

Study of Subsurface Temperature in Six Soils During the Winter of 1953 - 1954

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During the winter of 1953-54 subsurface temperature measurements were performed on six New Jersey soils. The studies revealed that:

1. Granular, non-plastic soils are better conductors of heat (and cold) than fine-grained soils and react to air temperature changes more quickly. Of the six soils studied, a clean sand (MRB A-3), was the best conductor and an MRB A-7-6 soil was the poorest conductor. Therefore, frost enters and goes out of granular soils more rapidly than in the case of fine-grained soils, causing more frequent freeze and complete thaw cycles.

2. A concrete slab is a better conductor of heat than soil of the same thickness. Therefore, freezing and complete thaw cycles occur more often below a concrete slab or pavement than in the adjacent shoulder.

3. A combination of a concrete slab over a granular soil is one that reacts most quickly to cold and warm spells. A shoulder of fine-grained soil shows little reaction to cold and warm spells (except at the surface) and reflects the over-all intensity of cold of the winter.

4. The freezing line generally penetrates to a greater depth in granular soils than in fine-grained soils.

5. There is a lag between the minimum air temperature of winter and the maximum penetration of the 32 degree line. In the cases studied the lag was one day, except for some of the shoulders of fine-grained soils, where the lag was several days.

6. Maximum heaving does not necessarily occur at the time of the maximum depth of the 32 degree line.

7. Most thawing in soil occurs from the top downward during thaw periods; however, some thawing takes place from the bottom.

8. Temperature studies indicate the necessity of measuring and knowing the surface temperature of the slab or ground surface.

● DURING the winter of 1953-54 subsurface temperature measurements were performed on six New Jersey Soils which were also being used for the purpose of frost heave and bearing-power loss studies. These soils had been compacted in 9 ft square pits and were topped by 4 ft square by 6 in. thick concrete slabs. Soil temperatures were measured at two inch intervals of depth under the centers of the slabs and in the adjoining shoulders.

INSTRUMENTATION

Thermistors

In order to measure subsurface soil temperatures some type of remote reading device was desirable. Type 17-A thermistors, obtained from the Western Electric Co., were selected. This type of thermistor is composed of an alloy of nickel oxide and manganese oxide. The material has a high negative temperature coefficient of electrical resistance. For example, as the temperature of a 17-A thermistor drops from 35 F to 25 F its electrical resistance increases from 3, 150 to 4, 250 ohms.

A 17-A Thermistor consists of a 3/16 in. diameter by a 1/32 in. thick disc having short wire leads soldered to each face. These leads were soldered to 20-strand plastic-covered wire used to conduct the thermistor circuits to the soil surface. The ther-

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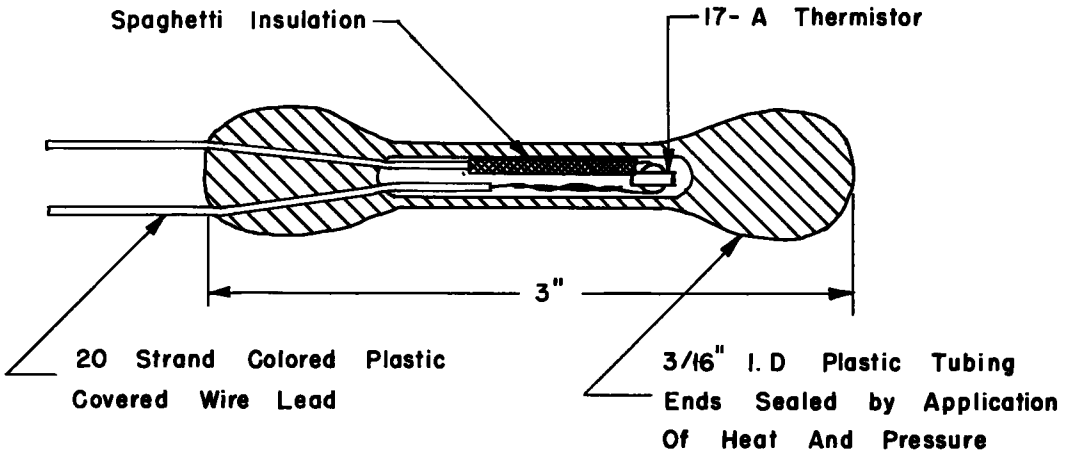


Figure 1. Section through a sealed thermistor unit.

mistors and underground connections were sealed within short lengths of plastic tubing (Figure 1). The thermistors were arranged in groups, spaced at proper intervals, and the wires cabled together.

Calibration

Figure 2 shows the standard temperature-resistance curve for 17-A thermistors. Manufacturing control of the thermistor material is such that all thermistors will have characteristics within ± 10 percent of the standard curve.

The thermistors were immersed, one group at a time, in an insulated tank of cir-

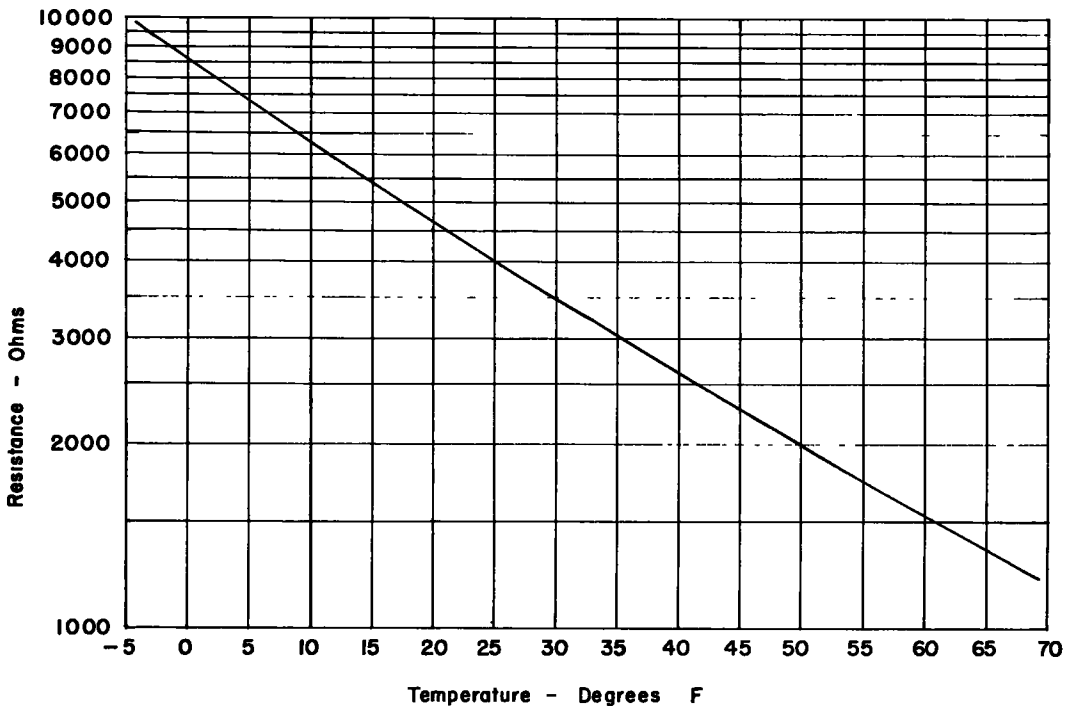


Figure 2. Standard temperature-resistance curve for 17-A thermistor.

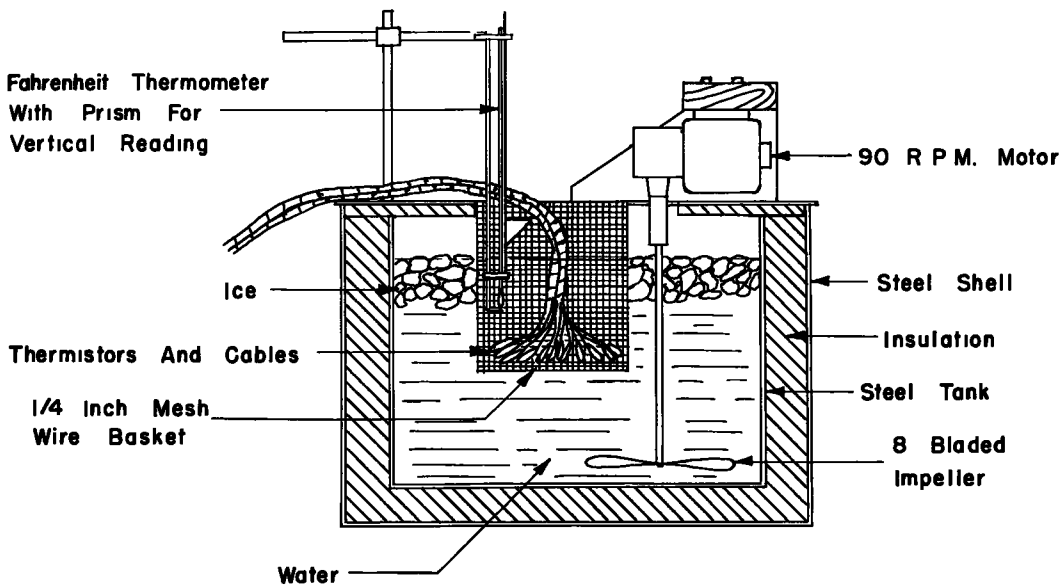


Figure 3. Thermistor calibration tank.

culating ice water at a temperature of 32 F (Figure 3). The resistance of each thermistor was then measured with a Wheatstone Bridge. A coefficient was determined for each thermistor by dividing the standard resistance at 32 F by the measured resistance.

Field Installation

The thermistor groups were installed at proper depths in 8 in. diameter auger holes at the center of the slab location and in the shoulder of each of the selected soils. The concrete slabs were then poured. A section of a completed installation is shown in Figure 4.

From the junction box at each installation underground multi-wire cables carried the thermistor circuits to an instrument shack. The cable resistance was measured and found to be negligible. Rotary selector switches, mounted conveniently on an instrument panel, were used to connect each thermistor individually to a Wheatstone

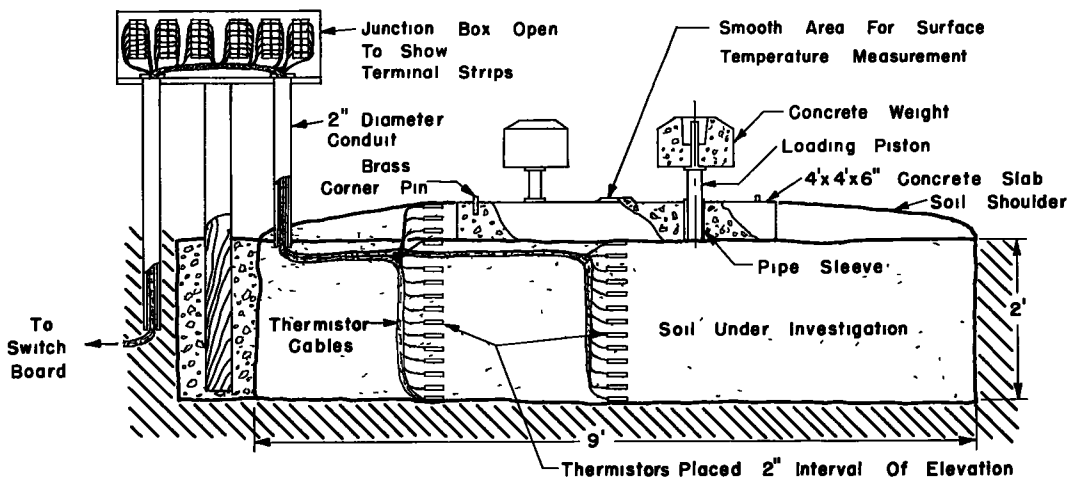


Figure 4. Field Installation.

Subsurface Temperatures

Soil No F-10

Date 2/13/54

Time 3:27 A.M.

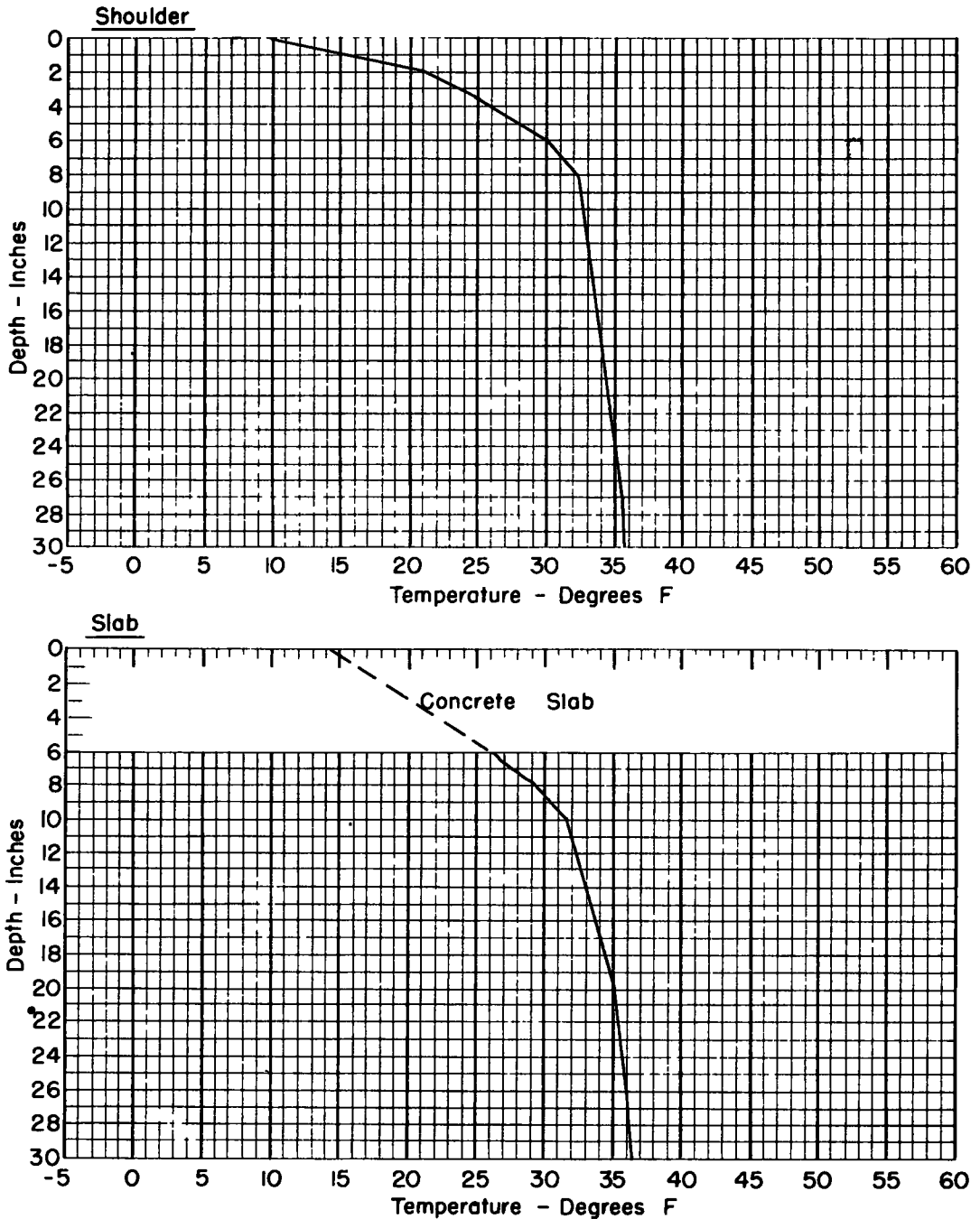


Figure 5. Subsurface temperature curves.

Bridge. When measuring thermistor resistance an optical galvanometer was used with the Wheatstone Bridge for ease in balancing.

Temperature Determination

From the standard temperature-resistance curve a table was prepared showing resistance ranges in ohms for each tenth of a deg F increment. The measured thermistor resistances were recorded on prepared data sheets. Standard resistances were determined by multiplying each measured resistance by the respective thermistor coefficient. Each thermistor temperature was then obtained from the table.

Slab surface temperatures were measured with a mercury thermometer. The thermometer was inserted in a small metal can filled with mercury and insulated against air temperature on the sides and top. The assembly was placed on prepared smooth areas at the center of each slab and left until the mercury attained the same temperature as the slab surface.

Temperatures of each soil were plotted as shown in Figure 5.

Air temperature measurements were made at a central location. Maximum-minimum thermometers were mounted on a post at elevations of 1 ft and 6 ft above the soil surface. The existing air temperatures were recorded at the time thermistor readings were made. Daily maximum and minimum temperatures were also recorded. A recording thermograph was mounted on the post at a 3 ft elevation. This instrument produced a continuous air temperature record.

SUBSURFACE TEMPERATURE STUDIES

General Notes

This study is based on subsurface thermistor readings in six soil installations in which readings were taken daily during the winter between December 31, 1953 and February 26, 1954, and between March 1 and March 9, 1954. Readings were taken four or more times a day during the periods January 12 to 14 and January 22 to February 17, 1954.

The six soils studied vary in type, ranging from a gravelly sand to a silty clay. The six soils with the Highway Research Board Classification and Atterberg limits for each are listed in Table 1.

TABLE 1

Soil Installation	HRB Classification	Liquid Limit	Plasticity Index	Fall 1953
				Dry Density Lbs. Per Cu.Ft.
F-10	A-1-b	Non-Liquid	Non-Plastic	116
F-17	A-3	Non-Liquid	Non-Plastic	105
F-5	A-5	41	7	94
F-13	A-2-4	32	9	106
F-15	A-7-6	41	15	80
F-24	A-4	31	9	98

Figure 6 shows the grain size distribution curves for these six soils.

Graphs were plotted during periods of frequent thermistor readings of:

1. Temperature at 2 in. intervals of depth against time (temperature oscillation graphs), and
2. Isotherms against time, in which air and subsurface isotherms for 4 F intervals were plotted.

TOPICS COVERED IN STUDY

1. Time of minimum air temperature, maximum penetration of 32 deg line, and maximum slab heave.
2. Freeze and complete thaw periods between December 31, 1953 and February 17, 1954.
3. Trend of 32 deg line during cold spells.
4. Observations from temperature oscillation graphs.

Time of Minimum Air Temperature, Maximum Penetration of 32 deg Line and Maximum Slab Heave

Notes: All depths in this report are referred to slab or shoulder surfaces.

Maximum heave in this report is defined as the maximum elevation to which a slab heaved about an original elevation which was assumed to be at zero at the start of the winter.

The minimum air temperatures of the winter were recorded four days apart, on January 14 and January 18. The minimum air temperatures at the 1 ft elevations were -5.5 deg and -11.0 F on January 14, and -6.0 F and -10.4 F on January 18.

The maximum penetrations of the 32 deg line and the date on which they occurred for each installation are listed in Table 2. There is also listed the heave of each slab at that time.

In all cases except the shoulders of F-13, F-15 and F-24, there was a one-day lag between the time of the low air temperature of January 18 and the time of the maximum depth of the 32 deg line. The date of the maximum depth of the 32 deg line for the shoulders mentioned (F-13, F-15, F-24), it was noted, was much later, which indicates a slower reaction to air temperature.

There was a snow cover of a few inches on the shoulders on January 19 and 20 remaining from the snow storm of January 11. The snow had been removed from the slabs so as to simulate highway conditions. It was difficult to evaluate the insulating effect of the snow cover because the maximum depth of the 32 deg line occurred at this time (January 19, 20) in three of the shoulders (F-10, F-17, F-5) and at a later time in the other shoulders (F-13, F-24, F-15). The snow cover probably was not deep enough to act as an effective insulator at this time.

The maximum heaves recorded for the slabs during the winter and the dates at which they occurred are listed in Table 3. The depth of the 32 deg line at these dates is also listed. Graphs showing slab movement throughout the winter are shown in Figure 7.

It was noted there was an interval of many days (6 to 14 days) between the date of

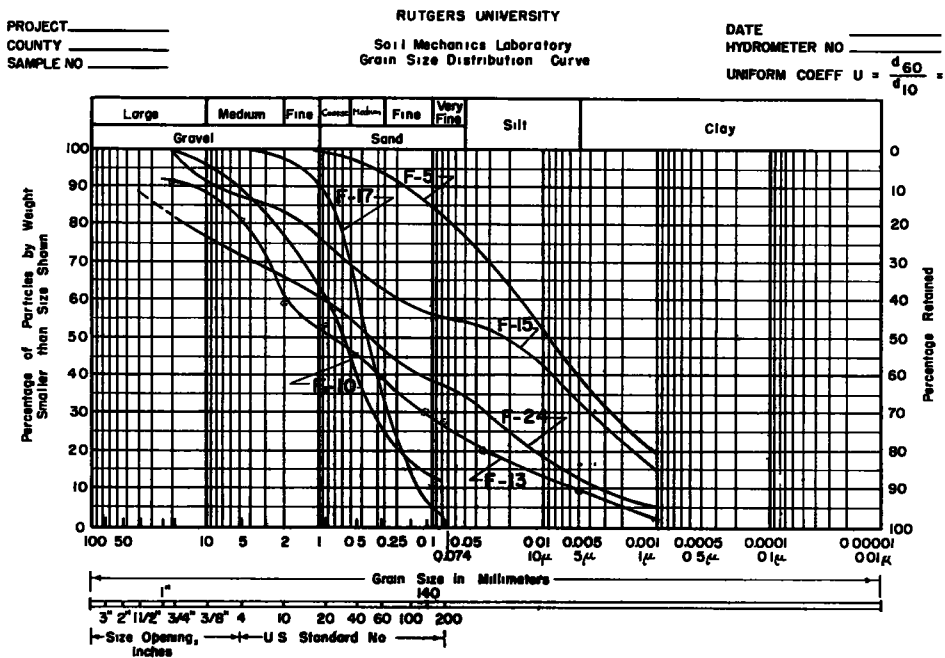


Figure 6. Grain size distribution curves of soils used for subsurface temperature measurements.

TABLE 2

Installation	Max. Depth of 32 deg Line	Date	Slab Heave
F-10 Slab	17.8 in.	Jan. 19	0.013 ft
F-10 Shoulder	15.8 in.	Jan. 19	
F-17 Slab	16.8 in.	Jan. 19	
F-17 Shoulder	10.0 in.	Jan. 19	0.012 ft
F-5 Slab	15.5 in.	Jan. 19	0.023 ft
F-5 Shoulder	12.1 in.	Jan. 19, 20	
F-13 Slab	14.5 in.	Jan. 19	0.020 ft
F-13 Shoulder	11.0 in.	Feb. 2	
F-15 Slab	13.8 in.	Jan. 19	0.036 ft
F-15 Shoulder	13.5 in.	Jan. 24	
F-24 Slab	12.0 in.	Jan. 19	0.064 ft
F-24 Shoulder	9.5 in.	Feb. 1, Feb. 14	

maximum penetration of the 32 deg line and the date of maximum heaving. Also, the depth of the 32 deg line at the time of maximum heaving was less than the maximum had been.

Increased moisture content in the soil installations is believed to be the reason that maximum heaving occurred at a later time than when the depth of the 32 deg line was a maximum. Examination of the weather records indicates that this is probably true because prior to January 19 (the date of maximum depth of the 32 deg line) little moisture could have entered the ground as a result of precipitation. Very little precipitation

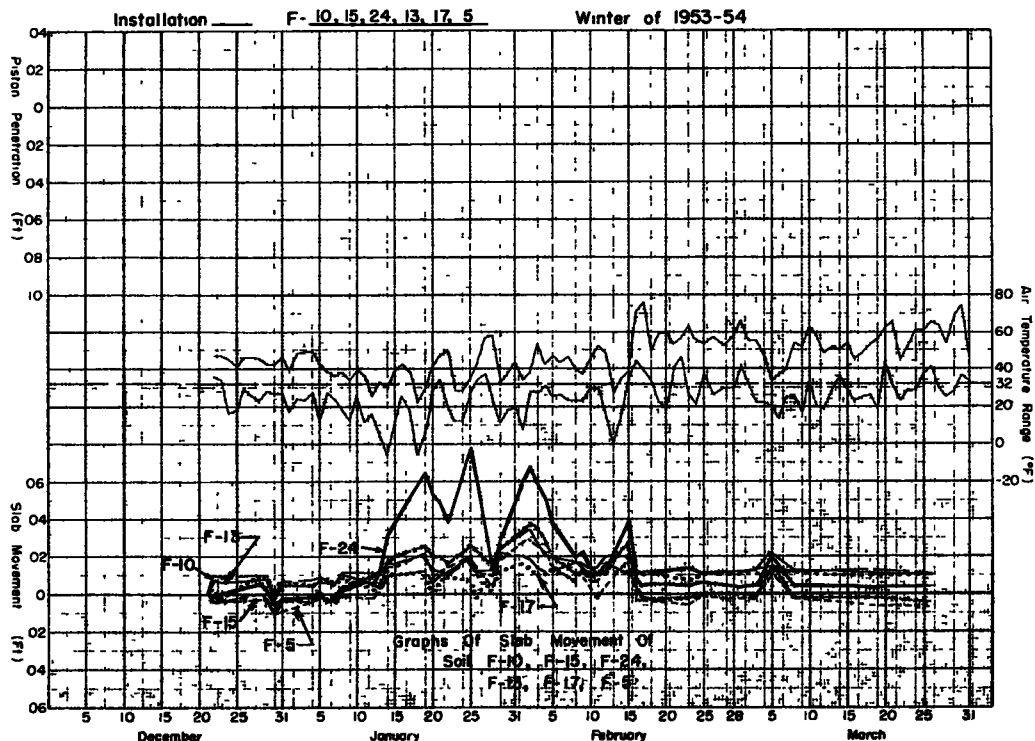


Figure 7.

occurred prior to January 19 except the snow storm of January 11, and that remained largely unmelted. After January 19 (between January 20 and January 22) the snow melted and thus increased the moisture content of the soil installations. Because moisture is essential for the growth of ice lenses which cause heaving, it seems reasonable to assume that an increase in moisture content would result in an increase in heaving.

The maximum heave of F-24 Slab of 0.076 ft, incidentally, was the greatest heave measured of all thirty soil installations on which level readings were taken during the winter.

TABLE 3

Installation	Max. Heave	Date	Depth of 32 deg Line
F-10 Slab	0.023 in.	Jan. 29	10.0 in.
F-17 Slab	0.016 in.	Feb. 1	9.5 in.
F-5 Slab	0.032 in.	Feb. 2	12.0 in.
F-13 Slab	0.034 in.	Feb. 2	9.0 in.
F-15 Slab	0.047 in.	Feb. 2	10.5 in.
F-24 Slab	0.076 in.	Jan. 25	11.0 in.

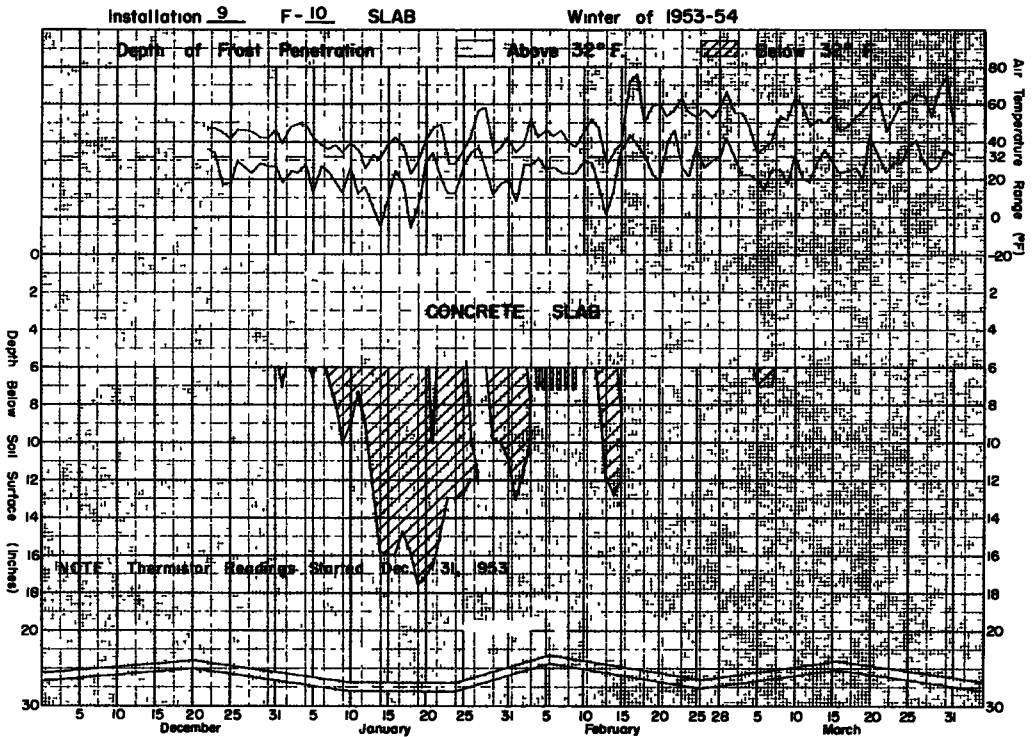


Figure 8.

Freeze and Complete Thaw Periods Between December 31, 1953 and February 15, 1954

December 31, 1953 was the date of the first thermistor readings and February 15, 1954 was the beginning of a general thaw period that caused all frost to come out of the ground. By complete thaw period, it is meant that the 32 deg line was completely above the ground.

The installations and a brief account of the freeze and complete thaw periods for each during this period, are as follows:

F-10 Slab—The 32 deg line entered the ground steadily on January 7 and remained in until February 3 except for one brief thaw. Between February 3 and February 12, the 32 deg line entered the ground only at night.

F-10 Shoulder—There were two brief complete thaws during the period.

F-17 Slab—The 32 deg line entered ground steadily on January 7 and remained in until February 3 except for one brief thaw. Between February 5 and February 9, the 32 deg line entered the ground only at night.

F-17 Shoulder—There were four complete thaws between December 31 and February 4. The 32 deg line entered the ground only at night between February 4 and February 11.

F-5 Slab—The 32 deg line entered the ground steadily on January 7 and remained in until the end of the period except for one brief thaw.

F-5 Shoulder—The 32 deg line remained below ground during the entire period.

F-13 Slab—The 32 deg line entered the ground steadily January 7, and except for one complete thaw remained in until February 6. Between February 6 and February 11, the 32 deg line entered the ground only at night.

F-13 Shoulder—The 32 deg line remained below ground during the entire period.

F-15 Slab—The 32 deg line penetrated the ground steadily on January 8 and remained in until the end of the period except for two complete thaws.

F-15 Shoulder—The 32 deg line remained below ground during the entire period.

F-24 Slab—The 32 deg line entered the ground steadily on January 8 and remained in until the end of the period except for one brief thaw.

F-24 Shoulder—The 32 deg line remained below ground during the entire period except for one brief thaw.

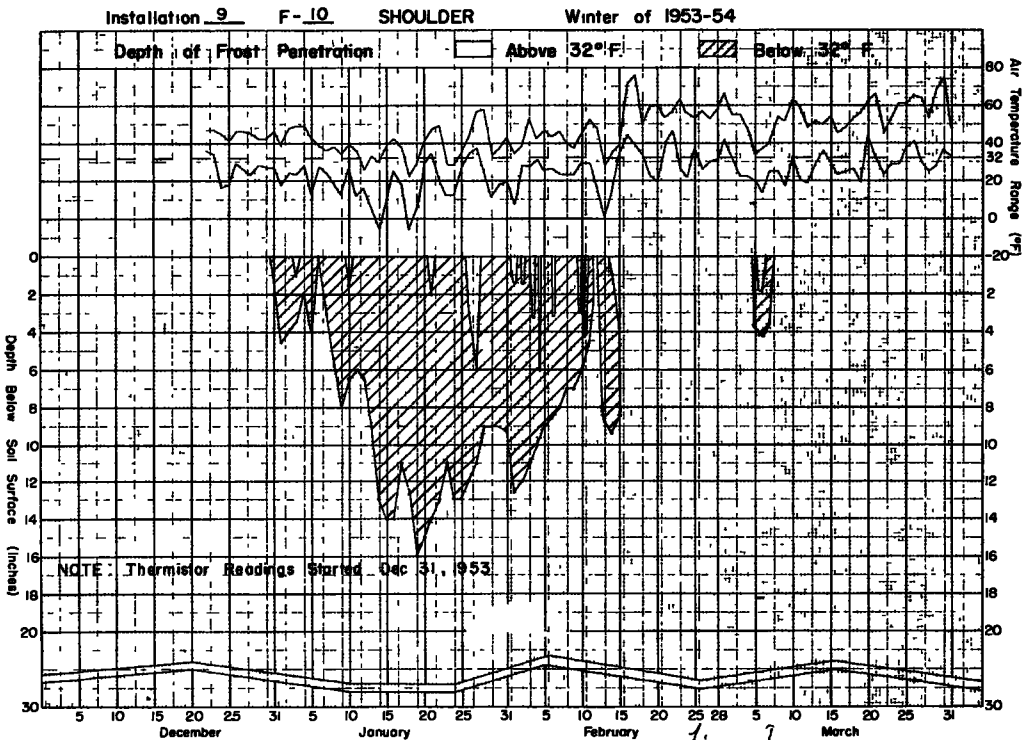


Figure 9.

Figures 8 through 19 are frost penetration curves for the winter based on daily morning readings which also illustrate the freeze and complete thaw periods.

A study of the freeze and complete thaw periods indicates that the slabs of F-17, F-10

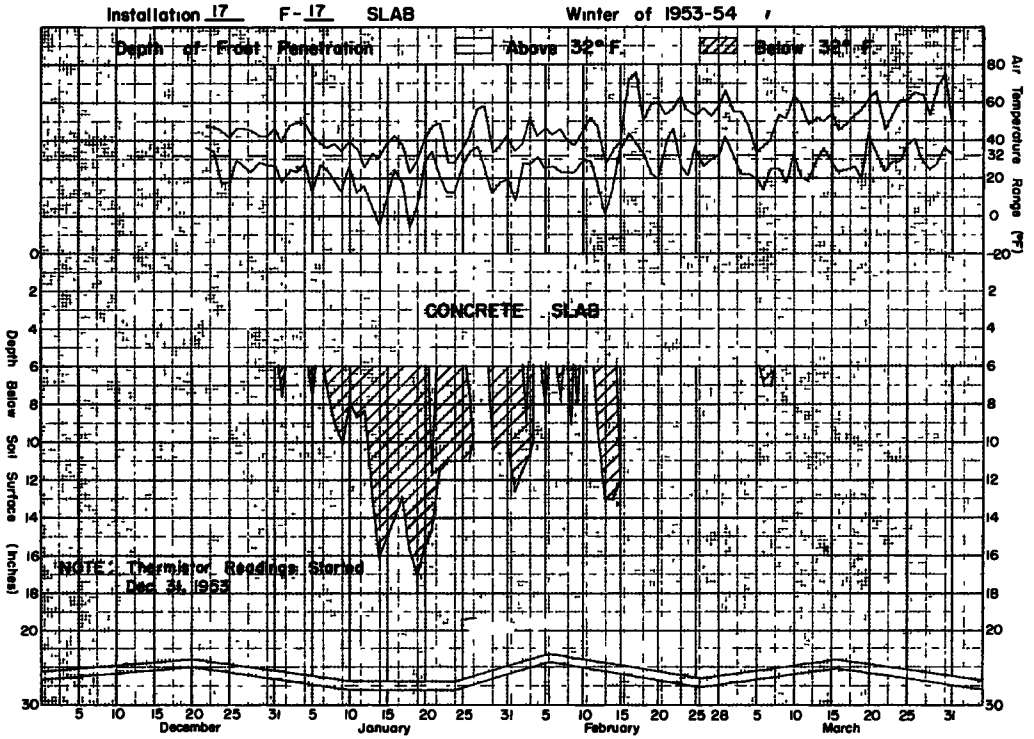


Figure 10.

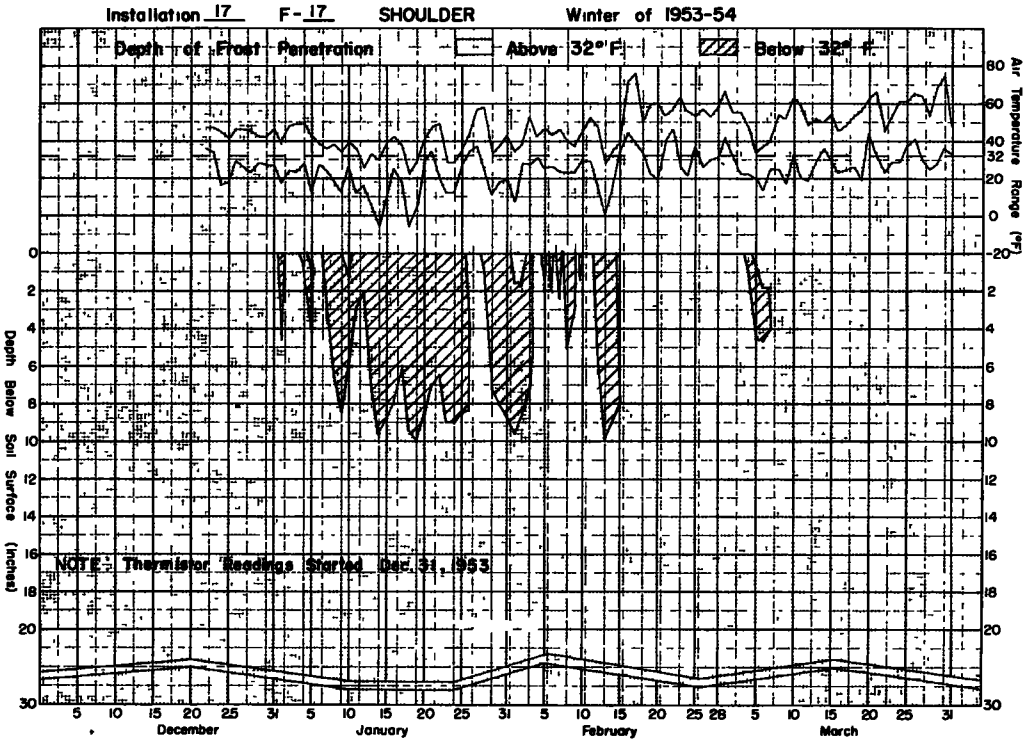


Figure 11.

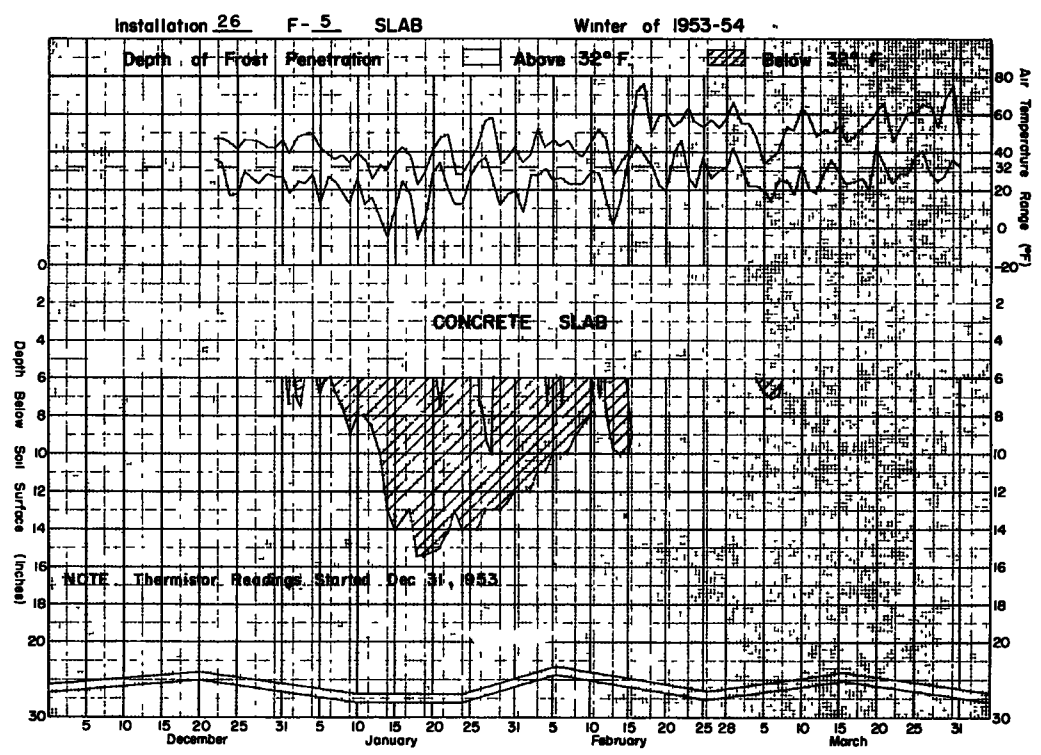


Figure 12.

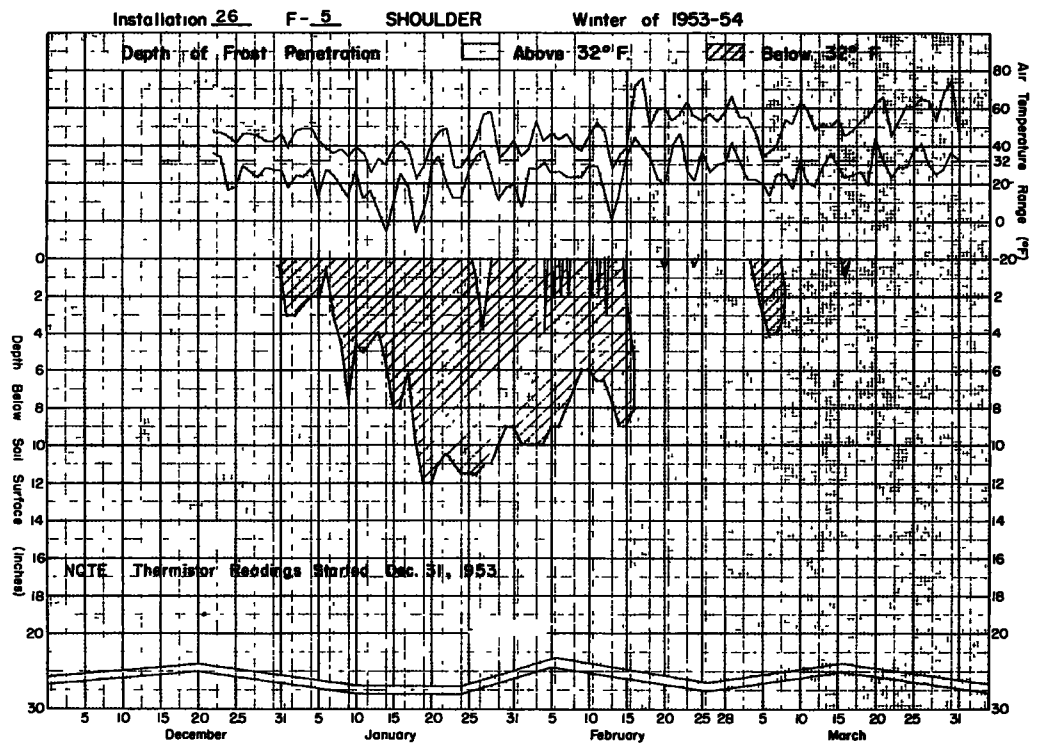


Figure 13.

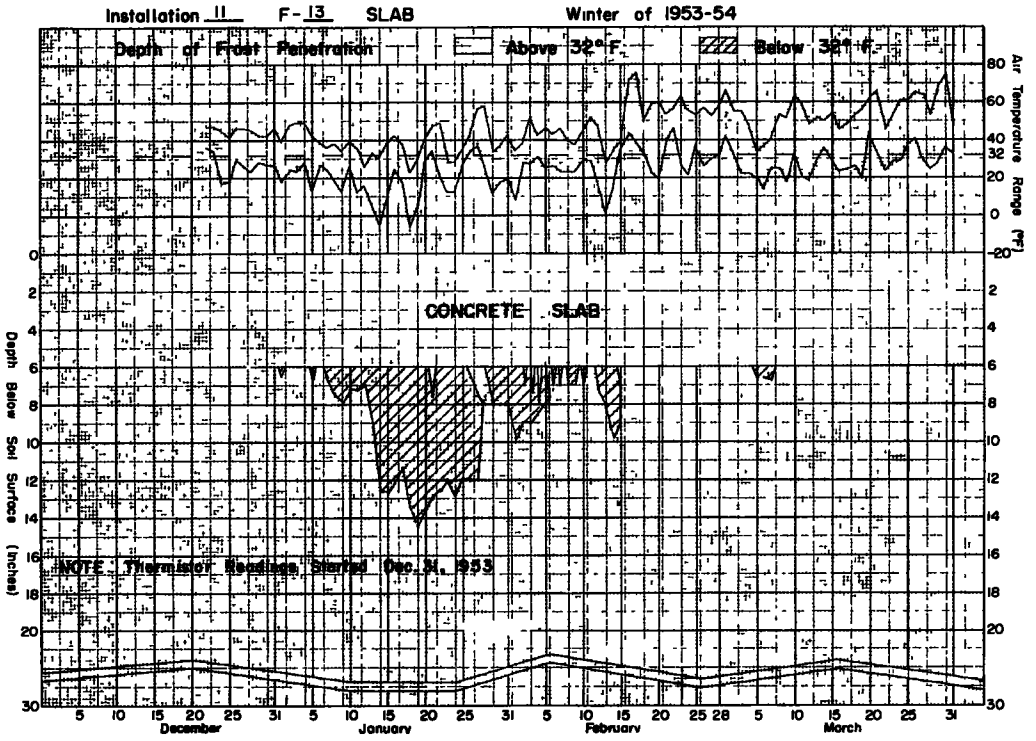


Figure 14.

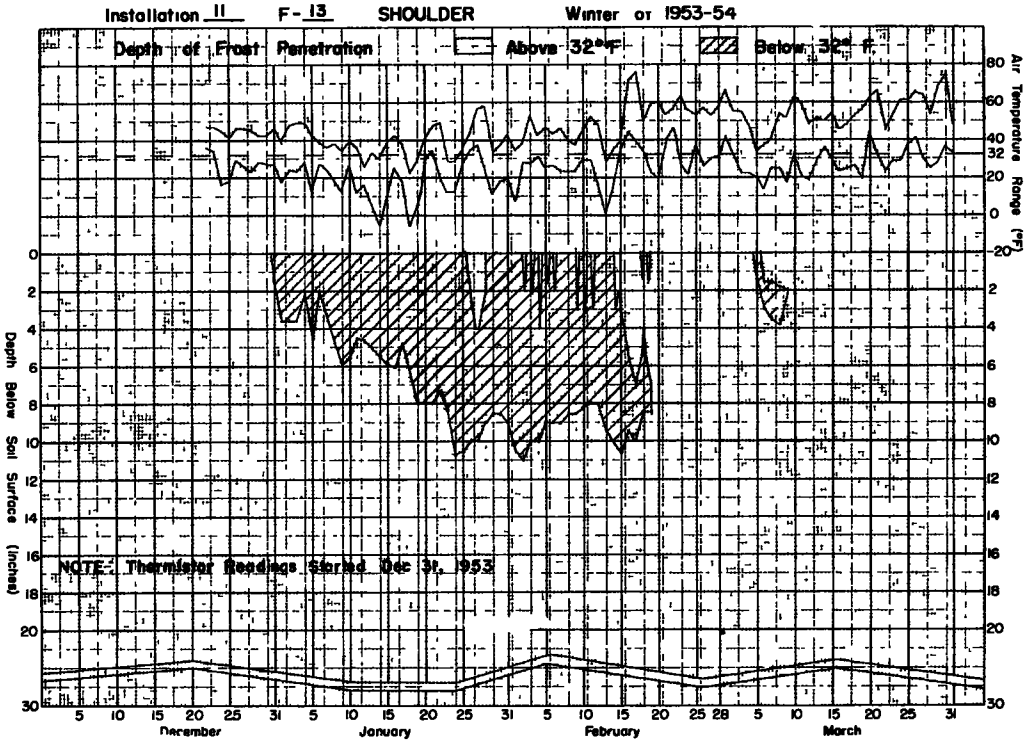


Figure 15.

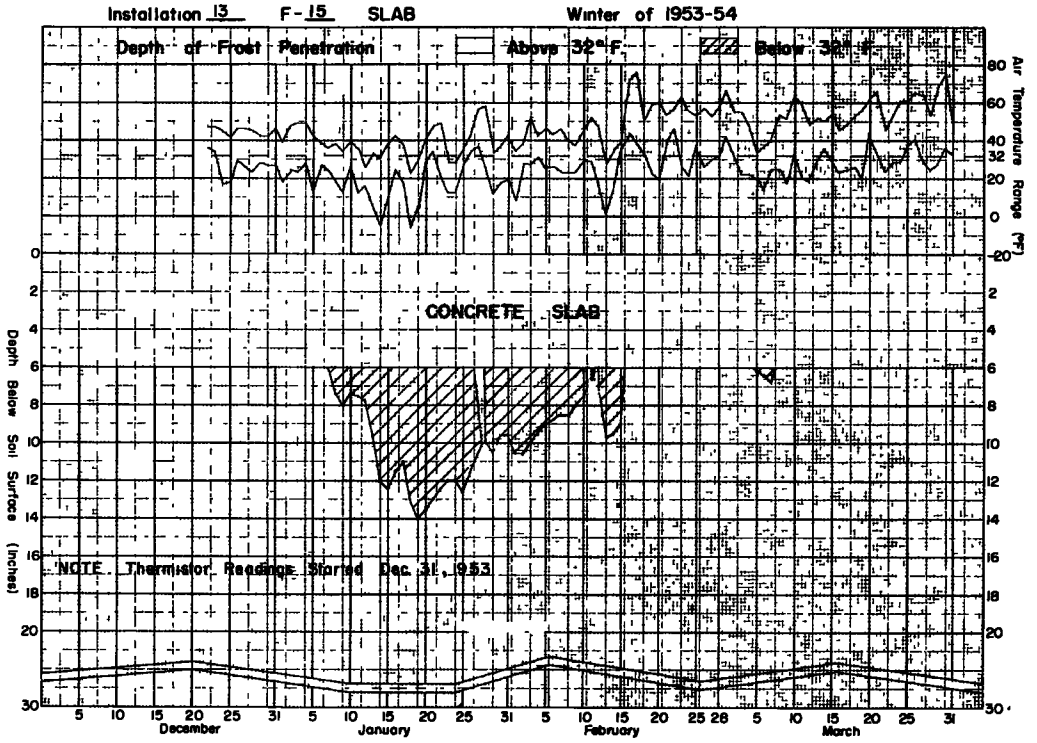


Figure 16.

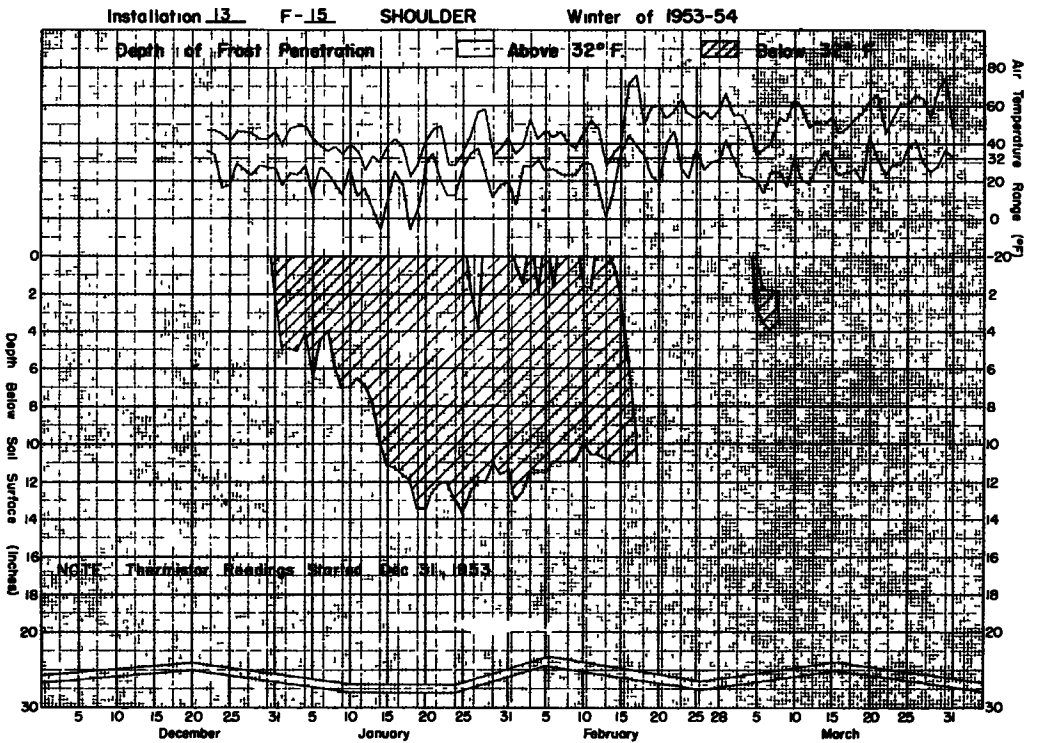


Figure 17.

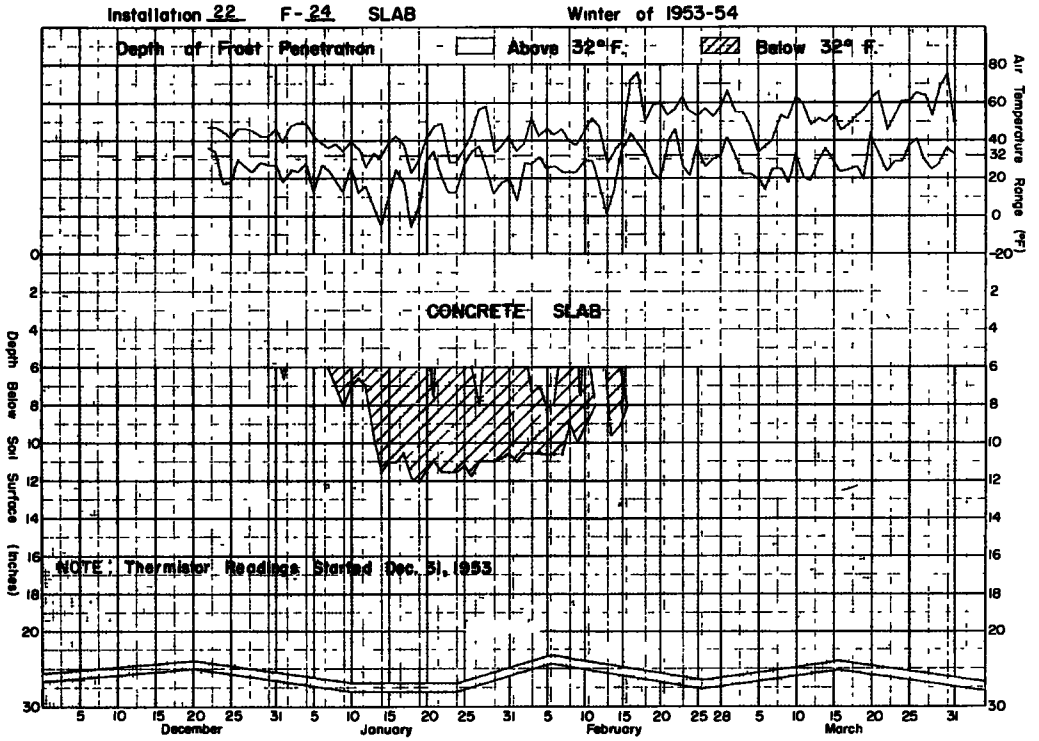


Figure 18.

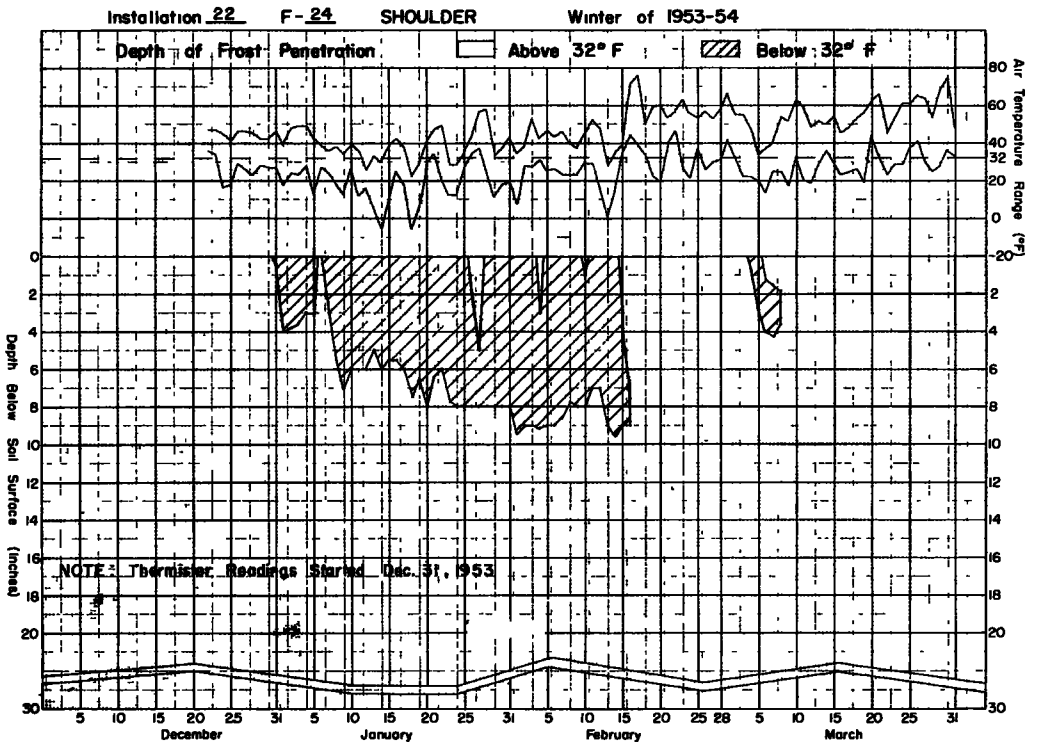


Figure 19.

and F-13 showed similar characteristics in that thawing occurred frequently in the latter part of the period while at the same time the slabs of F-15, F-5 and F-24 maintained below-freezing temperatures. In the shoulders, F-17 showed a rapid reaction to air temperatures, resulting in frequent freeze and complete thaw cycles. The other five shoulders showed a much greater capacity for retaining below-freezing temperatures, particularly F-13, F-5 and F-15, which maintained below-freezing temperatures throughout the entire period of December 31 to February 15.

In the early part of the period (December 31 to January 7) the frost did not penetrate the ground beneath the slabs steadily, while at the same time the shoulders were frozen to a depth of 3 to 5 in. Apparently the 32 deg line was at some level in the slab but not deep enough to penetrate steadily into the ground beneath it.

Trend of 32 deg Line During Cold Spells

Between December 31, 1953 and February 15, 1954, there were five cold spells (periods when air temperatures were below freezing for most of the time) and frequent thermometer readings were taken in all but the January 18-19 cold spell. The cold spells during which frequent readings were taken with the depth of the 32 deg at the start and at the end of the cold spells for each installation are listed in Tables 4, 5, 6 and 7.

TABLE 4
JANUARY 12 TO JANUARY 14 COLD SPELL

Installation	Depth of 32 deg Line, Inches		Change, Inches
	Start	End	
F-10 Slab	9.0	15.9	-6.9
F-10 Shoulder	6.8	13.5	-6.7
F-17 Slab	8.5	15.0	-6.5
F-17 Shoulder	2.0	9.5	-7.5
F-5 Slab	9.0	13.5	-4.5
F-5 Shoulder	4.5	6.5	-2.0
F-13 Slab	7.0	12.8	-5.8
F-13 Shoulder	4.5	5.5	-1.0
F-15 Slab	7.5	12.5	-5.0
F-15 Shoulder	7.0	10.5	-3.5
F-24 Slab	7.0	11.5	-4.5
F-24 Shoulder	5.5	5.5	0.0

It can be noted that there was a greater penetration of the 32 deg line in the granular soils F-10 and F-17 than in the other installations. In F-10 and F-17 the penetration in shoulders and slabs were about the same while in the other finer-grained soils, penetration was greater beneath the slabs.

The 32 deg line depth during the cold spell shown in Table 5 also reflects somewhat the effects of the cold spell on January 18-19, which was a colder period. The rise in F-10 is probably due to a comparative warming after the January 18-19 cold spell. The lowering of the 32 deg line in the shoulders of the other installations indicates a greater lag behind the same spell. At the same time there was practically no change in the slabs of these other installations.

Table 6 shows that all shoulders but F-17 were frozen at the start of the period, which again illustrates the inability of F-17 to retain below freezing temperatures. In contrast, it is seen that both shoulders and slabs of F-5 and F-24 remained frozen throughout.

Table 7 highlights characteristics in the installations that were observed earlier, which are (a) greater changes occur beneath the slabs than in the shoulders; (b) the granular soils F-17 and F-10 react much more quickly to air temperature changes

TABLE 5
JANUARY 22 TO JANUARY 24 COLD SPELL

Installation	Depth of 32 deg Line, Inches		Change, Inches
	Start	End	
F-10 Slab	15.0	13.0	+2.0
F-10 Shoulder	13.5	13.0	+0.5
F-17 Slab	11.5	11.5	0.0
F-17 Shoulder	6.5	9.0	-4.0
F-5 Slab	14.0	14.0	0.0
F-5 Shoulder	10.0	11.9	-1.9
F-13 Slab	12.5	12.5	0.0
F-13 Shoulder	7.0	11.0	-4.0
F-15 Slab	12.5	12.0	+0.5
F-15 Shoulder	11.5	13.5	-2.0
F-24 Slab	11.4	11.5	-0.1
F-24 Shoulder	6.0	8.0	-2.0

than the other four soils (it can be seen that the shoulders of F-5, F-13, F-15 and F-24 retained below-freezing temperatures throughout the period); (c) the 32 deg line penetrates deeper in the F-17 and F-10 than in the other soils.

The 32 deg line entered the soil of installations F-17 and F-10 very quickly with the beginning of the cold spell and also came out quickly with the beginning of the warm spell.

The soil below the slabs of F-24, F-15, F-5 and F-13 was not frozen at the start of the period but the shoulders were frozen to a depth of 6.5 to 11 inches. The 32 deg line reached about the same depth beneath the slabs as in the shoulders of these four installations (F-24, F-15, F-5 and F-13) during the cold spell but came out much more quickly with the warm spell. The shoulders of these four installations did not thaw out completely until one to three days after the soil beneath the slabs thawed out. It

TABLE 6
JANUARY 28 TO FEBRUARY 1 COLD SPELL

Installation	Depth of 32 deg Line, Inches		Change, Inches
	Start	End	
F-10 Slab	0	13.0	-13.0
F-10 Shoulder	10.5	13.0	- 2.5
F-17 Slab	0	12.5	-12.5
F-17 Shoulder	0	9.5	- 9.5
F-5 Slab	13.0	13.0	0.0
F-5 Shoulder	10.5	10.0	+ 0.5
F-13 Slab	0	10.0	-10.0
F-13 Shoulder	9.0	10.5	- 1.5
F-15 Slab	0	10.5	-10.5
F-15 Shoulder	12.0	13.0	- 1.0
F-24 Slab	11.0	10.8	+ 0.2
F-24 Shoulder	8.0	9.5	- 1.5

TABLE 7
FEBRUARY 11 TO FEBRUARY 14 COLD SPELL

Installation	Depth of 32 deg Line, Inches		Change, Inches
	Start	End	
F-10 Slab	0	12.7	-12.7
F-10 Shoulder	0	9.5	- 9.5
F-17 Slab	0	13.0	-13.0
F-17 Shoulder	0	9.0	- 9.0
F-5 Slab	0	10.0	-10.0
F-5 Shoulder	6.5	10.0	- 3.5
F-13 Slab	0	9.0	- 9.0
F-13 Shoulder	8	10.5	- 2.5
F-15 Slab	0	9.5	- 9.5
F-15 Shoulder	11.0	11.0	0.0
F-24 Slab	0	9.5	- 9.5
F-24 Shoulder	7.0	9.5	- 2.5

can be seen a thin lens of soil remained frozen in F-13 shoulder about two days after the other shoulders were completely thawed.

It was noted that with this sudden thaw period, most thawing of the soils was from the top downward.

Observations from Temperature Oscillation Graphs

The soils F-17 and F-10 showed a marked difference from the other soils throughout the winter because they reacted to air temperature changes much more quickly. Lower temperatures also penetrated deeper in these two soils, causing a smaller temperature gradient with depth. Of the two, F-17 reacted more rapidly than F-10 to air temperature changes.

In comparing the finer-grained soils F-5, F-24, F-13 and F-15, it was found that lower temperatures penetrated deeper in F-5 and F-24 than in F-13 and F-15, with a corresponding lower temperature gradient with depth. Of all six soils studied, F-15 showed the least reaction to air temperature changes.

There was a period in February during which the daily variation in temperature was quite uniform. There was a daily variation in temperature in F-17 to a depth of about 18 in. to 22 in. and in F-10 to a depth of about 10 in. to 18 in. and that there was a lag of about 4 to 6 hours behind the air temperature. In the other four soils there was little or no change in temperatures except to 8 in. or 10 in. below the surface, and here the change was generally slight.

A study of the temperatures at the bottom of the installation (30 in. below the surface) during the winter indicated that there was a slight but general lowering of temperatures in F-5, F-24, F-13 and F-15 with only a faint reflection of cold spells. At the same time and at the same depth in F-17 and F-10, there were definite rises and falls with warm and cold spells.

SUMMARY

The granular, non-plastic soils, F-17 and F-10, reacted to air temperature changes much more quickly than the finer-grained soils, F-5, F-13, F-15 and F-24, and therefore are better conductors of heat and cold. The frost entered into and went out of these granular soils more quickly than the finer-grained soils because of their greater conductivity.

The granular soils, F-17 and F-10, in general reacted in a similar manner during the winter. Of the two soils, F-17 was a better conductor and showed the least capa-

city for retaining low temperatures.

The finer-grained soils, F-5, F-13, F-15 and F-24, as a group, reacted similarly and it was difficult to find consistent differences as to frost penetration, temperature gradient with depth, and freeze and thaw periods. However of these four soils, F-15 (HRB Classification A-7-6) appeared to react the most slowly to air temperature changes and can be considered to be the poorest conductor (or best insulator). The dry density of F-15 in the fall of 1953 was 80 lb per cu ft, which was considerably lower than the other soils.

The 32 deg line generally penetrated to a greater depth in the granular soils (F-17, F-10) than in the finer-grained soils (F-5, F-13, F-24, F-15) during cold spells. The greatest penetration of the 32 deg line during the winter occurred below the slabs of F-17 and F-10.

Freeze and complete thaw cycles occurred more often below the slabs than in the adjacent shoulders. Therefore it can be said that the concrete slabs are better conductors of heat and cold than soil of the same thickness.

The shoulders of the finer-grained soils (F-5, F-13, F-24, F-15) showed little reaction to cold and warm spells (except at the surface) during the period studied, but instead tended to reflect the overall cold weather of the period itself. The shoulders of F-5, F-13 and F-15 retained 32 deg or below temperatures throughout the period.

There was a lag between the second minimum air temperature period of the winter and the time of the maximum penetration of the 32 deg line. The lag was one day for all but for the shoulders of F-13, F-15 and F-24, for which the lag was 6 to 14 days.

Maximum heaving did not occur at the same time as the maximum depth of the 32 deg line. In the cases studied, the maximum heave occurred many days (6 to 14 days) after the maximum depth of the 32 deg line and was attributed to an increase in the moisture content of the soils. Also, the depth of the 32 deg line at the time of maximum heaving was less than its maximum depth had been.

During the thaw periods, most of the thawing in the soils occurred from the top downward.

CONCLUSIONS

1. Granular, non-plastic soils are better conductors of heat and cold than fine-grained soils and react to air temperature changes more quickly. Of the six soils studied, F-17, a clean sand (HRB Classification A-3), was the best conductor and F-15 (HRB Classification A-7-6) was the poorest conductor. Therefore frost enters and goes out of granular soils more rapidly than fine-grained soils, causing more frequent freeze and complete thaw cycles.
2. A concrete slab is a better conductor of heat and cold than soil of the same thickness. Therefore freezing and complete thaw cycles occur more often below a concrete slab or pavement than in the adjacent shoulder.
3. A combination of a concrete slab over a granular soil is one that reacts most quickly to cold and warm spells. A shoulder of fine-grained soil shows little reaction to cold and warm spells (except at the surface) and reflects the over-all intensity of cold of the winter.
4. The freezing line generally penetrates to a greater depth in granular soils than in fine-grained soils.
5. There is a lag between the minimum air temperature of winter and the maximum penetration of the 32 deg line. (In the cases studied the lag was one day except for some of the shoulders of fine-grained soils, where the lag was several days.)
6. Maximum heaving does not necessarily occur at the time of the maximum depth of the 32 deg line.
7. Most thawing in soils occurs from the top downward during thaw periods.

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DISCUSSION

MILES S. KERSTEN, Professor, University of Minnesota—Temperature data beneath a simulated roadway surface such as presented in this paper are useful for checking methods which have been developed for calculating depths of freeze from air temperatures and certain soil data. (1) The New Jersey measurements could be of particular value since they are for a variety of soil textures and would help in depicting the effect of such a variable. They are also for a location where the magnitude of the cold, as measured by degree-days of freeze, is sufficient to cause some freezing of subgrades, but of a much lesser magnitude than is typical for Minnesota and other more northern states where some previous measurements have been made.

One very important item of needed information to calculate or estimate frost depths from air temperature data is the moisture content of the soil. No mention seems to have been made of this in the report. If it can be furnished it would be useful. One would suspect that the two sandier soils, F-10 and F-17, had much lower moisture contents than the other four soils. This would have a great influence on the rate of freezing and depth of freeze.

I believe care should be exercised in some of the terms which are used in problems of frost penetration. For example, conclusion (1) reads in part "Granular, non-plastic soils are better conductors of heat and cold than fine-grained soils—." Referring to the words "better conductors", this property is usually indicated by a coefficient of thermal conductivity, k , measured in such units as Btu per deg F per in. temperature gradient per square foot of area per hour. According to measurements made at the University of Minnesota (2) a sandy soil at a dry density of 116 lb per cu ft and at a moisture content of 5 percent would have a k of about 10 (units as above) in a frozen condition. A soil such as the F-5 silty soil in the New Jersey tests with a dry density of 94 lb per cu ft, if it existed at a moisture content of 22 percent, would have a k of 12. Even though the conductivity of the sand is less than that of the silt, the frost penetration for a given magnitude of "cold" could be much greater in the sandy soil than in the silt soil; this would be due to the much greater quantity of water in the silt which must be frozen, and the consequent greater quantity of heat represented by the latent heat of fusion which must be conducted out of the soil. With numerical values as indicated above, calculations of frost penetration in the sandy soil, without any pavement surfacing, would give depths about 1.7 times as great as calculated frost depths for the silt. Hence, it may not be entirely proper to designate soils in which frost penetrates rapidly or to great depths "good conductors."

A similar reasoning could be applied to conclusion (2) which states that a concrete slab is a better conductor than soil of the same thickness. Most concrete has a thermal conductivity, k , of about 10 to 12 Btu per deg F per in. per sq ft per hour. Frozen soils with relatively high moisture contents might have k -values appreciably greater than this. Even so, the frost might penetrate a few inches below a concrete pavement 6 in. which, resulting in a total depth of say 8 or 9 in. while it was penetrating only 4 or 5 in. into the soil in the shoulder alongside the slab. Again this would be due to the appreciable magnitude of the latent heat of fusion of the soil in the shoulder, whereas the concrete might contain only a small, almost negligible amount of moisture which would give it a small volumetric latent heat of fusion.

The conclusion that the freezing line penetrates to a greater depth in granular soils than in fine-grained soils is in agreement with measurements made in Minnesota.

REFERENCES

1. Carlson, Harry and Kersten, Miles, "Calculation of Freezing and Thawing Under Pavements." Highway Research Board Bulletin No. 71, 1953.
2. Kersten, Miles S., "The Thermal Conductivity of Soils." Highway Research Board Proceedings Vol. 28, 1948.

A. R. Jumikis, Closure—Mr. Kersten's remarks concerning the lack of mention of soil moisture content in this report are pertinent. Moisture content in soil has a great influence on the rate of freezing and depth of frost penetration.

Although moisture contents of these six soils in question were determined in the fall prior to the freezing season of 1953-4, and then again in the following spring after the frost went out of the ground, the soil moisture content data were not reported in this article. There were no moisture gages installed in the soil during the winter of 1953-4. Hence the variation in thermal properties of the soils because of the moisture changes during the freezing season could not be ascertained.

Being aware of the importance of and necessity for information on soil moisture contents during a freezing season, the authors installed soil moisture gages the following winter (1954-5) and included data on soil moisture contents obtained during the 1954-5 freezing season in a subsequent report*, actually being published prior to the discussion of the present article (concerning 1953-4). Illustrations on frost penetration depths and soil moisture contents and their variations are shown on pp. 97-108 of the previously mentioned report.

Mr. Kersten is quite right in saying that the property of heat conductivity of soil (referring to the expression "better conductors") can be characterized by a coefficient of thermal conductivity; for example, in Btu per foot per hour per degree F or calories per centimeter per second per degree C. With such data on hand, the soil thermal properties are readily characterized quantitatively. However, if such data are not on hand and one has to say something about the soil, the performance and the end results of the performance of the soil, as in this case, when subjected to freezing, can also be described qualitatively, especially when comparing the performance of several different soils among themselves, and particularly when heat transfer measurements and calculations are not and/or could not be done.

Under the circumstances, therefore, it is quite proper to compare the performance of several soils among themselves because all of the six soils were subjected to the same climatic and geographic environment (in one and the same frost yard and same position of the ground-water table) at the same time and during the same length of time. Thus, naturally, because of the varying properties among the soil types under consideration (their magnitudes are masked out, but they are there) one soil is obviously a "better conductor" of heat than another when compared for various climatic and geographic environmental conditions; then, of course, it is very difficult to say which soil is a "better conductor".

The author agrees that numerical heat conduction values of soils for varying moisture contents, even for one and the same type of soil, are very desirable factors in thermal soil mechanics. Much effort is still to be devoted to obtain such data for various types of soils, at various densities, moisture contents, and temperatures. Such data facilitate thermal calculations in highway and earthwork technology.

The same can be said about "good conductors" of concrete pavement slabs. The authors' conclusions were based on careful observations and considerations.

Mr. Kersten has studied frost penetration problems in Minnesota soils and it is gratifying to learn that temperature measurements made by the Joint Highway Research Project at Rutgers beneath a simulated roadway surface are useful in highway technology, and that some observations regarding frost penetration depths in granular soils made in New Jersey are in agreement with measurements made in Minnesota.

* Turner, K. A. Jr., and Jumikis, A. R.

"Subsurface Temperatures and Moisture Contents in Six New Jersey Soils, 1954-5." HRB Bulletin 135, p. 77 (1956).