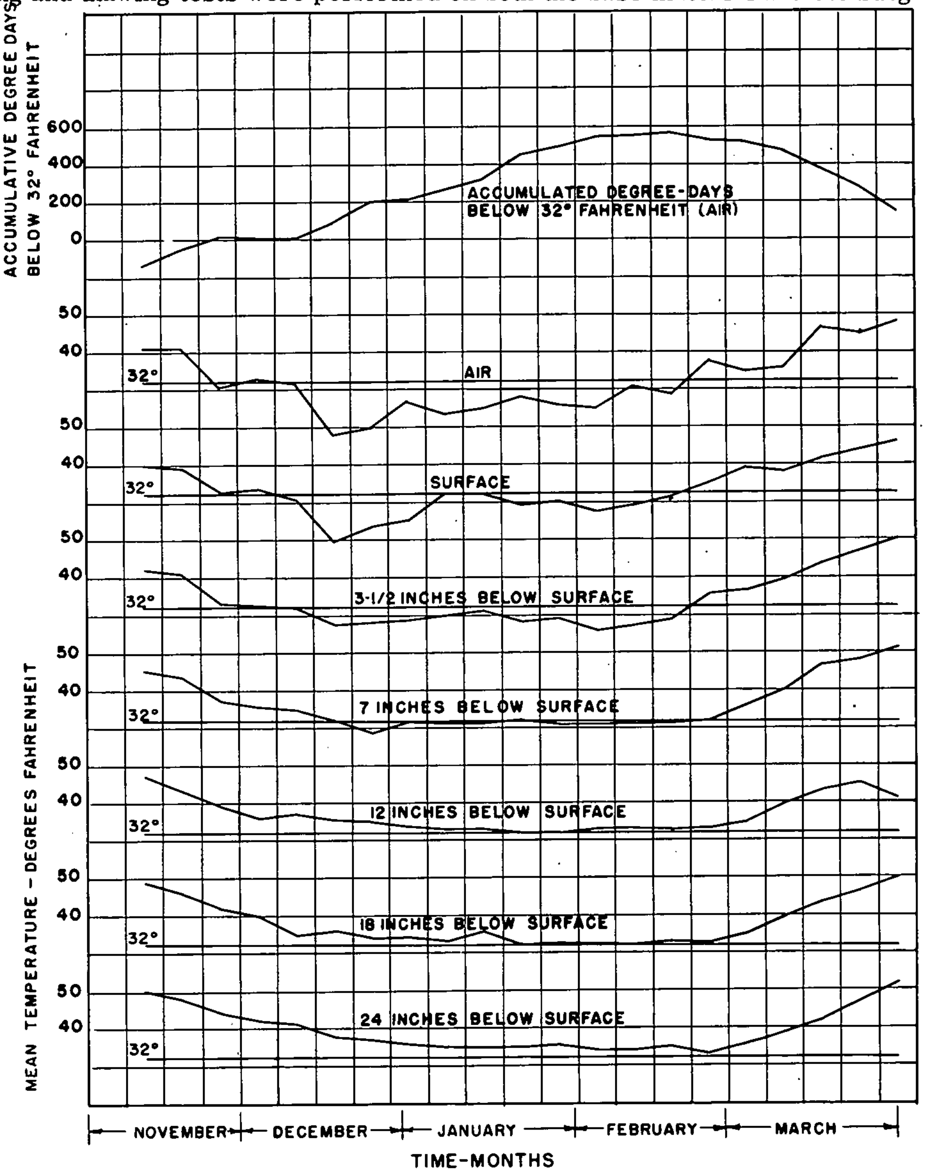

Figure 4. Three-Year Average Air and Soil Temperature - West Lafayette, Indiana 1943-46

TABLE 1

MOISTURE CONTENT IN PERCENT OF DRY WEIGHT

Date	Depth, inches											
	2	3	4	5	6	7	3½	7½	12	18	24	42
12-27-49							12.7	20.2	22.0	21.5	20.2	29.1
1-4-50							13.0	22.0	24.0			
1-9-50							12.4	19.8	25.0	24.6	27.2	26.3
1-10-50							11.3	14.4				
1-16-50	10.4*						7.7*	17.5*	17.1*	20.3*	18.2	23.1
1-16-50							10.9	22.1	22.1	20.2	20.0	23.8
1-17-50	9.2*						8.9*					
1-17-50	10.2						9.5					
1-19-50	17.1*	9.3*	7.8*	7.3*	6.9*	7.7*						
1-19-50	20.2	17.9	11.3	10.7	9.1	8.9						
1-23-50							11.3	21.0	24.0	25.0	23.1	25.0
1-30-50							15.6	21.5	21.9	21.1	19.5	21.1
2-16-50							12.5	23.2	23.0	23.0	22.2	25.3
2-27-50	12.3*	14.0*	14.1*	7.3*	6.7*	6.7*						
3-3-50	10.0	7.8	8.9	8.2	7.4	8.9						
4-10-50	7.9	8.1	7.4	7.4	7.6	7.9		20.0				
5-2-50							14.4	21.5	22.4	21.4	21.4	27.9
5-8-50							9.8	21.4	18.8	19.9	19.1	21.6
6-12-50							6.8	12.2	14.0	18.2	16.2	18.9

* Moisture contents taken at the center line of the pavement. All other determinations were made at the edge.

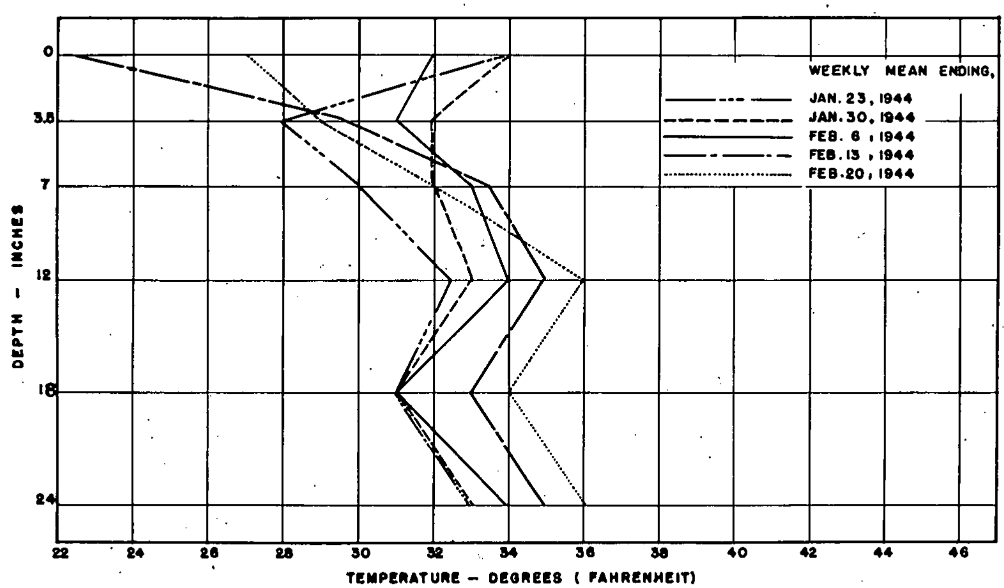

Figure 5. Variation of Soil Temperature with Depth

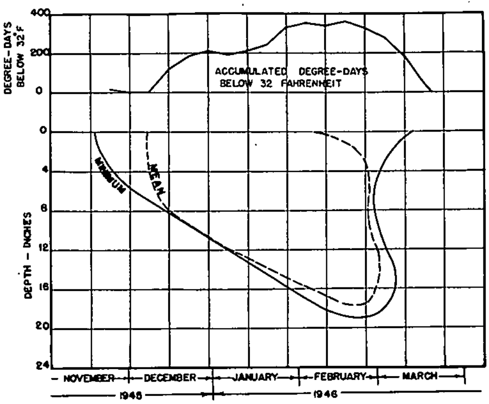

Figure 6. Penetration of 32 F.

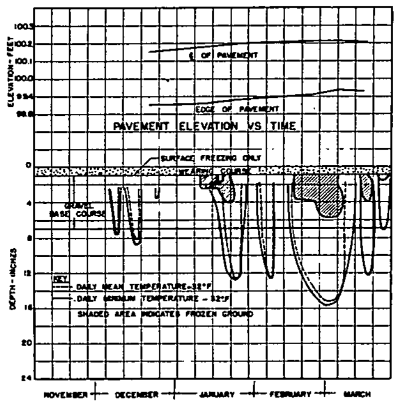

Figure 8. Penetration of 32 F., Depth of Frost Penetration, and Pavement Elevation Winter 1949-1950

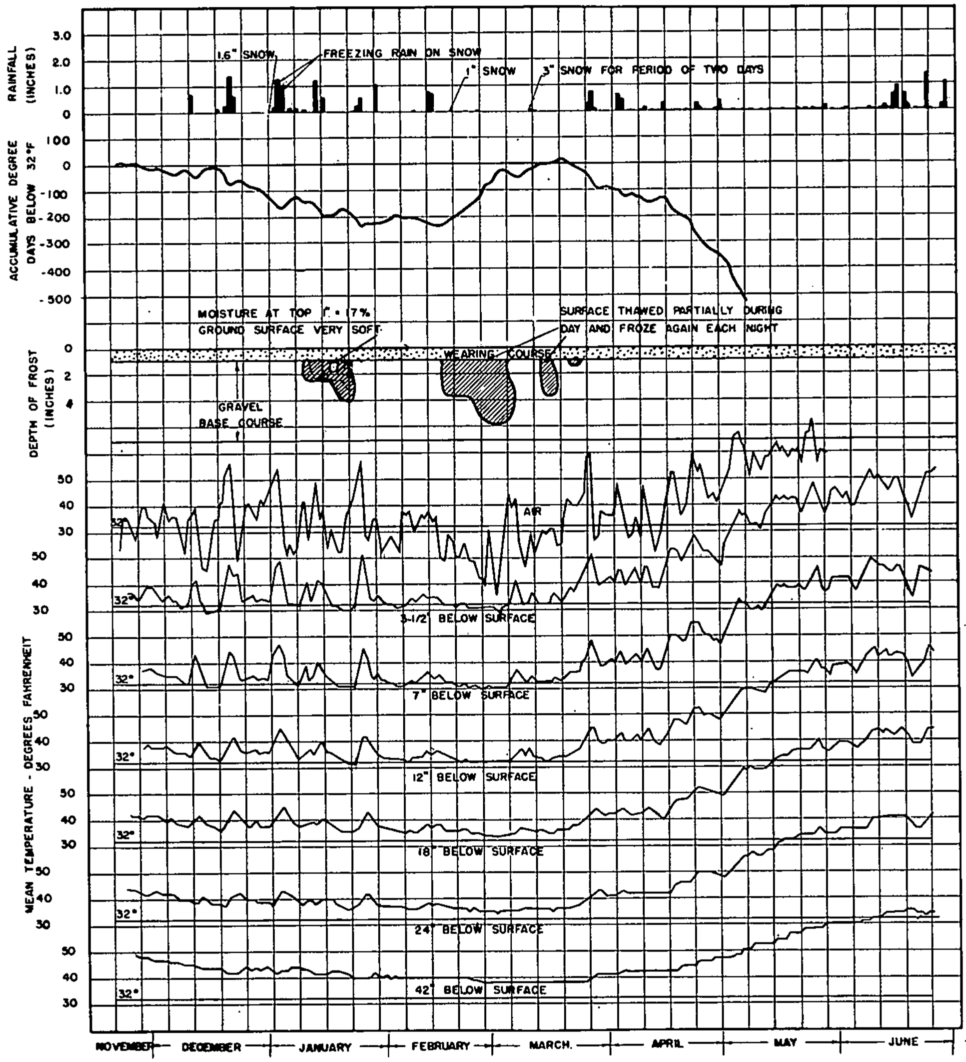

Figure 7. Air and Soil Temperatures for West Lafayette, Indiana, November 1949-July 1950

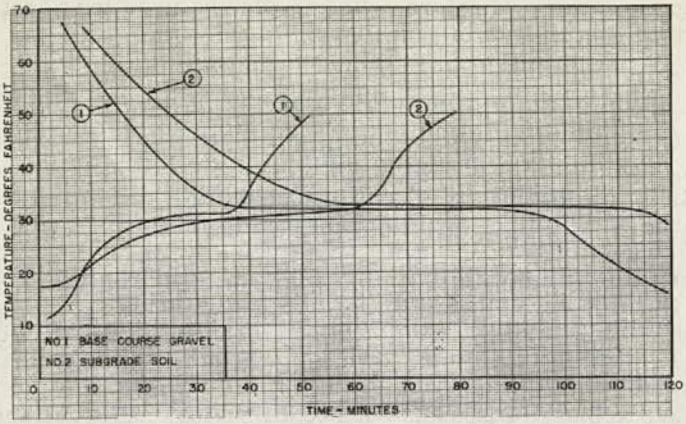

Figure 9. Temperature vs. Time

In these tests undisturbed samples were brought into the laboratory and frozen, their temperature being reduced to -18 F. The samples were then allowed to thaw slowly at room temperature. The temperatures of the soils were measured periodically throughout the thawing period. The samples were again moistened and refrozen, temperature measurements being made during the freezing period (see Fig. 9). The flat portions of the curves represent the latent heats of fusion for the soil-water mixtures during the freezing and thawing. The freezing range for the base course material was indicated to be between 30 and 31 F., while that of the subgrade was 31 F.

Bouyoucos (14), in a series of laboratory experiments to determine the freezing point of soils, found the degree of super-cooling required for freezing of soils was approximately 6 degrees. He also found that unless the soils were vigorously stirred they remained almost indefinitely at 32 F. without freezing. The actual freezing point of soils depends on several factors, including the amount of soluble salts in the water and degree of disturbance. It appears that in the interpretation of soil temperatures from the standpoint of the highway engineer, these factors should be considered.

Mean temperatures of 32 F. were registered at 3-1/2 in., although minimum temperatures registered at 3-1/2 in. during the early periods of December were only 31 F. (Fig. 8). No frost(other than surface freezing)was noticed during this period. Conversely, during the freezing period in January minimum temperature recorded at 3-1/2 in. was 29 F., and frozen ground to a depth of 3-1/2 in. was noted. The same applies throughout the winter; unless minimum temperatures reached at least 29 F. for a period of time no freezing was noted.

Throughout most of the winter the moisture content of the base material immediately under the pavement was extremely high (Table 1). This was true even though no ice crystal segregation was noticed.

These high-moisture contents were probably due, in part, to condensation and movement of moisture in the form of vapor. This was indicated in several instances, upon removal of the surface material from the road. It was noticed that a very thin layer of frost existed on the under side of the pavement material, much as frost accumulates on refrigerator coils from condensation. This phenomenon warrants further study in regard to softening of the material immediately under a pavement due to high moisture content.

Future Studies

The soil-temperature program of the Joint Highway Research Project will be expanded in future years. It is hoped that several thermocouples may be installed under several other pavements for periodic checks. These pavements will be of various types, including concrete, bituminous concrete, and gravel surfaces. Gauges will also be installed under grass cover. Moisture cells will also be installed to determine fluctuations in moisture content with temperature.

Bibliography

1. Winn, H. F., "Frost Action in Stabilized Soil Mixtures," Proceedings, Highway Research Board, Vol. 18, Part I, 1938.

2. Woods, K. B. and Shelburne, T. E., "Report No. 1 on 1943 Survey Secondary Roads (Spring Break-Up)," Joint Highway Research Project, April 1943. (Unpublished)

3. Shelburne, T. E. and Waner, A. W., "Analysis of Spring Break-Up Data in Virginia," Bulletin No. 20, Highway Research Board, September, 1949.

4. Radcliffe Observatory, "Radcliffe Observations," London, England, 1915.

5. Bouyoucos, G. J., "An Investigation of Soil Temperatures and Some of the Factors Influencing It," Michigan Agricultural College Experiment Station, Technical Bulletin No. 17, February, 1913.

6. Casagrande, Arthur, "Discussion of Frost Heaving," Proceedings, Highway Research Board, Vol. II, 1931.

7. "Report on Frost Investigation 1944-1945," War Department, Corps of Engineers, New England Division, Boston, Massachusetts, April, 1947.

8. Baver, L. D., Soil Physics, Chapt. VIII, "Soil Temperatures," John Wiley and Sons, 1940.

9. "Frost Investigations 1949-1950, Report of Pavement Surface Temperature Transfer Study," War Department, Corps of Engineers, New England Division, Boston, Massachusetts, June 1950.

10. Patten, H. E., "Heat Transference in Soils," US Department of Agriculture, Bureau of Soils, Bulletin No. 59; 1909.

11. "Frost Investigation 1944-1945, Report on Laboratory Tests on Frost Penetration and Thermal Conductivity of Cohesionless Soils," War Department, Corps of Engineers, New England Division, Boston, Massachusetts, 1945.

12. Kersten, M. S., "The Thermal Conductivity of Soils," Proceedings, Highway Research Board, Vol. 28, pp. 391-409, 1948.

13. Belcher, D. J., "Subgrade Soil Temperatures," Proceedings, Purdue Conference on Soil Mechanics and Its Applications, 1940.

14. Bouyoucos, G. J., "Degree of Temperature to Which Soils Can Be Cooled Without Freezing," Journal Agriculture Research, Vol. 20, 1920-21.

15. Bouyoucos, G. J., "Soil Temperature," Michigan Agricultural College, Experiment Station, Technical Bulletin No. 26, January, 1916.

16. Callendar, W. H. and McLeod, C. H., "Observations of Soil Temperatures with Electrical Resistance Thermometers," Transactions, Royal Society of Canada, Vol. 2, Section 3, pp. 109-126, 1896.

17. Highland, S. G., "Study of Year-Round Soil Temperatures," Journal American Waterworks Association, Vol. 16, No. 13, pp. 342-354, September, 1926.

18. Legget, R. F. and Peckover, F. L., "Soil Temperature Studies - A Progress Report," paper presented at 29th Annual Meeting, Highway Research Board, December, 1949.

19. Sourwine, J. A., "A Method of Analysis of Data on Frost Occurrence for Use in Highway Design," Public Roads, Vol. 11, No. 3, 1930.