71
C.2

File Copy

HIGHWAY RESEARCH BOARD

Bulletin 71

Soil Temperature and Ground Freezing

National Academy of Sciences—
National Research Council

Publication 262

HIGHWAY RESEARCH BOARD

1953

2101 Constitution Avenue, Washington 25, D. C.

HIGHWAY RESEARCH BOARD

Bulletin 71

Soil Temperature and Ground Freezing

PRESENTED AT THE

Thirty-Second Annual Meeting

January 13-16, 1953

1953

Washington, D. C.

DEPARTMENT OF SOILS INVESTIGATIONS

Harold Allen, Chairman
Principal Highway Engineer
Bureau of Public Roads

COMMITTEE ON FROST HEAVE AND FROST ACTION IN SOIL

George W. McAlpin, Jr., Chairman

Charles W. Allen, Research Engineer, Ohio Department of Highways

Earl F. Bennett, Tar Products Division, Koppers Company

Ellis Danner, Professor of Highway Engineering, University of Illinois

L. E. Gregg, Associate Director of Research, Highway Materials Laboratory, Kentucky

Frank B. Hennion, Office, Chief of Engineers, Department of the Army

Miles S. Kersten, Associate Professor, University of Minnesota

J. E. Lawrence, 90 Lothrop Street, Beverly, Massachusetts

R. F. Legget, Division of Building Research, National Research Council, Ottawa, Canada

LCDR. O. L. Lund, ROin. CC. Ordinance Aero Physics Laboratory, Daingerfield, Texas

A. E. Matthews, Assistant Engineer of Soils, Testing and Research Division, Michigan State Highway Department

George W. McAlpin, Jr., Director, Bureau of Soil Mechanics, New York Department of Public Works

Lloyd H. Morgan, Soils Engineer, Washington Department of Highways

Frank R. Olmstead, Bureau of Public Roads

Paul Otis, Materials and Research Engineer, New Hampshire State Highway Department

A. W. Potter, Materials Engineer, South Dakota Highway Commission

James R. Schuyler, U. S. Naval Civil Engineering Research and Evaluation Laboratory, Construction Batallion Center, Port Hueneme, California

T. E. Shelburne, Director of Research, Virginia Department of Highways, University of Virginia

H. R. Smith, Solvay Sales Division, Allied Chemical and Dye Corporation

J. H. Swanberg, Engineer of Materials and Research, University of Minnesota

John Walter, Assistant Highway Engineer, Department of Highways, Toronto, Canada

K. B. Woods, Associate Director, Joint Highway Research Project, Purdue University

Contents

Cold-Room Studies of Frost Action in Soils, A Progress Report

JAMES F. HALEY, Assistant Chief, Frost Effects Laboratory,
New England Division, Corps of Engineers

THIS paper is a progress report of cold-room studies of frost action in soils performed between February 1950 and October 1952 by the Frost Effects Laboratory, New England Division, Corps of Engineers. They are part of a comprehensive field and laboratory investigational program for the improvement of engineering design, construction, and evaluation criteria for pavements and other structures constructed on soils subject to seasonal freezing and thawing.

Cold-room tests are being performed to determine the effects of individual factors considered to influence ice segregation in soils. Tests have been conducted on a large number of natural soils obtained from several locations and on specimens prepared by blending soil fractions in proportions to give desired investigational gradations.

Data from phases of the investigation which are substantially complete indicate that (1) the intensity of ice segregation in soils is dependent not only on the percentage of grains finer than 0.02 mm., but also on the grain-size distribution or physical-chemical properties of these fines; (2) fine soil fractions with a high percentage of fine clay sizes appear to be more effective than silt sizes in producing ice segregation in soils of near borderline frost susceptibility; (3) in well-graded frost susceptible gravelly soils, the intensity of ice segregation increases moderately with initial density up to approximately 95 percent of Modified AASHO density, above which there is a decrease in ice segregation with increase in density; (4) in inorganic silt soils, the intensity of ice segregation increases with initial density for the full range of densities attainable in the laboratory specimens; (5) the intensity of ice segregation in soils is decreased appreciably by an increase in overburden pressure, all other factors, such as rate of frost penetration being equal, (6) the intensity of ice segregation in a frost susceptible soil varies directly with the initial degree of saturation, where water is available only by withdrawal of a portion of that existing in the voids of the soil underlying the surface of freezeng; (7) the rate of heave of the surface is generally independent of rate of freezing within the range of 1/4 to 1-3/4 in. per day, but the heave per unit depth of frozen material is inversely proportional to the rate of penetration of the freezing temperature; (8) neglecting effect of salinity of pore water, virtually all water present in clean sands and inorganic silt soils freezes at 32 F. while in lean clay soils the freezing temperature of the soil moisture is not constant but decreases below 32 F. with decrease in water content; (9) the percentage heaves of specimens with fine soil fraction (minus 200 mesh) composed of the three common clay mineral groups decreased in the order of kaolinite, illite, and montmorillonite; (10) soils may be made less susceptible to frost by means of trace (less than 1 percent of dry weight of soil) chemicals which either disperse, aggregate, or waterproof the soil grains.

● THE increase in the weights of military and commercial aircraft and the increased use of highways by heavily loaded trucks during the last decade has intensified problems encountered in design of airfield and highway pavements, particularly in the northern latitudes where seasonal freezing and thawing of the ground takes place. The occurrence of ice segregation in soils may result in nonuniform heaving of pavements and loss of pavement-supporting capacity during the frost-melting period so that costly maintenance of repair measures may be required.

To develop pavement design and evaluation criteria for such frost conditions, the Frost Effects Laboratory was established in the New England Division, 1944, by the chief of engineers, Department of the Army. The laboratory has since conducted field investigations including traffic tests at various fields in the northern part of the United States to observe and study the effects of frost action (1, 2). The field studies demonstrated the need for comprehensive laboratory investigations in which each of the several variables considered to influence frost action in soils could be isolated and studied under controlled conditions. To meet this need, cold-room facilities were constructed in 1949 and 1950 and laboratory investigations were initiated.

These facilities enable subgrade soils and material proposed for use as base-course borrow to be tested in the cold room to determine their behavior under freezing conditions. A more precise determination of the relative degree of frost susceptibility of the soils is thereby made possible to aid in the selection of satisfactory base materials which will not lose strength due to frost melting and to allow proper consideration in pavement design of the relative frost susceptibility of subgrade soils.

This paper presents the results of cold room investigations conducted from the initiation of the program up to about October 1952 and includes nine separate investigational items. The present indications and tentative conclusions are subject to revision as additional related factors are examined in the future. However, presentation of these interim results may be of interest or aid to other investigators in this field.

DEFINITIONS

Definitions of the specialized words and terms employed in this paper are as follows:

Frost action is a general term used in reference to freezing and thawing of moisture in the materials and the resultant effects on these materials and on structures of which they are a part or with which they are in contact.

Ice segregation in soils is the growth of ice as distinct lenses, layers, veins, and masses commonly, but not always, oriented normal to the direction of heat loss.

Open system is a condition in which free water in excess of that contained originally in the voids of the soils is available to be moved to the surface of freezing to form segregated ice in frost-susceptible soil.

Closed system is the condition in which no source of free water is available during the freezing process beyond that contained originally in the voids of the soil at the immediate zone of freezing.

Frost heave is the raising of a surface due to the formation of ice in the underlying soil.

Percentage heave is the ratio, expressed as a percentage, of the amount of heave to the thickness of the frozen soil before freezing.

Frost-susceptible soils are those in which significant ice segregation will appear when the requisite moisture and freezing conditions are present. (Previous information has indicated that most soils containing 3 percent or more of grains finer by weight than 0.02 mm. are susceptible to ice segregation, and this limit has been widely applied to both uniformly and variably graded soils. Although it has been found that some uniform sandy soils may have as high as 10 percent of grains finer than 0.02 mm. by weight without being considered frost susceptible, there is some question as to the practical value of attempting to consider such soils separately, because of their rarity and tendency to occur intermixed with other soils.)

Non-frost-susceptible materials are materials such as crushed rock, gravel, sand, slag, cinders, and other cohesionless material in which ice segregation does not occur under natural freezing conditions.

Degree-hour is a variation of 1 deg. F. from 32 F. for a period of 1 hour. The degree-hour is negative if below 32 F. and positive if above 32 F.

FROST CLASSIFICATION, SOILS AND PROCEDURES

Test Procedures

In the cold room where conditions can

be controlled and varied within small limits, soil specimens are subjected to conditions simulating the most-severe probable field freezing conditions. The soil specimens are generally prepared for freezing in a 5.91-in.-inside-diameter steel molding cylinder to an approximate height of 6 in. and to a predetermined density by means of static load or vibration. In some instances, however, undisturbed samples of cohesive soils are trimmed to this same size. The trimmed specimens, or those ejected from the molding cylinder, are placed in a 6-in.-diameter heavy-cardboard container coated inside with silicone to prevent friction between the specimens and the container walls during heaving. In the more recent tests, a liner consisting of 1-in.-high cellulose-acetate strips are lapped in the form of a telescope within the cardboard containers. The acetate strips are coated on both sides with silicone.

Cohesionless soils are molded at a low moisture content to improve the apparent cohesion and aid specimen handling after molding, while all other materials are molded at optimum moisture content, as determined by the Modified AASHO test procedure. The specimens are then evacuated from top and bottom and saturated from the bottom using de-aired water and allowed to temper for a minimum of 24 hr. at 38 F. before start of the freezing test. Thermocouples are inserted at intervals along the length in at least one sample of four placed in each freezing cabinet to measure the temperature changes, and granulated cork is placed around the sides for the full height of the specimens. A section and plan of a test cabinet showing the soil specimens in place is shown in Figure 1.

A free water surface is maintained approximately 1/8-in. above a porous stone at the bottom of each sample. A surcharge weight of 0.5 psi. is placed on top of the samples. The samples are then frozen from the top by gradually decreasing the temperature above the samples in the freezing cabinet, while the bottoms of the samples are exposed to a cold-room temperature maintained between 35 F. and 38 F. The temperature in the test cabinet is lowered to obtain approximately 1/4-in.-per-day penetration of the 32 F. temperature into the samples. Heave measurements are taken daily. At the completion of the tests, usually after 24 days, the samples are removed from the freezing cabinet, measured, split longitudinally, photographed, examined for ice segregation, and finally broken up to determine water-content distribution.

Since the majority of the tests performed in the investigation have an unlimited supply of water available at the base of the specimens, which is an extreme condition insofar as water availability is concerned and generally results in the maximum rate of ice segregation and rate of heave which the soils could exhibit under natural field conditions, the results are not usually quantitatively applicable. The cold-room-test procedures are considered satisfactory, however, for determining the relative degree of frost susceptibility of various soils.

Measure of Frost Susceptibility

The following tentative scale of average rate of heave has been adopted for rates of freezing between 1/4 and 3/4 in. per day:

Average rate of heave	Corresponding frost susceptibility classification
mm. per day	
0-0.5	Negligible
0.5-1.0	Very low
1.0-2.0	Low
2.0-4.0	Medium
4.0-8.0	High
> 8.0	Very high

Soils Tested

Approximately 60 different soils have been tested to date. Some of these have also been tested in combination with each other in order to obtain various artificial gradations. These soils have been obtained from locations distributed over the United States from Maine to Washington, as well as from locations in Alaska, Canada, and Greenland. Most of these are from airfield and highway project locations. They range from a well-graded sandy gravel (GW) to a medium plastic clay (CL).

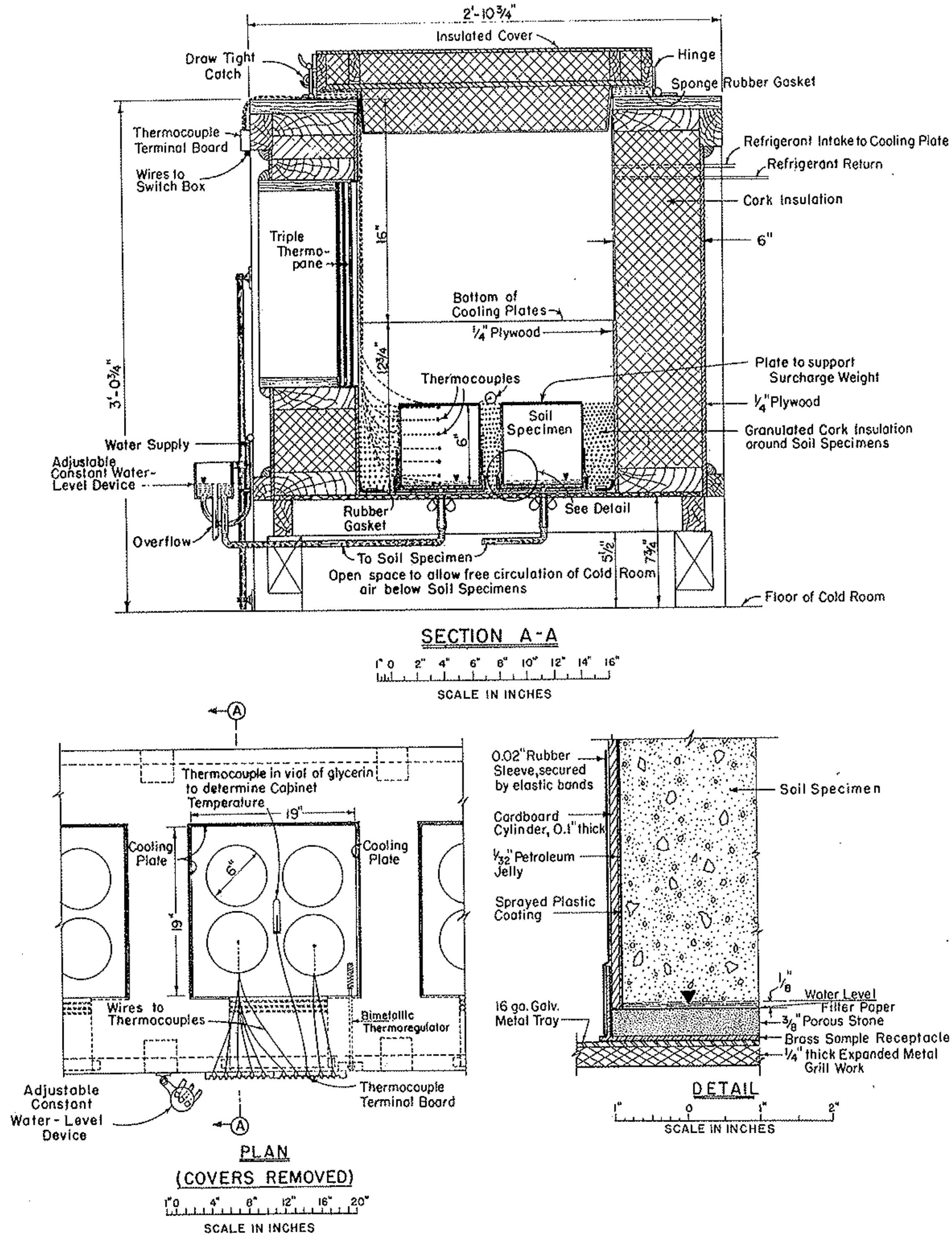


Figure 1. Details of test cabinet and samples, showing specific setup with samples 6 in. high and 6 in. in diameter. The constant-water-level device is adjusted to maintain the water level at 1/8 in. above porous stone.

COLD-ROOM INVESTIGATIONS

Effect of Percentage Finer Than 0.02 mm.

A series of tests were performed to check the validity of the present criteria for frost-susceptible soils and to determine, with soils of various gradations ranging from well-graded sandy gravel to very-uniform fine sand, the minimum percentage of grains finer by weight than 0.02 mm. at which significant ice segregation will occur. The study included both tests on artificial soil gradations prepared by blending various combinations of the soils, whose grain-size-distribution curves are shown in Figure 2, and also on natural soils with various gradations and percentages finer than 0.02 mm. in order that the relationship between average rate of heave and percentage finer than 0.02 mm. could be determined.

The results of tests on specimens prepared by blending various fine and coarse soil fractions are summarized in Figure 3. Examination of this figure reveals that, for equal percentages of material finer than 0.02 mm., relatively large variations in the average rates of heave were recorded. The fine soil fraction of the Limestone sandy gravel constitute the most-potent fine soil fraction tested in this series. When blended with the two sandy gravels and the two coarse sand fractions, it resulted in greater average rates of heave than when either the fine fraction of East Boston till or New Hampshire silt fines were used. Also, in two out of three instances the East Boston till fines were more effective in producing heave than were the New Hampshire silt fines.

Based exclusively on grain size, it appears that the finer the grains or the higher the percentage of colloidal sizes contained in the fine soil fraction the more effective the finer soil fraction is in producing ice segregation. The Limestone sandy gravel fines that were combined with Limestone sandy gravel to give a sample composed of 3 percent finer than 0.02 mm. produced average rates of heave of 1.0 mm. per day. Such a soil, considered to be of borderline frost susceptibility by existing criteria, would nevertheless be classified as a soil of low frost susceptibility, in accordance with the scale presented in this paper. For a freezing test of 24 days duration, a 6-in.-high sample, when frozen to the bottom, would heave approximately 1 in. By comparison, when the coarse and fine fractions of Truax Drumlin soil were blended together to contain 3 percent finer than 0.02 mm., an average rate of heave of 0.35 mm. per day resulted. This soil would be classified as a soil of negligible frost susceptibility, in accordance with the adopted scale.

A second phase of the study to determine the relationship between percentage finer than 0.02 mm. and average rate of heave, consisted of performing freezing tests on base course and subgrade soils from various airfields and on materials from proposed base-course borrow sources. The samples used were obtained from locations with a wide geographical distribution as shown in Table 1. Data from the freezing tests are summarized in Figure 4. Examination of this figure reveals that soils exhibiting equal rates of heave contain a relatively wide variation in percent of material finer than 0.02 mm. For an average sandy gravel or gravel (GW) soil, with 3 percent of the grains finer than 0.02 mm., the average rate of heave was approximately the same as exhibited by a silty sandy gravel (GM) having 9 percent of the grains finer than 0.02 mm. and by silty sand and silty gravelly sand (SM) having 18 percent of the grains finer than 0.02 mm. One outstanding exception was the Alaska fine sand (AFS-1 and AFS-2) which had average rates of heave of 0.9 and 1.7 mm. per day with only 3 percent of grains finer than 0.02 mm. It is also noteworthy that the sandy gravel soils from Alaska and Greenland showed average rates of heave of between 0.5 mm. per day and 1.7 mm. per day even though the soils contained only 1 percent of grains finer than 0.02 mm. By the frost-susceptibility classification system presented here, the susceptibility of these soils would be classed as low to very low; although, by the usual standards, these would be considered very satisfactory base-course materials of negligible frost susceptibility. However, it is visualized that during the frost-melting period, the water released from the segregated ice in these soils would be quickly drained or redistributed through the soil so that the

TABLE 1

NATURAL SOILS TESTED TO DETERMINE THE RELATIONSHIP
BETWEEN RATE OF HEAVE AND PERCENTAGE FINER THAN 0.02mm SHOWN IN FIGURE 4

SAMPLE NUMBER	SOURCE OF SOIL	CORPS OF ENGINEERS UNIFORM SOIL CLASSIFICATION		GRAIN SIZE PERCENTAGE FINER THAN					ATTERBERG LIMITS	
		DESCRIPTION	LETTER SYMBOL	#4 SIEVE	#40 SIEVE	#200 SIEVE	0.02 mm.	0.005 mm.	L.L.	P.I.
BPR-5	Alaska	Sandy GRAVEL	GW	39	6	2	1	0.5	Non-Plastic	
BPR-1			GW	40	11	2	1	0.5	"	"
BPR-3			GW	49	13	3	1	0.5	"	"
PBJ-11	Greenland	Sandy GRAVEL	GW	45	16	3	1	0.5	"	"
LSG-9	Limestone AFB, Maine	Sandy GRAVEL	GW	42	8	4	2	2	"	"
ADG-1	Alaska	Sandy GRAVEL (Decomposed Granite)	GW	41	10	3	2	1	"	"
ADG-2			GW	55	13	4	2	1	"	"
PBJ-5	Greenland	Sandy GRAVEL	GW	38	18	4	2	1	"	"
LSG-36	Limestone AFB, Maine	Sandy GRAVEL	GW	41	8	4	3	3	"	"
LSG-10			GW	42	9	4	3	2	"	"
LSG-37			GW	49	10	6	4	3	"	"
AMS-1	Alaska	Sandy GRAVEL (Mica Schist)	GW	28	9	5	3	1	"	"
AMS-2			GW	44	16	7	4	5	"	"
LSG-13	Limestone AFB, Maine	Sandy GRAVEL	GW	41	9	6	5	3	"	"
LSG-14			GW	49	12	7	6	4	"	"
BPR-2	Alaska	Sandy GRAVEL	GP	68	12	5	3	1	"	"
ACR-1	Alaska	Silty Sandy GRAVEL (Alaska-Canadian Rock)	GM	34	18	11	7	3	26	4
ACR-2			GM	38	19	11	8	5	26	4
RC-1	Rapid City AFB, South Dakota	Silty Sandy GRAVEL	GM	58	30	12	8	6	19	2
SF-1	Sioux Falls Airfield, South Dakota	Silty Sandy GRAVEL	GM	72	28	15	8	5	24	6
WN-1	Wendover AFB, Utah	Silty Sandy GRAVEL	GM	60	27	14	9	6	22	3
BPR-4	Alaska	Silty Sandy GRAVEL	GM	58	38	27	11	2	Non-Plastic	
CL-1	Clinton County AFB, Ohio	Clayey Sandy GRAVEL	GC	53	29	20	14	5	25	7
PT-1	Patterson AFB, Ohio	Clayey Sandy GRAVEL	GC	62	34	22	15	5	22	6
GF-1	Great Falls AFB, Montana	Clayey Sandy GRAVEL	GC	45	36	22	17	12	43	25
SPK-1	Spokane AFB, Washington	Gravelly SAND	SP-GP	68	11	7	4	1	Non-Plastic	
PBJ-13	Greenland	Gravelly SAND	SW	54	32	10	4	2	"	"
PBJ-3	Greenland	Silty Gravelly SAND	SM	71	46	10	4	2	"	"
PBJ-9			SM	82	53	21	7	3	"	"
PA-1	Pierre Airfield, South Dakota	Silty Gravelly SAND	GM-SM	68	31	17	9	4	25	7
PAFB-8	Portsmouth, New Hampshire	Silty Gravelly SAND	SM	68	45	23	14	6	Non-Plastic	
CA-3	Casper AFB, Wyoming	Silty Gravelly SAND	SM	92	47	23	15	11	22	5
TD-5	Truax AFB, Wisconsin	Silty Gravelly SAND	SM	92	79	28	16	9	Non-Plastic	
PBJ-7	Greenland	Silty Gravelly SAND	SM	70	54	31	18	8	16	4
TD-6	Truax AFB, Wisconsin	Silty Gravelly SAND	SM	92	78	35	21	11	14	2
AFS-1	Alaska	Silty SAND	SM	100	100	33	3	0	Non-Plastic	
AFS-2			SM	100	100	33	3	0	"	"
PAFB-7	Portsmouth, New Hampshire	Silty SAND	SM	98	94	29	8	4	"	"
HF-1	Hill AFB, Utah	Silty SAND	SM	100	94	27	13	8	"	"
CA-1	Casper AFB, Wyoming	Silty SAND	SM	98	62	21	16	12	22	6
CA-2			SM	97	67	29	18	14	22	5
FA-1	Fargo Airfield, North Dakota	Clayey SAND	SC	98	34	16	9	6	31	11
PBJ-1	Greenland	Clayey SAND	SC	73	55	35	22	15	25	8
LA-1	Lowry AFB, Colorado	Clayey SAND	SC	99	86	36	24	17	24	8

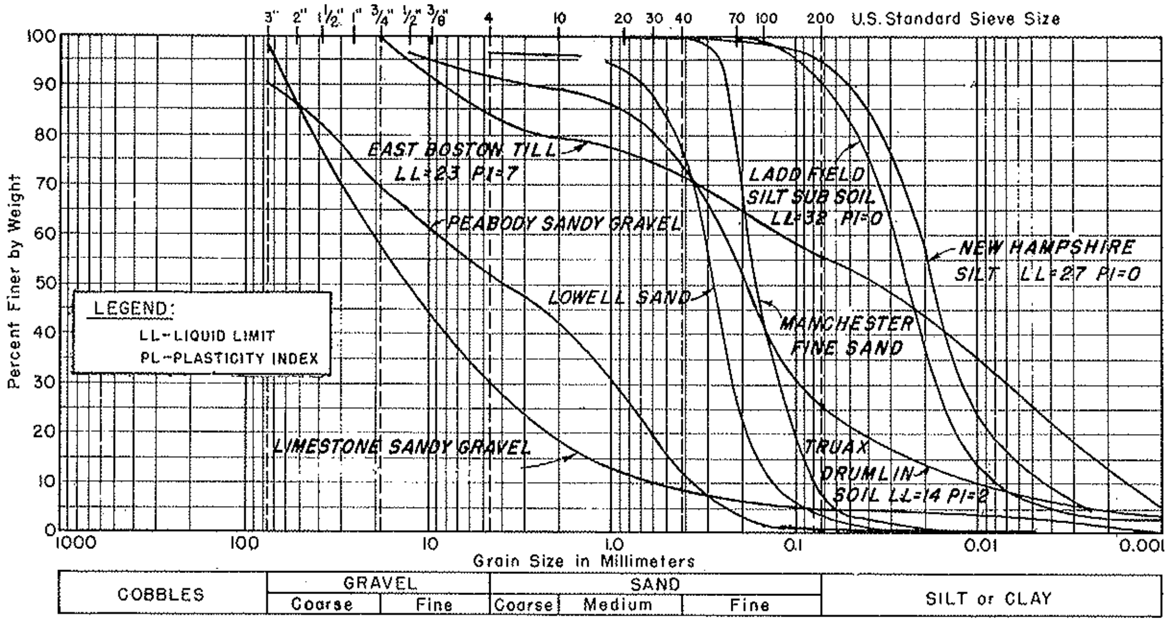


Figure 2. Conditions of soils used to prepare soil blends for the study of effect of percentage finer than 0.02 mm.

weakening would be slight and of short duration.

Effect of Percentage and Size of Aggregates Greater than 2.0 mm. in Soil Gradation

In applying the present criteria for frost-susceptible soils, questions have frequently arisen concerning the effect of the percent and gradation of the coarse soil fraction on ice segregation. The inclusion or exclusion of even a small number of gravel sizes, (2- to 4-in. diameter) in a 25-lb. sample from a proposed base course borrow area or a construction control sample, can appreciably affect the indicated over-all percentage, by weight, of sizes finer than 0.02 mm.

A series of tests were performed using Limestone sandy gravel and Truax Drumlin soil, the gradations of which are shown in Figure 2. Desired investigational gradations were obtained by scalping the maximum size aggregate in increments from the 2-in. size down to the 10-mesh sieve, and allowing the percentage of fines to increase as the maximum sizes were removed. The weight of grains finer than 0.02 mm. range from 3 to 22 percent. The average rates of heave recorded for these tests, plotted in relation to percentage finer than 0.02 mm., are shown in Figure 5. As the percentage of the total sample finer than 0.02 mm. is increased by the removal of stone, the rate of heave increased in the same manner as if the weight of coarse fraction had been kept constant, and fines added to increase the percentage finer than 0.02 mm. It is apparent, therefore, that the addition of coarse sizes to a given soil would result in a proportionate decrease in percentage finer than 0.02 mm. with consistent decrease in over-all heave potential. The coarse aggregate in a frost-susceptible soil appears to have the function of an inert filler, which reduces the volume of the frost susceptible matrix and effects a reduction in heave of the total soil mass. Whether such lesser over-all heave represents a reduction in bearing capacity in the spring is a matter for further consideration.

In a limited test series in which the maximum size or percentage of coarse fraction was altered while holding the percentage finer than 0.02 mm. constant, there appeared to be no effect of maximum size or percentage of coarse fraction within the range of gradations tested (2 in. to ¼-in. maximum size). When the percentage finer than 0.02 mm. was kept nearly constant, the rate of heave did not change appreciably, all other conditions being equal.

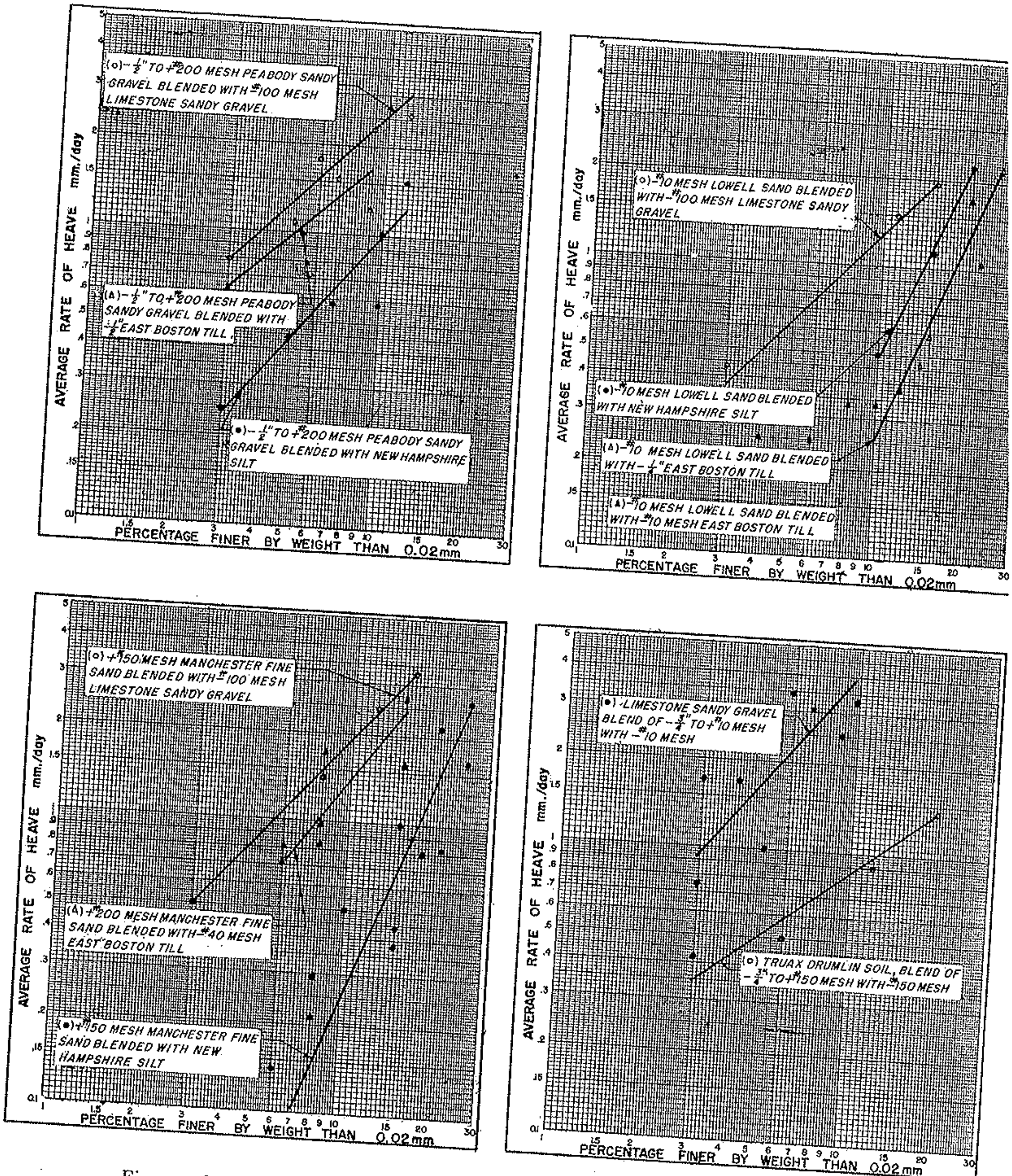


Figure 3. Relationship between rate of heave and percentage finer than 0.02 mm. using soil blends.

Effect of Variation in Dry Unit Weight

In a given soil, variation in the dry unit weight may be used to study the combined effect on ice segregation of such soil characteristics or conditions as permeability, void size, and internal structure. Freezing tests were performed on various soil types to study the effect of initial dry unit weight on intensity of ice segregation.

Plots of rate of heave versus ranges of dry unit weight are shown in Figure 6. The gradation and percentage of fines in the samples were held constant while the initial dry weights of the specimens

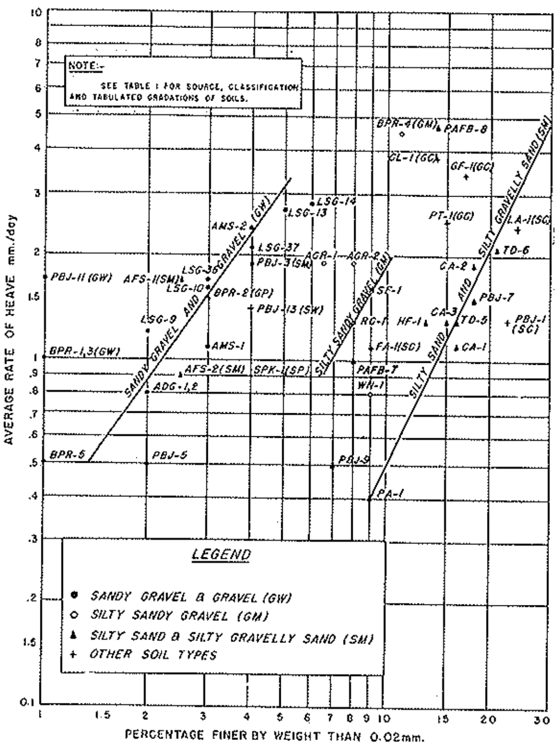


Figure 4. Relationship between rate of heave and percentage finer than 0.02 mm. in natural soils.

before freezing were varied. The results indicate that heaving increases with increase in original dry unit weight for inorganic silt soils, such as New Hampshire silt and Ladd Field subsoil for the full range of unit weights attainable in the laboratory specimens. Tests on East Boston till show increase in heaving with an increase in dry unit weight, up to 120 lb. per cu. ft. followed by a decrease in heaving with further increase in dry unit weight. Truax Drumlin soil and Limestone sandy gravel show increased heaving with an increase in dry unit weight up to approximately 130 lb. per cu. ft., followed by a gradual decrease in heaving with further increase in dry unit weight. The results of tests on sandy soils, such as Manchester fine sand, Indiana dune sand, and Alaska fine sand, show negligible variation in heave with change in density. Clayey sand from Fargo AFB shows an apparent decrease in heave with increase in initial dry unit weight.

From the standpoint of decreasing the effects of frost action, there appears to be no advantage in compacting the soils tested, except possibly the well-graded soils. The advantage of getting a high degree of compaction in these latter soils is, however, questionable; if the soils are not made virtually non-frost susceptible by the compaction, a loosening of the soils could result after a few freezing cycles.

Effect of Surcharge

A series of tests have been performed to determine the effect of surcharge on ice segregation in soils of various gradations. Surcharge loads of 0, ½, 1, 2, 3, 4, and 6 psi. were placed on 6-in.-diameter specimens during freezing. Plots of average rates of heave versus intensity of surcharge are presented in Figure 7. The test data indicate the average rate of heave decreases with increases in the surcharge load for the soils tests. In using a semilogarithmic plot, the data are arranged along a series of lines which are nearly parallel.

Additional testing of a wider range of soil gradations is believed necessary before attempting to generally apply the relationships determined in this test series. Although this test series indicates the rate of heave for a soil with an overburden pressure of 6 psi. is only of the order of 10 percent of the rate of heave with a 0.5-psi. overburden pressure, it is visualized that the effect of overburden in decreasing rate of heave in the field may be counterbalanced by a closer proximity to the ground-water table. Also, the total heave per unit depth in the field usually increases with depth as the rate of frost penetration is reduced.

Tests are continuing in this series to evaluate the magnitude of frictional restraint on heaving offered by the specimen

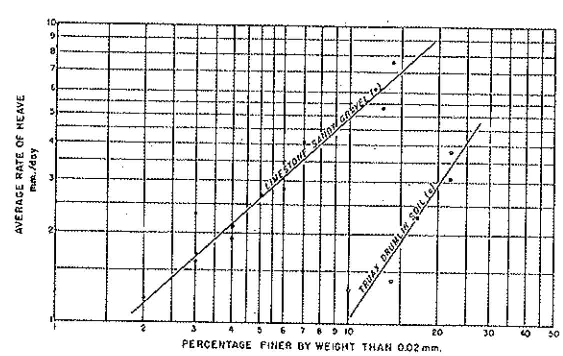


Figure 5. Effect of varying percentage of coarse fraction on rate of heave.

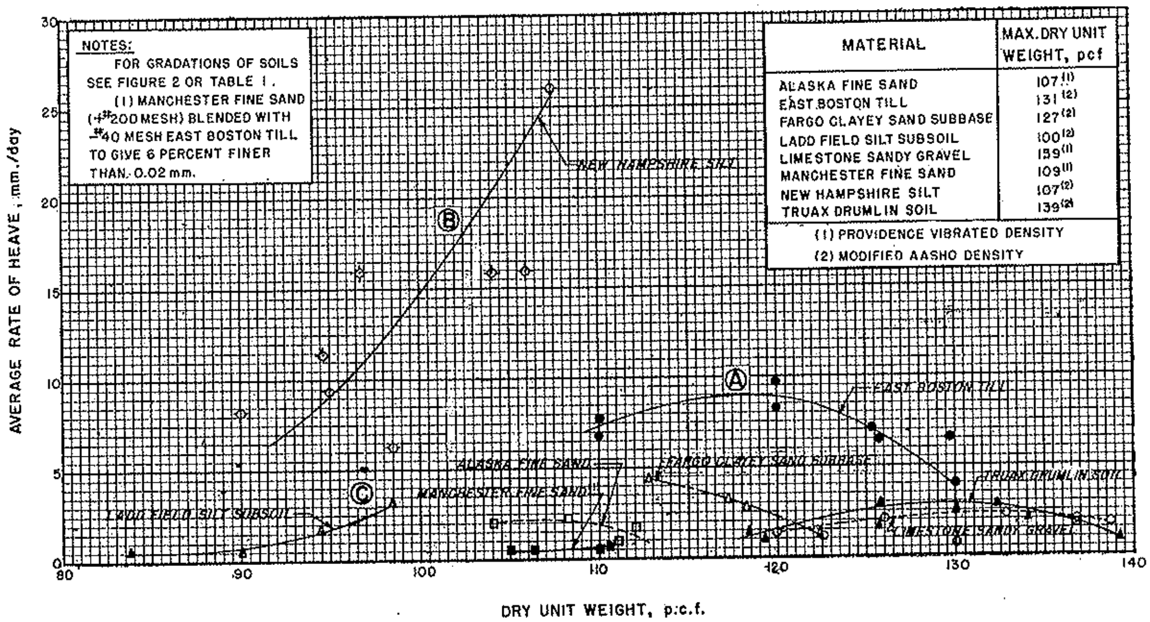


Figure 6. Effect of variation in dry unit weight.

containers, together with a study of methods of minimizing the frictional forces. Studies are also planned to determine the effect of surcharge on delaying the start of freezing of the specimens, and a possible effect in the alteration of the freezing point of soil moisture.

Effect of Rate of Penetration of 32 F. Temperature

A series of tests has been made to determine the effect of various rates of penetration of the 32 F. temperature on ice segregation in frost-susceptible soils of various gradations. Nominal penetration rates of ¼, ½, ¾ and 1 in. per day were used in the test. A summary plot showing rate of penetration of 32 F. temperature and average rate of heave is shown on Figure 8, together with the grain-size-distribution curves of the eight materials used in the test series.

The results of this test series indicate that, superficially at least, the rate of heave is approximately independent of the rate of penetration of the 32 F. temperature for the range investigated, ¼ to 1¾ in. per day. Though the data for Dow AFB clay apparently shows the rate of heave to decrease with increase in rate of 32 F. temperature penetration, the undisturbed samples of Dow clay used for testing contained many fissures due to weathering which may account for the results not being comparable to the results of the other tests in the series.

This test series, besides demonstrating that the rate of heave does not vary appreciably with rate of freezing, within the range of tests, also shows conversely that the total percentage of heave of the frozen material and the intensity of ice segregation should vary directly with the rate of freezing. This has been observed in field explorations where the greatest accumulation of segregated ice results from slow penetration of freezing temperatures. Thus, for example, if the rate of penetration of the freezing temperature is reduced to one half, with the heave per day remaining constant, the heave for any one day will represent the freezing of only half as much of the original soil, and the expansion of that soil per unit depth must be doubled, with twice as much segregated ice, in order to maintain the rate of heave.

Freezing Point of Soil Moisture

Previous laboratory studies by Bouyoucos (4) at Michigan State College and others have demonstrated that the freezing point of soil moisture in fine-grained soils is generally below 32 F. and for a given fine-grained soil the freezing point decreases with decrease in water content.

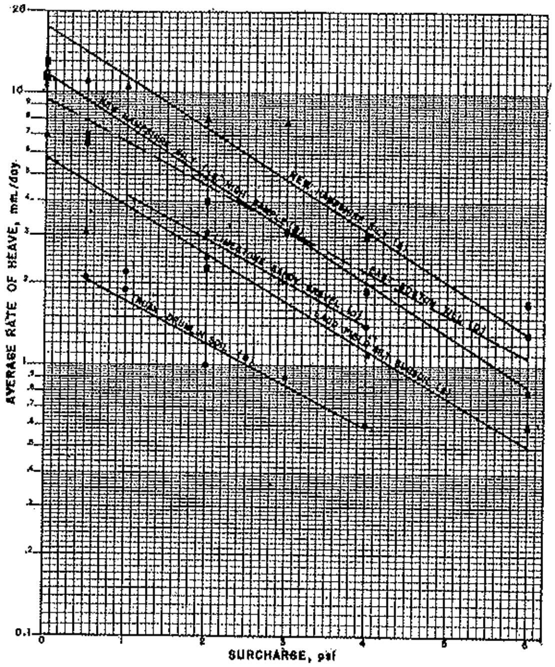


Figure 7. Effect of surcharge.

Most investigators attribute the depressed freezing point of soil moisture to: (1) soluble salts in the pore water and (2) the adsorptive forces by which the water is held to the soil grains. Pore water at the center of the interstices is considered to freeze at a higher temperature than the water closer to the surfaces of the fine soil grains.

The freezing point of soil moisture has been determined by the Frost Effects Laboratory by measuring with thermocouples the temperature at the visual boundary between frozen and unfrozen soils in test pits and cold-room test samples. For proper correlation of these results, however, comprehensive laboratory studies are required to analyze the effects of such factors as moisture content, dry unit weight, soil mineral characteristics, and the dynamics of the freezing process. Exploratory laboratory studies, therefore, were initiated to obtain test techniques and the freezing history of several soil types at varying moisture content. The soils selected for this exploratory test series were Lowell sand, Manchester fine sand, New Hampshire silt, and Boston blue clay. Each soil type was prepared at several water contents by adding distilled water to the oven-dried materials, with the exception of the clay soil, which was air-dried. Test specimens were prepared by placing each sample into a ¾-in.-diameter copper tube, 3.5 inches long, with a thermocouple inserted at the midpoint of the sample. A cross section showing the details of the test specimen is shown on Figure 9. These specimens were placed in a freezing cabinet held at a constant temperature and the temperature change within the sample measured continuously throughout the freezing cycle. Typical temperature-time plots for a specimen of Boston blue clay and Manchester fine sand are shown on Figure 9 together with pertinent test conditions. The grain-size distribution curves in these samples are contained in Figure 2. It is noted that during the initial stages of cooling, the temperature of the specimens dropped at a relatively constant rate to a temperature considerably below 32 F. and then suddenly rose to a higher temperature. In the case of Manchester fine sand, the temperature rose to 32 F. and remained constant for approximately 25 min. and then the temperature dropped off at a relatively constant rate. On the other hand, the temperature of the clay specimen rose to 29.7 F., then immediately began to decrease with time.

The sudden temperature rise in the specimens after they have been lowered below 32 F. is attributed to the start of crystallization of the supercooled pore water. The temperature at which the crystallization starts appears to be principally controlled by factors outside of the test specimens, since there does not appear to be a direct correlation between soil type, moisture content and this temperature. Outside effects such as vibrations appear to cause the initial crystallization in the pore water. It is recognized that the characteristics of the pore water and the presence of nuclei for initiation of crystal formation have an important influence on the temperature of initial crystallization.

The same phenomenon of supercooling has been observed in the cold-room test specimens that are frozen at a constant rate of penetration of the 32 F. temperature. The start of crystallization causes a rise of temperature in the upper portion of the sample after the 32 F. temperature has penetrated 2 to 3 in. below the surface

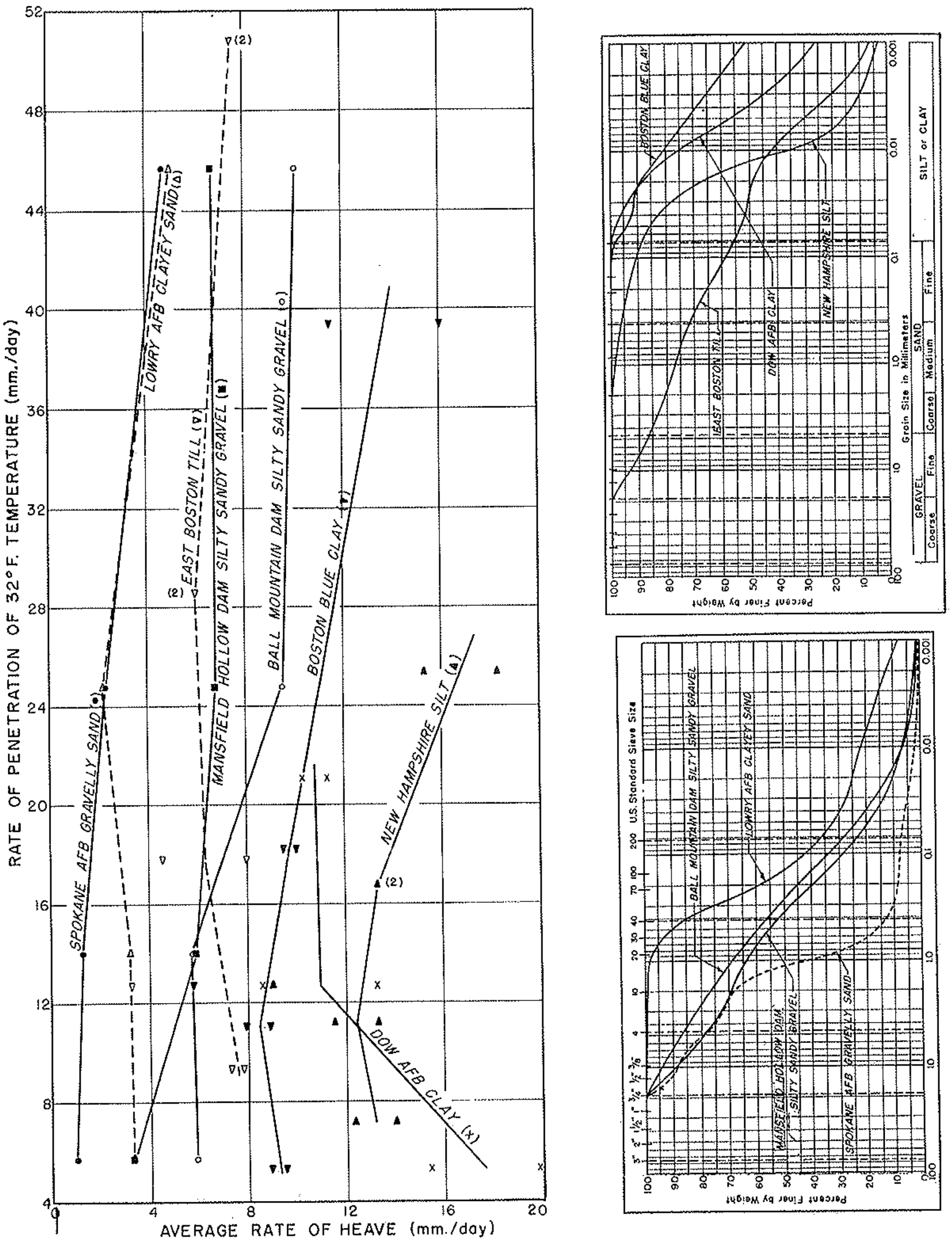


Figure 8. Effect of rate of freezing.

of the specimen. In order to prevent this effect and attain a more uniform rate of freezing-temperature penetration, the top of the samples are seeded with ice flakes at the time the 32 F. temperature penetrates slightly below the surface of the specimens.

Figure 9, together with results of other tests in this series, indicate that the temperature to which the specimens rise after start of crystallization is a function of soil type and water content. The specimens prepared using the two sand soils and the inorganic silt soil, rose to a temperature of 32 F. and the temperature remained constant for a period of time which was a direct function of moisture content. It is visualized that in these soils, after the start of crystallization and rise of temperature, virtually all of the pore water froze at 32 F. with the release of latent heat maintaining constant specimen temperature. In the specimens of clay soil the temperature to which the specimens rose after start of crystallization is a function of moisture content. For moisture contents of 11, 17, and 21.5 percent, the maximum temperatures reached after start of crystallization were 26.8, 29.7, and 30.8 F., respectively. After reaching these temperatures, the specimen temperatures then gradually decreased, indicating that the latent heat of soil moisture was not being released at a constant temperature but that only a portion of the soil moisture became available for freezing as the specimen temperature was lowered. The curvature of the temperature-time curve for this portion of the freezing cycle indicates that a smaller and smaller quantity of water is available to freeze as the temperature is lowered, otherwise the temperature-time plot would tend to become asymptotic to the temperature of the freezing cabinet.

This test series is being contained at the present time with consideration being given to the minerals present in the fine soil fraction. Since the surface of the clay minerals provides the major absorption surface, the thickness of the absorbed films and the absorption characteristics towards water in various ions and organic molecules vary for different clay minerals. The surface area of the soil grains should also be considered since grains of similar size but different mineral composition have widely different surface areas.

Information on the freezing point of moisture in soils is required because of the influence of this factor on the theoretical prediction of depth of frost penetration. Present theoretical methods either assume the soil moisture freezes at 32 F. or at some constant temperature below 32 F. Increased knowledge of the freezing point of soil moisture will aid our insight into the phenomena of ice segregation.

Effect of Initial Degree of Saturation In a Closed System

A series of tests was performed to determine the effect of initial degree of saturation on ice segregation in frost-sysceptible soils in a closed system, i. e., a system in which no water is made available to the bottom of the sample.

The soils used in this test series and the pertinent results obtained are summarized in Table 2. The tabulated data indicated that the water content at the top of the sample after freezing varies directly with the initial degree of saturation. The water content at the bottom of the sample decreased to a relatively constant value which appears to be independent of the initial degree of saturation within the range tested. The water content in the unfrozen zone of the undisturbed and remolded lean clay specimens decreased approximately to the shrinkage limits, as water was supplied for ice-lens growth to the zone of freezing. However, in remolded and undisturbed inorganic silt and remolded glacial till samples, the water content of the unfrozen zone decreased considerably below the shrinkage limits with the greatest decrease being in the New Hampshire silt.

The test results demonstrate that an outside source of free ground water is not a requisite for frost action in soils. The need of water for ice segregation can be satisfied to the extent that water is obtainable through a decrease in the moisture content of the material directly beneath the zone of freezing. The increase in water content at the top of the samples in the cold-room test is not necessarily considered quantitatively representative of the results that would occur in nature, since the samples were only 6 in. in height. In nature, of course, water may be supplied for ice segregation from soil at much greater depths. Plastic soils, tested in the closed system, exhibited a tendency to shrink in diameter and pull away from the container at the lower portions of the specimens.

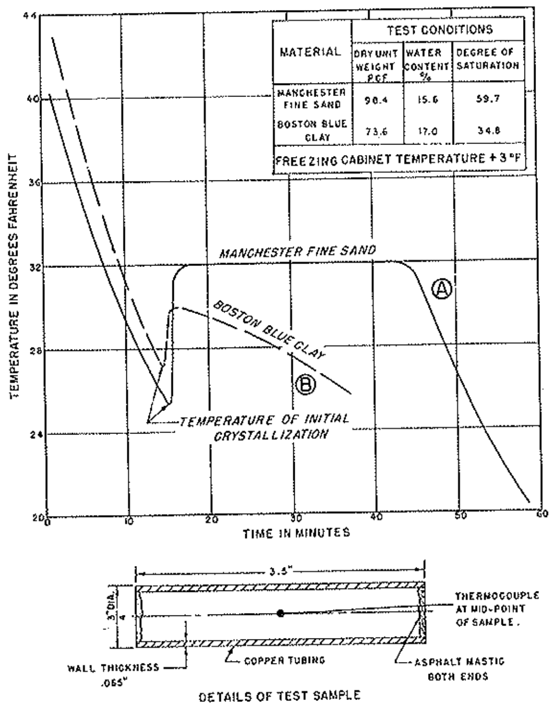


Figure 9. Plot of temperature change during freezing cycle.

Presence of an appreciable consolidating force in the lower portions of all samples is indicated by the marked decrease in water content at bottom of the samples, as compared with the original water contents. In nature, it is visualized that there would be a tendency for vertical shrinkage cracks to develop in plastic soils, particularly during the initial freezing cycle. The lateral shrinkage in the field, however, would probably be minimized due to the restraint offered by the materials above and below the zone of shrinkage.

Effect of Mineral Composition of Soil Fines

The tests performed to determine the effect of percent finer than 0.02 mm. on ice segregation in soils indicated that the particle size and distribution of the nature of the fines (minus 200 mesh) influenced the formation of ice lenses in a soil. To explore the relation between the mineral composition of the fines and frost susceptibility, the identity and percentage of each of the mineral constituents present in the fines were determined by the differential thermal analyzer (5). Also, the surface area per unit mass of the minus-200-mesh soil fractions were determined by the ethylene-glycol-retention test (6).

In the series of tests discussed under paragraph entitled "Effect of Percentage Finer than 0.02 mm.," the fines from Limestone sandy gravel were found to be more effective in producing ice segregation than the fines from East Boston till and New Hampshire silt. The Limestone sandy gravel fines (minus 200 mesh) had 40 percent kaolinite and 20 percent illite; the East Boston till fines 20 percent kaolinite and 40 percent illite; and the New Hampshire silt fines were composed of 55 percent quartz with no kaolinite, montmorillonite, or illite. This might appear to indicate that kaolinite has somewhat greater frost susceptibility. However, the fines from these soils were not of similar gradation, as shown in Figure 2, which also may account for the difference in ice segregation in the specimens into which they were blended. Also, correlation of the mineral composition of the minus 200 mesh with intensity of ice segregation in the soil blends and natural soils tested is complicated by the fact that there were usually several types of minerals present and differences in the total percentage of fines present in the soils being compared.

In order to isolate some of the variables, a series of tests is currently in progress in which small percentages of 12 different monomineral fines are each blended into a non-frost-susceptible sand to study the effect on ice segregation. Montmorillonite, one of the monominerals in this series, has been prepared with six different exchangeable cations. The principal indications so far obtained from this test series are that:

(1) The nature of fines is important.

(2) The percentage heave for the fines of the three common clay-mineral groups

TABLE 2

EFFECT OF INITIAL DEGREE OF SATURATION
(CLOSED SYSTEM)

SAMPLE NUMBER	SOURCE OF SOIL	CORPS OF ENGINEERS UNIFORM SOIL CLASSIFICATION		GRAIN SIZE PERCENTAGE FINER THAN					ATTERBERG LIMITS (1)			DRY UNIT WEIGHT	WATER CONTENT DETERMINATIONS IN PER CENT					PER-CENTAGE HEAVE
													TOTAL SAMPLE BEFORE FREEZING		AFTER FREEZING			
															FROZEN ZONE		UNFROZEN ZONE	
		DESCRIPTION	LETTER SYMBOL	#4 SIEVE	#40 SIEVE	#200 SIEVE	0.02 mm.	0.005 mm.	Lw	Iw	Sw	pcf.	WATER CONTENT	G (2)	TOP INCH	SOIL BETWEEN ICE LENSES		
TD-15	Truax AFB, Wisconsin	-3/4" Silty Gravelly SAND (Remolded)	SM	93	78	35	21	11	14	2	-	130	7.8	70	8.3		-	0.0
TD-16												130	7.7	69	9.3		-	0.0
TD-17												130	9.7	89	10.0		-	1.0
TD-18												130	10.9	99	13.7		6.5	5.1
PAFB- 9	Portsmouth, New Hampshire	-3/4" Silty Gravelly SAND (Remolded)	SM	87	58	29	18	8	Non-Plastic		-	126	8.9	71	15.5		5.2	1.3
PAFB-10												128	9.3	80	15.1		4.8	1.7
PAFB-12												125	11.4	88	22.4		4.7	6.8
PAFB-11												128	11.0	92	22.0		4.6	7.1
NH-48	Goff's Falls, New Hampshire	SILT (Remolded)	ML	100	100	85	62	16	24	6	22	102	22.8	91	38.2	33.7	2.2	7.8
NH-49												103	23.4	96	43.5	34.3	2.7	9.[illegible]
LFT- 1	Fairbanks, Alaska	SILT (Undisturbed)	ML	100	100	94	40	12	33	6	22	97	26.8	100	45.0		6.8	15.1
EBT-40	East Boston, Massachusetts	-3/4" Gravelly Sandy CLAY (Remolded)	CL	82	65	46	32	22	23	8	12	128	11.9	96	20.2	12.7-15.9	7.6	8.6
EBT-41												128	12.2	98	20.6	15.1-22.1	10.0	7.3
EBT- 5				84	72	56	44	26	23	7	-	125	9.5	70	10.6		-	0.3
EBT- 6												126	10.9	81	13.7		-	1.8
EBT- 7												125	12.2	90	13.7		-	2.3
EBT- 8												127	12.9	100	20.9		-	4.7
DFC- 1	Dow AFB, Maine	CLAY (Remolded)	CL	99	98	93	72	40	34	17	-	115	18.0	100	23.1		14.9	9.7
DFC- 2												111	13.3	68	18.4		-	2.0
DFC- 3												113	15.2	82	21.5		-	1.5
DFC- 4												113	17.1	92	20.9		-	2.7
DFC- 5												119	16.3	100	23.9		-	7.5
SC- 4	Searsport, Maine	CLAY (Undisturbed)	CL	100	100	99	80	12	36	18	-	95	28.0	95	33.8		18.1	5.8
SC- 5												97	27.0	95	28.8		15.8	7.3
SC- 3												97	27.3	96	34.6		17.5	4.5
SC- 8		CLAY (Remolded)	CL	100	100	99	80	12	36	18	18	97	27.0	95	35.6		17.5	9.7
BC-19	North Cambridge, Massachusetts	CLAY (Undisturbed)	CL	100	100	100	94	81	53	26	25(3)	86	34.3	94	51.1		21.8	11.1
BC-18												86	34.0	94	46.5		21.5	8.9
BC-22												85	35.8	96	52.3	29.1-33.4	18.9	10.7
BC-21		CLAY (Remolded)	CL	100	100	100	94	81	53	26	21	88	35.2	100	48.0	20.1-21.2	19.9	11.0

NOTES:
(1) Lw - Liquid Limit
Iw - Plasticity Index
Sw - Shrinkage Limit
(2) Degree of Saturation in Per Cent.
(3) Undisturbed Shrinkage Limit.

decreased in the order of kaolinite, illite, and montmorillonite. This is the order that one would expect from permeability considerations, since the permeabilities vary in the same order. This result was predicted by Grim (7).

(3) Specimens, in which the fines consisted of montmorillonite with Fe++ as the exchange cation, showed greater heave than other specimens prepared with montmorillonite fines, with sodium montmorillonite giving the lowest percentage of heave. This also is as expected based on lesser permeability and greater thickness of absorbed water layers in sodium montmorillonite.

(4) Carbonate fines were generally found to be the most effective in producing ice segregation.

(5) Finally, the highest percentage heave occurred with fines of attapulgite.

Effect of Admixtures

Limited studies were made by the Frost Effects Laboratory from 1944 to 1946 to determine the effectiveness of calcium chloride, sodium chloride, and various bituminous materials in preventing ice segregation in soils. It was found that the soluble salts tended to be leached out of the soil after a few cycles of saturation and drainage, and therefore, field treatments with these materials would only be of temporary benefit. It was found that ice segregation could be prevented by the addition of sufficient bitumen to render the soil impervious. However, the quantity required to reduce ice segregation to a negligible amount approached the bitumen content commonly employed for construction of bituminous pavements. Cold-room studies performed in 1950 indicated that the admixture of calcium acrylate was very effective in preventing ice segregation in a clay soil but was not as completely successful in a silt soil.

From the results of other test series, it is evident that changing the permeability of a soil is accompanied by a change in the intensity of ice segregation. In the case of the coarser grained frost-susceptible soils, such as inorganic silts, the intensity of ice segregation decreases with decrease in unit dry weight and increase in permeability. In borderline frost-susceptible soils, reducing the percentage of the fine-particle fraction reduces frost heaving. On the other hand, in the finer-grained plastic soils there appears to be a decrease in frost susceptibility with decrease in permeability, with a specimen of bentonite showing negligible frost heaving. Also, remolding lean clay soils has been found to reduce the rate of heave to less than half those for specimens of undisturbed material; the permeability in the remolded state is in the order of 1/200 of that in the undisturbed state.

Recent advances which have been made in knowledge of the properties of clay minerals and base exchange characteristics of soils give somewhat greater promise of success to our quest for admixtures than was previously possible. T. William Lambe, of Massachusetts Institute of Technology and director of the Soil Stabilization Laboratory, was retained by contract to search for admixtures which he considered to have desirable characteristics from the standpoint of minimizing or preventing ice segregation in soils.

There are several possible means by which soils, at least theoretically, can be made less susceptible to frost action. One such method would be to prevent or inhibit the migration of water necessary for ice lens formation. This might be accomplished by use of an admixture that will: (1) fill the soil voids to the extent necessary to cut off moisture migration; (2) increase the adsorptivity of soil grains for water, thereby decreasing the channels in the soil available for flow; (3) absorb large quantities of water, thereby reducing the channels in the soil available for flow; (4) reduce the attractive forces between soil grains so the soil will disperse and may be compacted more readily to a greater unit weight thus decreasing the volume of voids and permeability.

A second method of treatment by use of admixtures is suggested by the susceptibility of a sandy material that is effected by removal of the fine particle fraction. This removal of fines can be brought about, to some extent, by causing the small particles to stick together and thereby form large particles. Also, treatment of inorganic silt soils with an admixture to join grains together would, in effect, increase the effective grain size, increase the permeability, and thus, tend to decrease frost susceptibility.

The cold-room studies in connection with this phase of the investigation have not advanced, at the present time, past the exploratory stage. The search for potentially suitable admixtures is concentrated on obtaining a material which, mixed with a soil in a very small quantity (less than 1 percent of the dry weight of soil) will permanently alter the forces between particles in the hope of decreasing the frost-susceptibility characteristics of the soil. Michaels (8) has described a number of mechanisms by which admixtures can cause forces of attraction or repulsion between particles and thereby either aggregate or disperse soil grains.

The available test data show that dispersing agents effectively reduce frost heaving in soils. Additional testing is required, however, to determine the most-effective percentage of admixture and the permanence of treatment. The following tabulation illustrates the effects of dispersing agents on frost heaving of laboratory specimens:

FROST-HEAVE DATA

Soil	Admixture	Admixture % of dry soil wt.	Percentage Heave
New Hampshire silt	0		150
	Sodium polyacrylate	0.05	37
	" "	0.10	69
	Sodium tetraphosphate	0.10	49
	" "	0.50	32
Fort Belvoir sandy clay	0		22
	Sodium polyacrylate	0.10	23
	" "	0.50	16
	Sodium tetraphosphate	0.30	5
	" "	1.00	3

In addition to the study involving aggregants and dispersing agents, freezing tests are being performed on soil specimens which have been treated with chemicals that waterproof the soil grains. The tabulation at the top of column 2 on this page illustrates the effect of adding small percentages of water-proofers to Boston blue clay.

Much additional data on the effect of admixtures on frost susceptibility must be accumulated before acceptance of these methods of treatment. Consideration also must be given to methods of mixing the additive into the soil in the field and the cost of material and equipment required for such treatment.

FROST-HEAVE DATA ON BOSTON BLUE CLAY

Admixture	Admixture % of Dry soil wt.	Percentage Heave
Sodium methyl siliconate	0.1	3.5
	0.5	0.5
	1.0	0.6
Methacrylate-chromic chloride	0.1	9.0
	0.5	6.4
	1.0	1.3
Stearato-chromic chloride	0.1	18.3
	0.5	12.5
	1.0	5.1
No admixture	0	20 +

Other Cold-Room Studies in Progress

In addition to the test series which have been summarized in the foregoing paragraphs, cold-room studies are currently in progress at the Frost Effects Laboratory on other phases of the frost problem. These investigations which are either not within the scope of this paper, or the available data are insufficient for reporting include: (1) investigations of the effect of proximity to water table on ice segregation; (2) controlled-freezing tests for correlation with theoretical frost penetration formulas; (3) investigation of strength and consolidation characteristics of thawing soils; (4) determination of percentage of water frozen in soils by calorimetric method; (5) determination of thermal conductivity of soils by transient-heat method using thermal probes; and (6) crystallographic studies of segregated ice phase in frozen soil.

ACKNOWLEDGMENTS

The Frost Investigations of which these cold-room studies are a part are being conducted by the Frost Effects Laboratory for the Airfields Branch, Engineering Division, Military Construction, Office of the Chief of Engineers. These studies are under the administration of Gayle McFadden, Chief, Airfields Branch assisted by Thomas B. Pringle, Head, Runway Section, and by Frank Hennion.

Colonel L. H. Hewitt is the division engineer, New England Division, Corps of Engineers, U. S. Army. John E. Allen is Chief of the Engineering Division to which the Frost Effects Laboratory is attached. Kenneth A. Linell is chief of the Frost Effects Laboratory. The studies are under the direct supervision of the writer.

Arthur Casagrande, Harvard University; P. C. Rutledge, Moran, Proctor, Meuser & Rutledge; and K. B. Woods, Purdue University, are the investigational consultants. Acknowledgment is also made to T. William Lambe of Massachusetts Institute of Technology, who was engaged as a consultant on studies of effect of mineral composition of soil fines and investigations of admixtures to prevent or minimize frost action in soils.

REFERENCES

1. Frost Effects Laboratory, New England Division, Corps of Engineers, U. S. Army, Boston, Massachusetts, "Report on Frost Investigation 1944-1945", dated April 1947.

2. Frost Effects Laboratory, New England Division, Corps of Engineers, U. S. Army, Boston, Massachusetts, "Frost Investigation 1945-1947. Addendum No. 1 to Report on Frost Investigation 1944-1945", dated June 1948.

3. Haley, James F. and Kaplar, Chester W., "Cold Room Studies of Frost Action in Soil", Highway Research Board Special Report No. 2, 1952, "Frost Action in Soils, A Symposium", pp. 246-267.

4. Bouyoucos, G. J., "Soil Temperatures" Michigan Agricultural College, Experimental Station, Technical Bulletin, No. 26, Jan. 1916, 133 pp.

5. Kerr, P. F., Kulp, J. L., and Hamiton, P. K., "Differential Thermal Analyses of Reference Clay Mineral Specimens", American Petroleum Institute Report of Project 49, New York, 1951.

6. Dyal, R. S. and Hendricks, S. B., "Total Surface of Clays in Polar Liquids as a Characteristics Index", Soil Science, Vol. 69, June 1950.

7. Grim, Ralph E., "Relation of Frost Action to the Clay Mineral Composition of Soil Materials", Highway Research Board Special Report No. 2, 1952, "Frost Action in Soils, A Symposium", pp. 167-172.

8. Michaels, Alan S., "Altering Soil-Water Relationships", Proceedings of Conference on Soil Stabilization, Massachusetts Institute of Technology, June 1952.

Frost Design Criteria for Pavements

KENNETH A. LINELL, Chief, Frost Effects Laboratory,
New England Division, Corps of Engineers

THE increases in traffic and wheel loadings on airfield and highway pavements in the past 10 to 15 years; the rising costs of pavement construction, maintenance, and repair; the greater need for maintaining pavements in fully serviceable condition at all times; and the increasing of operating speeds have made it necessary to consider frost action in greater detail in pavement design. This paper describes criteria formulated by the Corps of Engineers to meet the needs of its construction in areas of seasonal frost.

The variation of subgrade strength through the seasons is illustrated, and it is indicated that the frost-melting period is critical when conditions are conducive to active frost action. Methods for recognition of conditions of soil, temperature, and moisture which result in detrimental frost action are described. Base composition requirements are given. Load design charts for airfield and highway flexible pavements for various types of loadings are presented. Load-design criteria for rigid pavements are also given. The application of these methods is illustrated by means of design examples. Needed studies to further improve the present design criteria are discussed.

● THE detrimental effects of frost action in subsurface materials are manifested by heave of pavements or other structures during the winter and by loss of strength of affected soils with a corresponding reduction in load-supporting capacity during the period of weakening which ensues. In pavements, these effects may result in unsatisfactory riding qualities, excessive maintenance, hazardous operational conditions, or pavement breakup.

In highways, the great increases in traffic and wheel loads in the past decade may cause pavements which formerly appeared adequate to deteriorate in the spring. The interruption or slowing of traffic and damage to equipment which may result from frost action involves much more money value under the increased traffic conditions than in the past. The corresponding cost for maintenance, repair, and rebuilding of frost-damaged pavements is also increased.

On airfields, the great increases in wheel loadings have created problems not encountered on highways, because of deeper and more intense stressing of the subgrade. There must also be considered the possibility of damage or hazard to expensive present-day planes and their crews. This involves the necessity for maintaining smooth surfaces on runways where speeds may exceed 100 mph.

Thus, the detrimental effects of frost action must be taken into account in pavement design. At the same time, we must strive to avoid over design, since every extra inch of pavement structure will add enormously to the cost of pavements when multiplied over all highway and airfield pavements constructed over soils subject to the frost action.

The present paper describes frost design criteria developed by the Corps of Engineers to meet design needs in areas of seasonal frost action. The criteria are based on the assumption that permanent military pavements should be designed so that there will be no interruption of traffic at any time of the year due to differential heave, reduction in load-supporting capacity, or deterioration of the pavement resulting from frost action.

The criteria have been developed in the Frost Effects Laboratory, New England Division, Boston, Massachusetts, for the Airfields Branch, Engineering Division, Military Construction, Office of the Chief of Engineers, U. S. Army. The studies are continuing, and it is anticipated that improvements will be made in the criteria from time to time in the future.

DEFINITIONS

The following specialized terms are used in this paper:

Degree-day is each degree in any one day that the average daily air temperature varies from 32 F. The difference between the average daily temperature and 32 F. equals the degree days for that day. The degree days are minus when the average daily temperature is below 32 F. and plus when above. A cumulative degree-days-time curve is obtained by plotting cumulative degree-days against time as illustrated in Figure 2.

Freezing index is the number of degree-days between the highest and lowest points on the cumulative degree-days-time curve for one freezing season (see Fig. 2). It is used as a measure of the combined duration and magnitude of below-freezing temperatures occurring during any given freezing season. The index determined for air temperatures at 4.5 ft. above the ground is commonly designated as the air freezing index, while that determined for temperatures immediately below the surface is known as surface freezing index.

Mean freezing index is the freezing index determined on the basis of mean temperatures.

Frost action is a general term used in reference to freezing and thawing of moisture in materials and the resultant effects on these materials and the structures of which they are a part or with which they are in contact.

Ice segregation in soils is the growth of ice as distinct lenses, layers, veins, and masses; commonly, but not always, oriented normal to the direction of heat loss.

Frost boil is the breaking of a highway or airfield surface under traffic and ejection of subgrade soils in a soft and soupy condition caused by the melting of the segregated ice formed by frost action.

Frost heave is the raising of a surface due to the formation of ice in the underlying soil.

Frost-melting period is an interval of the year during which the ice in the foundation materials is returning to a liquid state. It ends when all the ice in the ground has melted or when freezing is resumed. Although in the generalized

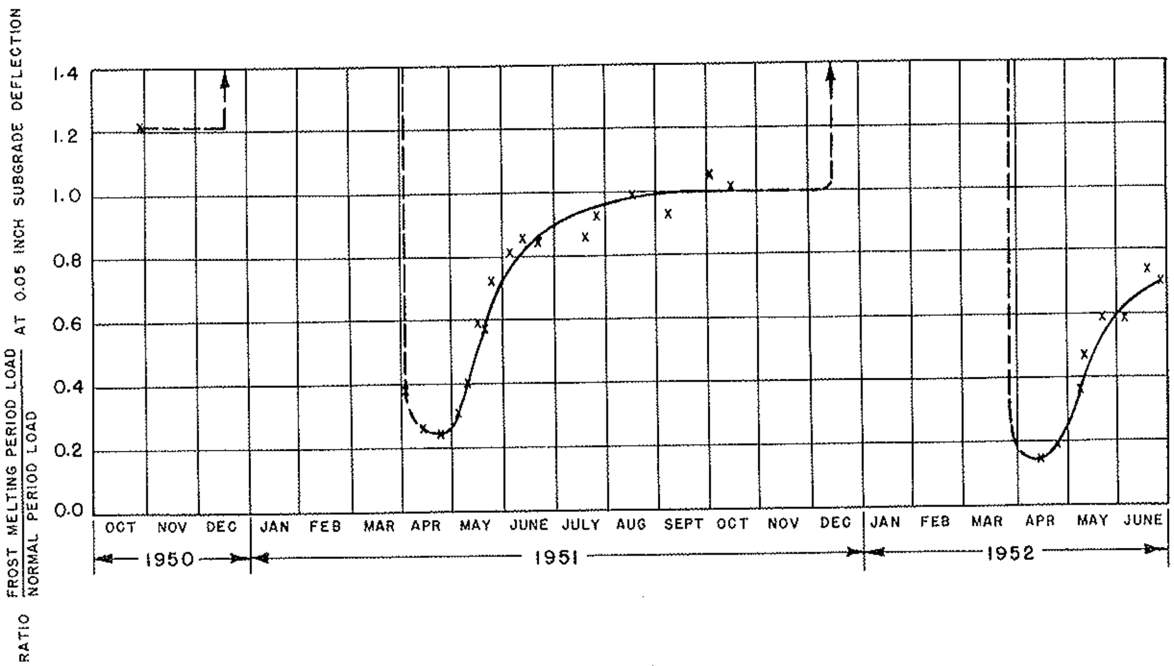


Figure 1. Results of static-load tests with 30-in.-diameter plate on 18-in. bituminous-surface-treated gravel base course for Limestone, Maine, frost test section, average of Positions 3 and 4.

case there is visualized only one frost-melting period, beginning during the general rise of air temperatures in the spring, one or more significant frost-melting intervals may occur during the winter season.

Frost-susceptible soils are those in which significant ice segregation will occur when the requisite moisture and freezing conditions are present.

Non-frost-susceptible materials are materials such as crushed rock, gravel, sand, slag, cinders, or any other cohesionless material in which ice segregation does not occur under natural freezing conditions.

Pavement pumping is the ejection of soil-water mixture from joints and cracks of rigid pavements under the action of traffic.

A coverage is one application of the wheel load over each point in the most heavily travelled area of the traffic lane. Four and 40 coverages are assumed here to correspond approximately to 30 and 300 landing and take-off cycles, respectively, on an airfield.

Frost capacity design is a pavement design which will be adequate under maximum traffic usage throughout the frost-melting period. For airfields, this usage corresponds to approximately 40 total coverages per day during the period of weakening due to frost, by the design wheel load and assembly. Greater frequencies of operation can be tolerated with loadings lighter than the design loading.

Frost limited design is design intended to be adequate under a definitely restricted number of coverages per day during the period of weakening due to frost, by the design wheel load and assembly. For airfields, this design corresponds to approximately four coverages per day. Greater frequencies of operation can be tolerated with loadings lighter than the design loading.

ICE SEGREGATION AND ITS EFFECTS

Evidence indicates that ice segregation will always occur in a frost-susceptible soil when it is frozen gradually, under conditions similar to those experienced in nature, with ample water available. A cross section through such a frozen soil will commonly show the segregated ice as lenses, layers, veins, and irregular masses. However, under some conditions and with some soils, the segregation may occur so uniformly through the soil mass that it may be difficult to determine visually the extent to which ice formation may have occurred.

In soils where appreciable water is drawn from below into the zone of freezing, pavement heave is the most obvious sign of ice segregation. However, in clays considerable ice segregation may occur without appreciable heave, the water to form ice lenses being obtained by pulling it out of the directly adjacent soil, which tends to be consolidated in the process. In this case, the only heave is that represented by the relatively small expansion resulting from change of a portion of the soil water from the liquid to the solid state. Spring breakup of pavements on fine-grained soils may sometimes be attributed erroneously to other phenomena than frost action simply because no heave has been noticed. Also, it is a normal tendency to dig an exploratory test pit only after the failure has become apparent; such an investigation may find no signs of ice segregation, the ice having, by that time, already melted.

Although pavement heave is definitely a problem in design, the subsequent weakening in the frost-melting period is more serious. As frost melting penetrates a frost-susceptible subgrade underlying a pavement, the melting of segregated ice releases an excess of water which must (1) escape upward to the surface of the subgrade or (2) be absorbed by the thawed soil. In either case, the thawed soil is loose, with a disrupted structure and an excess of moisture. Its shearing strength is therefore low. Even though ice segregation may have been weak, marked weakening of the load-supporting capacity may result if the soil conditions are such that a small increase in moisture content resulting from the frost action will cause appreciable loss of strength. The most critical period is usually from a few days to 3 week's duration, and as the excess water drains from the subgrade, the pavement gradually regains strength. The time during which strength continues to be regained varies from a few weeks to several months, depending upon the intensity of ice segregation, depth of frost penetration, rate of thawing, permeability of the soil, drainage, and traffic conditions.

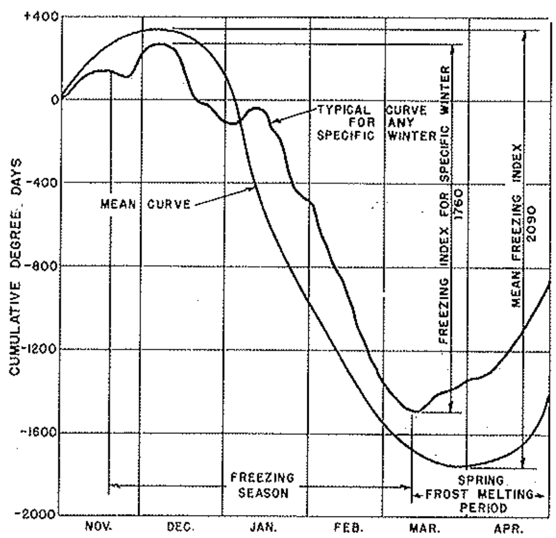


Figure 2. Determination of freezing index.

Figure 1 shows the variation of subgrade strength under a bituminous-surface-treated, 18-in. gravel base course at Limestone Air Force Base in Maine during 1950 to 1952, as measured by plate-bearing tests. A plate bearing test on a frost-softened subgrade is not considered a good measure of magnitude, of reduction in bearing capacity under traffic. However, it does provide a means of picturing (1) the relative change of strength through the season and (2) the duration of weakening. Conditions represented by the series of tests shown in Figure 1 are not a typical of many pavements on frost-susceptible soils, in areas subject to frost action. The regain of bearing capacity after the sudden drop during the spring frost-melting period is seen to be rapid at first, then somewhat slower. It is interesting to note that the loss of strength was apparently considerably greater in the spring of 1952 than in the spring of 1951. The test area did not receive traffic during the series of tests. If it had, the wheel loadings might have hastened the reconsolidation, but also the remolding effect of the traffic might have increased the degree of weakening.

It is obvious from Figure 1 that under seasonal frost conditions the bearing capacity of the pavement is not a fixed thing, but is something which is constantly changing. If our design is based on field soil tests and natural conditions, we are

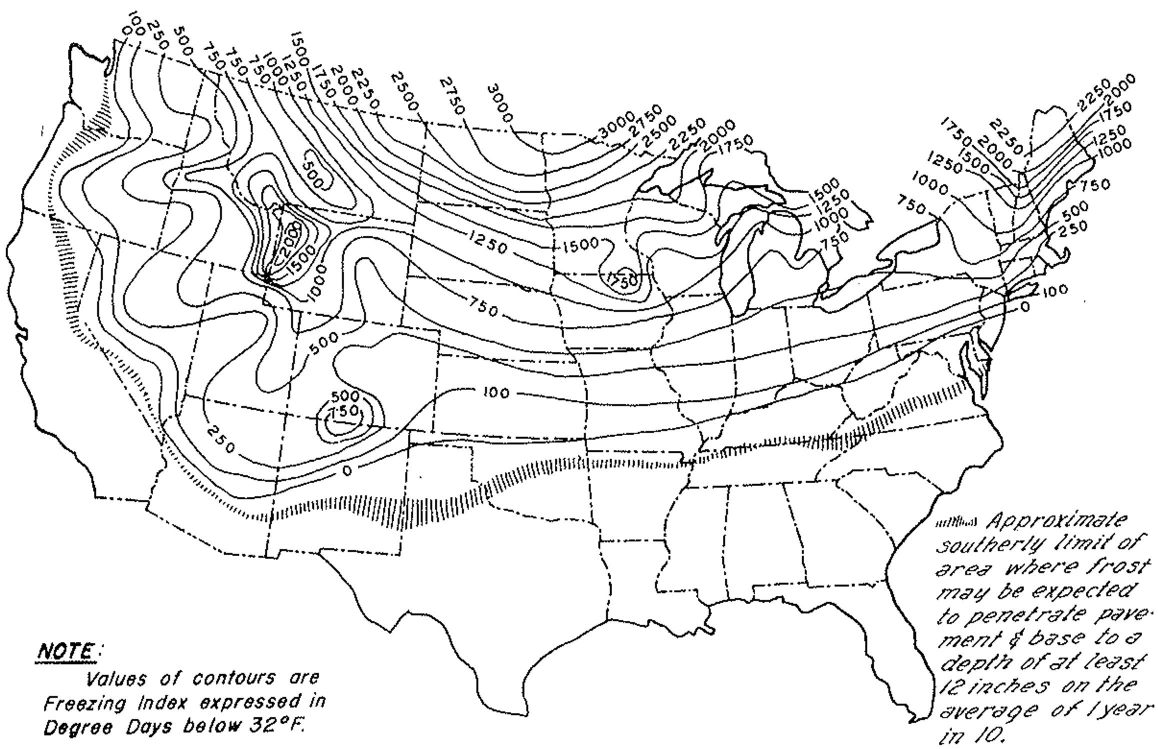


Figure 3. Mean freezing-index data influencing frost action.

likely to obtain different designs depending upon the particular time of year when we obtain our field data.' The strength in the frost-melting period is seen to be the critical value which must be considered in design. This spring weakening has long been recognized in the practice of limiting wheel loads to arbitrarily reduced values in the spring. On some airfields a comparable result has been obtained by limiting number of daily landings and take-offs during the weakened period. While such approaches are practical in many instances, they present an enforcement problem and are impractical for high-traffic-capacity roads or airfields.

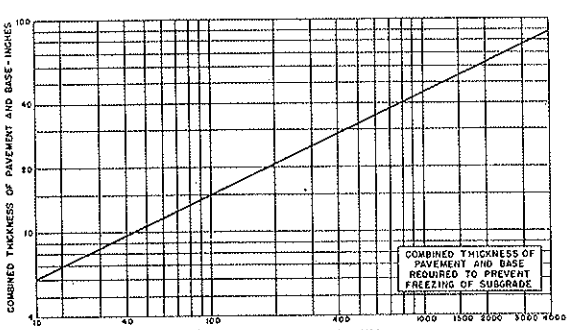


Figure 4. Combined thicknees of pavement and base required to prevent freezing of subgrade.

Less conspicuous than either heave or weakening due to frost melt is the general roughening of an initially level pavement with time as a result of either differential changes in subgrade density as a result of frost action, or of overstressing during the frost-melting period, causing deterioration at a faster rate than otherwise would apply and which logically must be considered as an economic loss.

RECOGNITION OF FROST-SUSCEPTIBLE CONDITIONS

Direct evidence of the frost activity of the subgrade may not be unavailable or inadequate, or it may not be feasible to perform necessary field invesitgations during the freezing and frost-melting periods. Therfore, determination as to whether or not frost-evaluation criteria are applicable is usually based on the gradations of the base course and subgrade soils, and on ground-water conditions and air-temperature records. However, all reliable information on past performance of comparable pavements in the area during the freezing season and frost-melting period should be considered. Maintenance and traffic records may assist in confirming whether or not frost-susceptible conditions exist. Visible surface effects which may contribute to the picture and which are associated with frost action are pavement heave and surface cracking during the winter season, and alligator cracking, frost boils, noticeable weakening, shoving or deflection, and pumping in cracks and joints during the frost-melting period. When the presence of such defects, or the absence of them, is used as a guide in the design, the freezing index and moisture-condition data for the location during the actual years of record must be examined carefully to determine whether the severity of the frost conditions during the period of observation can be considered representative.

In order for ice segregation to occur, three conditions must exist simultaneously: the soil must be frost susceptible; freezing temperatures must penetrate the frost-susceptible soil, and a sufficient supply of water must be available.

Soil

The potential intensity of ice segregation in the soil is dependent to a large degree on its void sizes and may be expressed as an empirical function of grain size as follows:

Inorganic soils containing 3 percent or more of grains finer than 0.02 mm. in diameter by weight are considered generally frost susceptible. Certain sandy soils may have as high as three or four times this percentage of grains finer than 0.02 mm. without being frost susceptible; however, because of their tendency to occur interbedded with other soils, it has been considered generally impractical to consider them separately. Inorganic soils containing less than 3 percent of grains finer than 0.02 mm. in diameter by weight are generally not frost susceptible.

In borderline cases the Frost Effects Laboratory performs freezing tests on the soils to measure the relative frost susceptibility to ice segregation. This service has been performed on soils from government construction projects covering a wide range of geographical locations.

Frost-susceptible soils have been classified into four groups, listed in order of increasing susceptibility. Group F4 soils have particularly high frost susceptibility. Soil names correspond with those defined in the Department of the Army Uniform Soil Classification.

Group	Description
F1	Gravelly soils containing between 3 and 20 percent finer than 0.02 mm. by weight.
F2	Sands containing between 3 and 15 percent finer than 0.02 mm. by weight.
F3	(a) Gravelly soils, containing more than 20 percent finer than 0.02 mm. by weight, and sands, except fine silty sands, containing more than 15 percent finer than 0.02 mm. by weight. (b) Clays with plasticity indices of more than 12 except varved clays.
F4	(a) All silts including sandy silts. (b) Fine silty sands containing more than 15 percent finer than 0.02 mm. by weight. (c) Lean clays with plasticity indices of less than 12. (d) Varved clays.

Temperature

The depth to which frost will penetrate below the surface of the pavement kept clear of snow depends principally on the magnitude and duration of below-freezing air temperatures, of which the freezing index provides a measure, and on the amount of water which is frozen in the subgrade. Figure 2 illustrates the computation of the freezing index. An approximate value of the mean freezing index may be obtained from Figure 3, on which are plotted isograms of mean freezing index for the continental United States. However, it is prefereble to compute the freezing index from actual daily mean air temperatures measured at a weather observation station in the particular locality, based on a long period of record.

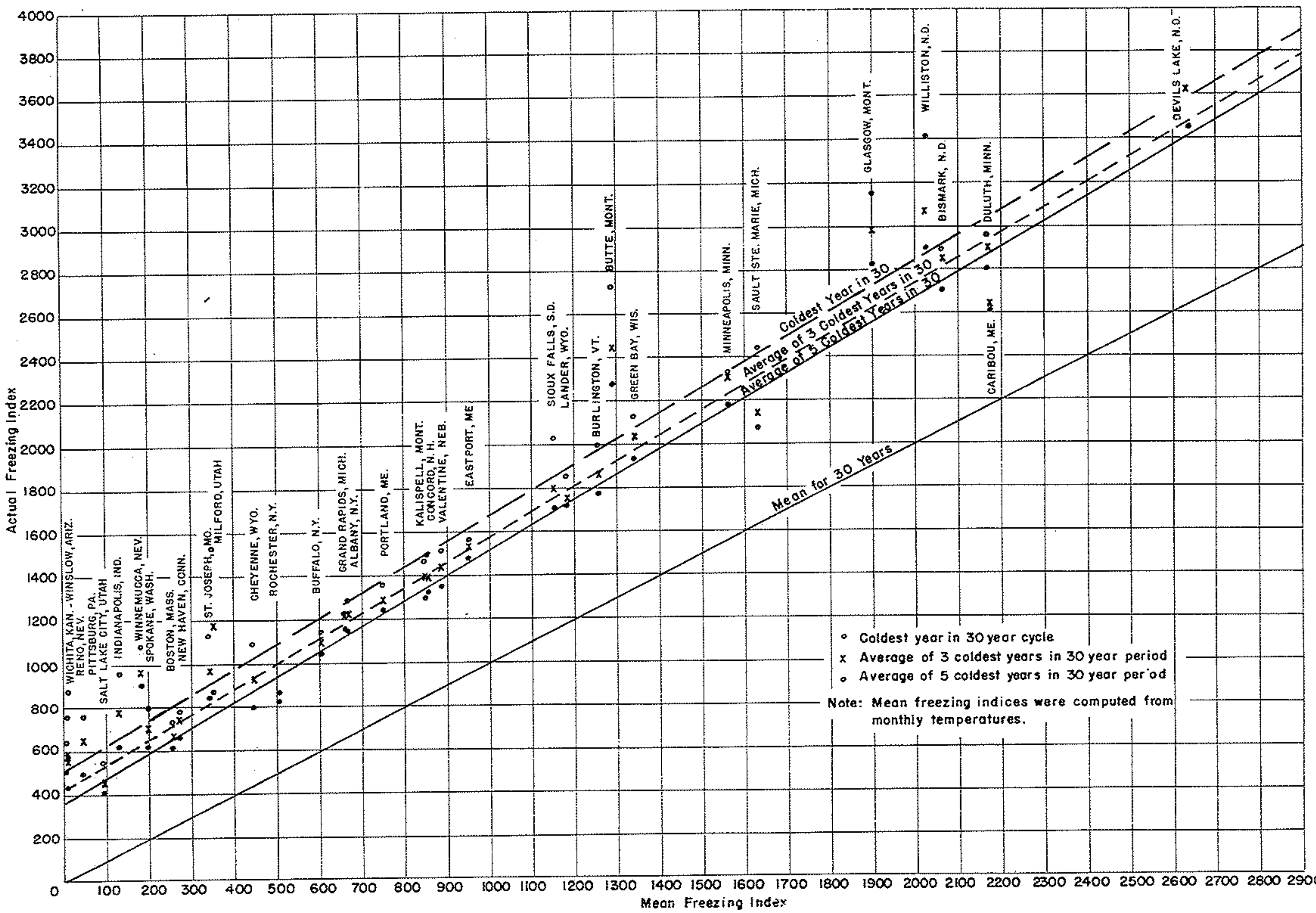


Figure 5. Relationship between mean freezing index and freezing indexes during colder years for 50 consecutive years.

An empirical chart showing the relationship between air freezing index and depth of frost penetration for the case of a drained, granular, non-frost-susceptible base course beneath a paved area kept free of snow, is shown on Figure 4. The relationship shown on this chart is an approximation, since it averages together the effects of such variables as pavement type and base-course density and moisture content. More comprehensive methods, which take these variables into account, have been studied in the Frost Effects Laboratory (1, 2) and the Permafrost Division, St. Paul District, Corps of Engineers. Carlson has described the Permafrost Division studies (3), in which emphasis is on calculation of depth of thaw. Improvement of these methods is still in progress. These methods should be used where detailed computations are required.

Fluctuations in the severity of winter freezing and in the rate of spring thawing, combined with fluctuations in seasonal ground-water conditions, cause wide variations in frost action from year to year and also between localities in any one year. Experience in the continental United States indicates that in 1 year out of perhaps every 5 to 10 years frost action conditions at any given locality are considerably more severe than the average. The results of a comparison between the mean freezing index and the freezing indices during the colder years, for a 30-year record from approximately 35 Weather Bureau Stations with a wide geographical distribution, is shown on Figure 5. It will be observed that in areas of relatively low mean freezing index the relative variation from mean temperature conditions may be very large. This condition also exists for some distance south of the zero mean freezing index isogram (see Fig. 3).

The design freezing index is, at present, usually based on the mean freezing index. However, the data on Figure 5 suggest that a more significant freezing index value would be obtained by selecting the value which occurs, let us say, about one year in ten, particularly in areas of low mean freezing index. On Figure 5 this would correspond to the average of the three highest freezing indices in the 30 years of record. In general, the magnitude of the freezing index value is not a measure of the intensity of ice segregation, but rather of the depth of frost penetration. Use of the one-year-in-ten freezing index in place of the mean freezing index would bring under the frost design criteria pavements and regions to which they would not otherwise apply. The greater depth of frost penetration would also correspond with longer critical weakened periods under traffic. The selection of design freezing index involves a balancing of the cumulative loss from frost damage over the life of the construction against the cost of protective measures. The proposal for use of a one-year-in-ten freezing index rather than the mean is tentative and is still under study.

Water

Moisture required for formation of segregated ice within the soil may be derived from an underlying ground-water table, from infiltration through the pavement or at the shoulders, from an aquifer, or from the water held within the voids of fine-grained soils adjacent to the freezing plane. A potentially troublesome water supply for ice segregation is considered to be present if the highest ground water at any time of the year is within 5 ft. of the proposed subgrade surface or of the top of any frost susceptible subbase materials used. When the depth to the uppermost water table is in excess of 10 ft. throughout the year, a condition of troublesome water supply is considered usually not present. However, these water-table criteria are not necessarily applicable for impervious clay soils if the water content is sufficiently high, since it has been found that ice segregation will occur in homogeneous clay soils at moisture contents down to approximately shrinkage limit of the clay, without any other water being available for freezing than that originally contained in the soil voids.

MAGNITUDE OF SUBGRADE WEAKENING DUE TO FROST ACTION

The degree to which the soil loses strength during the frost-melting period and the length of the period during which the strength of the soil is reduced depend on the type and condition of the soil, depth of frost penetration, temperature conditions during freezing and thawing periods, the amount and type of traffic during the frost-melting period, the availability of water during the freezing period, and drainage conditions. The application of traffic may cause remolding or develop hydrostatic pressures within the pores of the soil during the period of weakening, resulting in subgrade strength reduced appreciably below that measured by static tests. Traffic tests performed by the Corps of Engineers (4) have shown that the wheel-load-supporting capacity of a flexible pavement during the frost-melting period may be of the order of one third of the normal period wheel-load evaluation. Rigid pavements, on the other hand, have been found to retain about three quarters of their normal period wheel-load-supporting capacities. The smaller reduction in strength of rigid pavements due to frost action is attributed to the fact that the supporting capacities of rigid pavements are not influenced to as great a degree as flexible pavements by changes in the subgrade strength, and in addition, there is less loss in strength due to shearing deformation and remolding during the critical spring frost-melting period.

BASE COMPOSITION REQUIREMENTS

All base-course materials specified by the design criteria are required to be not frost susceptible, except for any portions which may extend below the predicted depth of frost penetration. Where the combined thickness of pavement and base over a frost-susceptible material is less than the predicted depth of frost penetration, the following additional design requirements apply:

1. For both flexible and rigid pavements, the bottom 4 in. of base course is required to be composed of any non-frost-susceptible gravel, sand, or crushed stone and is required to be designed as a filter between the subgrade soil and overlying base course, in order to prevent mixing of a frost-susceptible subgrade with the base during, and immediately following, the frost-melting period. The gradation of this filter material is determined in accordance with the filter criteria used in subsurface drainage design, with the added overriding limitation that the filter material shall, in no case, have more than 3 percent by weight finer than 0.02 mm.

2. For rigid pavements, the 85-percent size of the filter or regular base-course material placed directly beneath the pavement is required to be equal to or greater than a given diameter in order to prevent loss of support by pumping soil through the joints of the rigid pavement. This diameter is presently specified as ½ in., but study has indicated that this is probably too conservative under modern construction practices and consideration is now being given to reducing this 85-percent-size value.

LOAD DESIGN CRITERIA

Where the investigations of soil, temperature, and moisture conditions indicate that a frost-weakening problem does not exist, the pavement design is made in accordance with the standard methods for flexible or rigid pavements. However, if the investigations show that a frost problem does exist, then two alternate methods of design are available which will assure safe carrying of the design wheel load. First, enough thickness of pavement and base can be provided so that frost does not enter the susceptible soil. Second, we can base our design on the reduced strength of the frost-susceptible soil during the frost-melting period and provide sufficient thickness of pavement and non-frost-susceptible base above it to carry, during the most critical days of the frost-melting period, the anticipated rate of coverages of the design load.

Preventing Freezing of Subgrade

In this method the combined thickness of rigid or flexible pavement and base is chosen to be not less than the depth of frost penetration determined from Figure 4, using the design freezing index determined for the particular locality. This method is required (1) over the extremely frost-susceptible, type F4 soils or (2) wherever significant differential pavement heave will be detrimental to high-speed traffic. However, the method is not required in the case of flexible-pavement areas where appreciable differential heave may be tolerated, such as parking areas. Exception is also permitted when the causes of nonuniform heaving can be satisfactorily corrected by the removal of isolated pockets of highly frost-susceptible soils for the full depth of frost penetration or by providing gradual transitions at abrupt changes in subgrade conditions. In these cases, frost may be permitted to enter the subgrade and design is then based on reduction in subgrade strength.

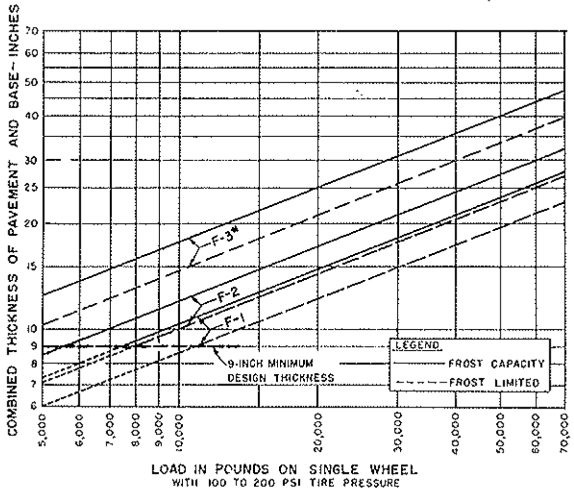
The full-protection-design method produces pavement-supporting characteristics which are fairly uniform through the year but which may be very conservative with respect to strength. The cost of this method rises with increase in depth of annual frost penetration. In regions of deep seasonal frost penetration the method is not feasible, even in cases where heavy wheel loadings would require heavy base courses in any event, and here arbitrary limits must be set upon the maximum thickness of base course. In extreme northerly areas the situation is reversed, and there full protection against thaw of the subgrade may be possible. The full-protection-design methods described should be considered limited to conditions comparable to those encountered within the continental limits of the United States.

Reduction in Subgrade Strength

Design based on the reduction in strength of the subgrade during the spring frost-melting period will frequently permit less depth of pavement and base than is required for prevention of freezing of the subgrade. This method is applicable for both flexible and rigid pavements on subgrade soils of Groups F1, F2, and F3, when subgrade conditions are sufficiently uniform to assure that objectionable differential heaving will not occur or where subgrade variations are correctible to this condition. As previously noted, the method may also be used where appreciable nonuniform heave can be tolerated, in flexible pavements of lesser importance not subject to high speed traffic. The design procedure provides a pavement which is just barely adequate during the frost-melting period but which necessarily has excess strength during the remainder of the year.

GROUP	DESCRIPTION
F1	GRAVELLY SOILS CONTAINING BETWEEN 3 AND 20 PER CENT FINER THAN 0.02 mm. BY WEIGHT.
F2	SANDS CONTAINING BETWEEN 3 AND 15 PER CENT FINER THAN 0.02 mm. BY WEIGHT.
F3	(a) GRAVELLY SOILS CONTAINING MORE THAN 20 PER CENT FINER THAN 0.02 mm. BY WEIGHT AND SANDS, EXCEPT FINE SILTY SANDS, CONTAINING MORE THAN 15 PER CENT FINER THAN 0.02 mm. BY WEIGHT. (b) CLAYS WITH PLASTICITY INDICES OF MORE THAN 12, EXCEPT VARVED CLAYS.
F4	(a) ALL SILTS INCLUDING SANDY SILTS. (b) FINE SILTY SANDS CONTAINING MORE THAN 15 PER CENT FINER THAN 0.02 mm. BY WEIGHT. (c) LEAN CLAYS WITH PLASTICITY INDICES OF LESS THAN 12. (d) VARVED CLAYS.

* When frost is permitted to penetrate group F4 soils, use same design curve as for group F3 soils. Frost should be permitted to penetrate F4 soils only under flexible paved areas of lesser importance where appreciable non-uniform pavement heave may be tolerated.



THE THICKNESS WILL BE REDUCED 10 PER CENT FOR CENTRAL PORTION OF RUNWAYS (AREA BETWEEN 1000 FT. SECTION AT EACH END)

Figure 6. Flexible-pavement design curves for taxiways, etc., for frost action in subgrade soil.

For airfield usage, two design categories have been chosen for design based on reduction in subgrade strength. Frost limited and frost capacity are used to denote approximately 4 and 40 total coverages per day, respectively, during the period of weakening due to frost, by airplane with weights equal to the design loadings. The frost-limited information represented here is tentative only. It is subject to revision and is presented only to illustrate the concepts involved in current studies. The frost-capacity category is normally used for design. The frost-limited category will normally be used only for evaluation of existing pavements to determine what loadings may be tolerated in the spring under a relatively small number of traffic operations. For flexible pavements, separate design curves have been prepared for the two operational conditions, the frost limited curves being tentative, as noted. No separate frost-limited design curves have been prepared for rigid pavements. However, where this condi-

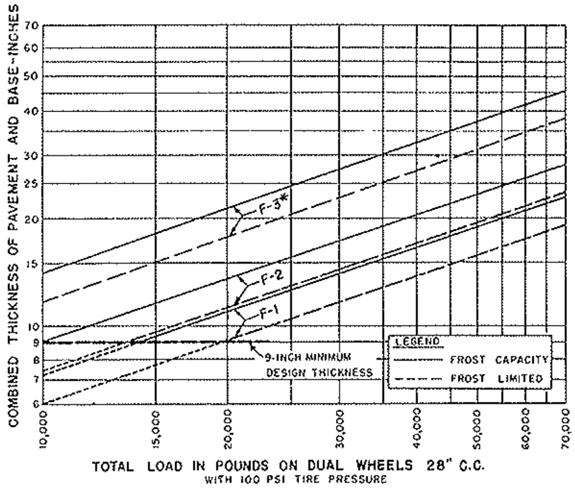


Figure 7.

tion must be considered, 10 percent less pavement thickness than that required for frost-capacity design is considered adequate for the frost-limited traffic.

1. Reduction in Strength Criteria for Flexible Pavements. When freezing is permitted in the subgrade, the combined thickness of flexible pavement and non-frost-susceptible base required for the design assembly and loading is determined from the applicable curve among Figures 6 through 10, Figure 10 being the highway design chart. The designs produced by these curves have previously been compared with the results of an extensive series of traffic tests in the frost-melting period, in a paper presented before the Highway Research Board in 1951 (4). However, since the referenced paper was presented, the curves have been adjusted to give approximately 10 percent less required pavement thickness and the frost-limited concept has been added.

The curves reflect the reduction in strength of the soil during the frost-melting period. It is considered that the reduction in strength of subgrades tends, generally, to be greater in cuts than in fills. If field data and experience definitely indicate that the reduction in strength in fill areas may be expected to be less, because of such factor as the greater depth to water table, a reduction in combined thickness of base and pavement for the fill area may be permitted. In no case is a combined thickness of pavement and non-frost-susceptible base less than 9 in. permitted in design, where frost action is a factor, although smaller combined thickness may have to be considered in evaluation of an existing pavement. Curves on Figures 6, 7 and 10 are therefore shown dotted below 9-in. thickness.

2. Reduction in Strength Criteria for Rigid Pavements. With certain exceptions, a non-frost-susceptible base course equal in thickness to the thickness of the concrete slab is required where frost penetration is permitted into a frost susceptible subgrade beneath a rigid pavement. The specific exceptions to this requirement are as follows:

A. Where soils of Groups F1, F2, and F3 occur under very uniform conditions of subgrade and the freezing index is less than 500, the thickness of the non-frost-susceptible base under a rigid pavement may be reduced to 4 in.; it is designed to meet filter requirements outlined previously under "Base Composition Requirements."

B. Where soils of Groups F1, F2, and F3 occur under uniform conditions and the depth to the uppermost water table is greater than 10 ft., the thickness of the non-frost-susceptible base under a rigid pavement may be reduced to 4 in., and the base is designed as a filter.

C. Over Group F4 soils the combined thickness of rigid pavement and base is determined according to the criteria for prevention of freezing of the subgrade.

The thickness of concrete pavement is determined on basis of anticipated flexural strengths and subgrade modulus using

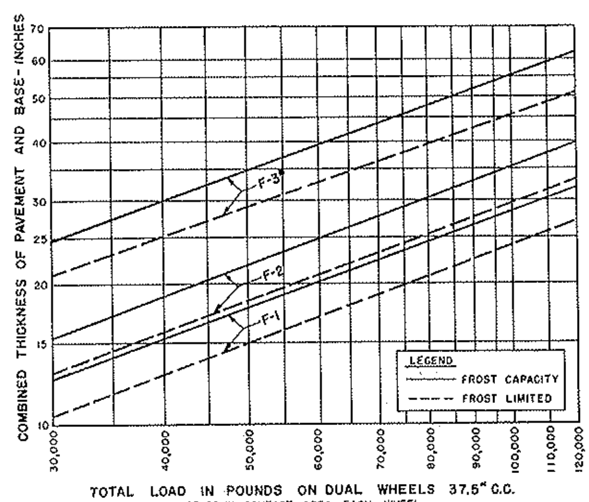


Figure 8.

standard Corps of Engineers rigid-pavement-design methods. Subgrade modulus values for use in these computations are determined from Figure 11, which allows for the reduced strength of the subgrade. Should actual field test subgrade modulus values prove to be lower than those obtained from Figure 11, the field test values govern the design.

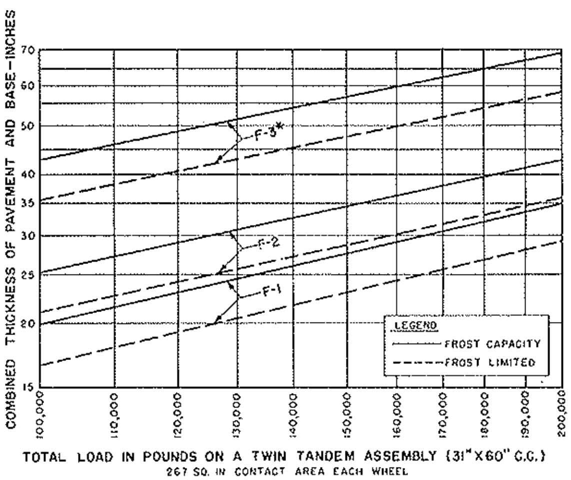


Figure 9.

EXAMPLES OF PAVEMENT DESIGN

Example 1

Design an access-road pavement for a flexible pavement to withstand a 12,000-lb. wheel load (24,000-lb. axle load) under maximum traffic conditions during the frost-melting period, for the following conditions:

Design freezing index, 700

Subgrade, silty sand 20 percent finer than 0.02 mm.

Highest ground water, 1 ft. below top of subgrade

Base CBR, 80 percent

1. Prevention of Freezing of Subgrade. From Figure 4 the combined thickness of pavement and base to prevent freezing of the subgrade for a design freezing index of 700 is 38 in.

2. Reduction in Subgrade Strength. From Figure 10, 23 in. combined thickness of pavement and base is required over the type F3 subgrade soil to provide sufficient supporting capacity during the weakened period in the spring. Since this thickness will still allow some frost penetration into the subgrade, some heave should be expected, but it should not be detrimental in this application provided it occurs uniformly, i.e., there are no abrupt changes in subgrade conditions.

Example 2

Design an airfield taxiway for both flexible and rigid pavements to withstand a 25,000-lb., single wheel load with 200-psi. tire pressure under maximum traffic conditions during the frost-melting period, for the following conditions.

Design freezing index, 300 degree-days

Subgrade, uniform lean clay and plasticity index 14.

Highest ground water, 2 ft. below surface of subgrade

Subgrade CBR, 8 percent (normal period)

Base CBR - 80 percent

Subgrade modulus, k - 100 lb. per sq. in. per in.

Concrete flexural strength, 650 lb. per sq. in.

1. Flexible Pavement. (a) Preventing freezing of subgrade: From Figure 4, the combined thickness of pavement and base to prevent freezing of the subgrade is 25 in.

(b) Reduction in subgrade strength: Soil is type F3. From Figure 6, the required total thickness of pavement and base for frost capacity operation is 28 in. This is greater than the depth of frost penetration; therfore, design on bases of reduction in subgrade strength is not applicable. Analysis by standard California Bearing Ratio procedures shows that a thickness of 22 in. is required for the normal period subgrade strength. Since the thickness of 25 in. required to prevent freezing of the subgrade is less than the value from Figure 6 and greater than the 22 in. required for the normal period, 25 in. would be selected as the combined thickness of pavement and base.

2. Rigid Pavement. (a) Preventing freezing of subgrade: From Figure 4 the minimum thickness of pavement and base required to protect the subgrade from frost action is 25 in. The required slab thickness from standard rigid-pavement-design charts, with no subgrade weakening, is 11.4 in. The Corps of Engineers' design manual specifies that when the thickness from the design curves indicates a

fractional value greater than 1/4 in., the next full-inch thickness is used for construction. The adopted slab thickness should therefore be 12 in., resulting in a base-course thickness of 25-12=13 in.

(b) Reduction in subgrade strength: Since subgrade conditions are uniform and freezing index is less than 500, exception to the rigid-pavement-base-course-design criterion is applicable. A minimum base course of 4 in. is required to protect against loss of support by pumping. The subgrade modulus during the frost-melting period is 25 lb. per sq. in. per in. as determined in Figure 11. The slab thickness required, from standard rigid-pavement-design charts, is 13 in. Cost comparison then indicates whether this design or the one obtained in the preceding paragraph should be used.

Example 3.

Design an airfield taxiway for both flexible and rigid pavements to withstand a 25,000-lb. single wheel load with 200-psi. tire pressure, under capacity operation during the frost-melting period, for the following conditions:

Design freezing index, 2000 degree-days

Subgrade, uniform lean clay and plasticity index 14

Highest ground water, 3 ft. below surface of subgrade

Subgrade CBR, 8 percent (normal period)

Base CBR, 80 percent

Subgrade modulus, k is 100 lb. per sq. in. per in.

Concrete flexural strength, 650 lb. per sq. in.

1. Flexible Pavement. (a) Preventing freezing of subgrade: From Figure 4 the combined thickness of pavement and base to prevent freezing of the subgrade, for the design freezing index, is 62 in.

(b) Reduction in subgrade strength: When allowing a reduction in strength of the subgrade due to frost action and allowing uniform heave of the pavement, a total thickness of 28 in. is required, according to Figure 6.

2. Rigid Pavement. (a) Preventing freezing of subgrade: From Figure 4 the minimum thickness of pavement and base required to protect subgrade from freezing is 62 in. The slab thickness according to standard rigid-pavement-design curves would be 11.4 in. A 12-in. slab thickness should be used in construction, thereby resulting in a base course of 50 in.

(b) Reduction in subgrade strength: Assuming a 12-in. base thickness, the subgrade modulus, as determined in Figure 11, is 65 lb. per sq. in. per in. Using this value, the required slab thickness, from standard rigid-pavement-design curves, is 12 in., which requires a 12-in. base thickness in accordance with the previously stated general criterion for base courses under rigid pavements. This confirms the original assumption of base thickness. For the uniform subgrade conditions, this would be the adopted design.

If, in this case, the ground-water-table depth should be in excess of 10 ft., with all other conditions the same, a 4-in.-minimum-thickness base would be permitted in accordance with exception previously outlined. The design subgrade modulus in accordance with Figure 11 would then be 25 lb. per sq. in. per in. Using this value of subgrade modulus, the required slab thickness, from standard rigid-pavement-design charts, would be 13.

NEEDED IMPROVEMENTS IN CRITERIA

Actual application of traffic on frost-susceptible areas is the only effective means we have at present of evaluating simultaneously all factors which influence weakening of frost-susceptible soils. The traffic method gives us, particularly, an evaluation of the remolding action of traffic and of any subtle changes in soil structure resulting from the frost action on the soil strength. Therefore, we should attempt to obtain additional fully correlated records of traffic experience on borderline designs during the frost-melting period. These should extend coverage over a full range of soil, temperature, and moisture conditions. Frost traffic tests to date have covered a fair variety of conditions, but much remains to be learned. It is essential that the surface observations be carefully correlated with data on the coverages, wheel loadings, soil mois-

We need better methods of analyzing those combinations of precipitation, freezing and rate of thaw which are conducive to especially severe spring pavement weakening.

We need to obtain better information on the duration of the maximum weakening period in various soils. In relatively pervious frost-susceptible soils, the melt water may escape nearly as rapidly as it becomes available. In soils of lower permeability the effective time of drainage may be slower and the duration of the weakening may be greatly extended. We also need more information on the effective permeability of soils during the frost-melting period, which may not be the same as the permeability of a homogeneous sample, due to fissured structure.

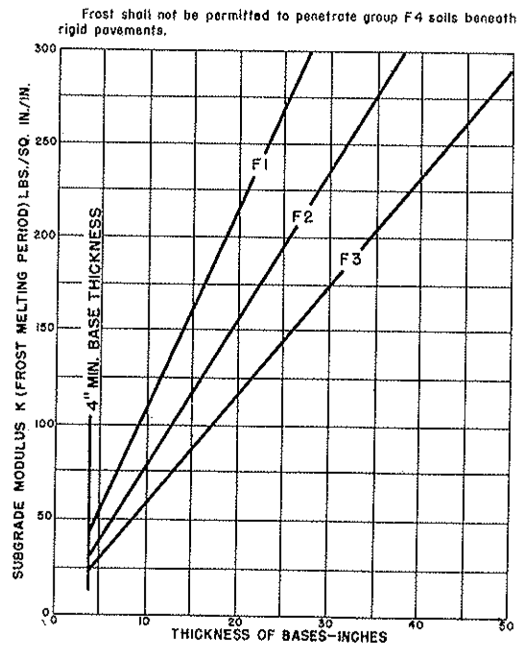


Figure 11. Rigid-pavement-subgrade modulus curves for frost action in subgrade soil.

Study is needed to determine whether the present rule, which states that a soil containing 3 percent or more of grains by weight finer than 0.02 mm. is generally frost susceptible, can be improved. Various possible methods of making use of borderline frost-susceptible base-course materials should be explored. More data are needed on the effects of depth to water table, degree of saturation, soil struc-

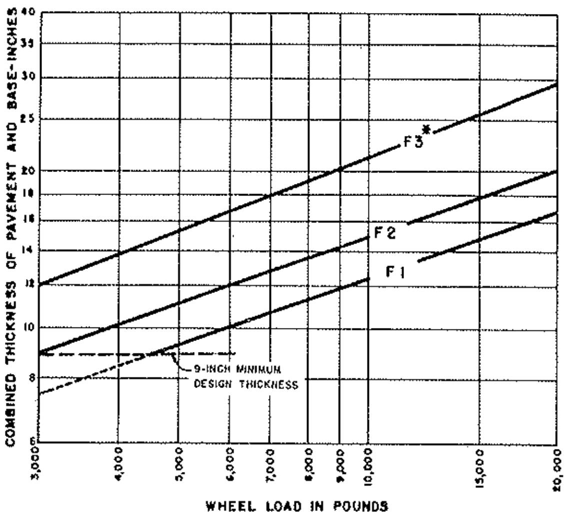


Figure 10.

ture, depth of freezing, soil density, and other basic soil information.

A thin base under a rigid pavement is believed to contribute relatively little structural effect, since the layer is so thin relative to the depth to which the material is stressed. However, a thin base course will definitely have some drainage function in distributing and removing infiltration through the pavement or excess melt water which emerges from the subgrade during the frost-melting period. This function will, of course, vary with the permeability of the subgrade, amount of ice segregation which has occurred, lateral drainage distance, rate of thaw. Also, it is assumed the thin base course will reduce or prevent pumping, if it is satisfactorily designed as a filter. Possibly conventional filter criteria may be too conservative for this special application. Much work needs to be done to crystallize design criteria in this field.

It may be that we should give greater attention to the difference in spreading effects of different base courses under pavements, as for example, between rounded natural gravels and angular crushed rocks. These effects possibly are of little consequence in relatively thin base courses but may be of distinct importance when base courses reach thicknesses of the order of 2 ft. or more.

The question of how much heave is permissible under a rigid pavement is also a thorny problem, not susceptible of theoretical analyses.

ture, surcharge, depth of cover and other variables. James F. Haley described in the previous paper cold-room studies presently being made in the Frost Effects Laboratory to investigate some of these effects with the objective of deriving improved design criteria (8). Actual field performance data and certain basic theoretical studies are needed in addition to the cold-room studies.

REFERENCES

1. Frost Effects Laboratory, New England Division, Corps of Engineers, U. S. Army, Boston, Mass., "Report on Frost Investigation 1944-1945", April 1947.

2. Frost Effects Laboratory, New England Division, Corps of Engineers, U. S. Army, Boston, Mass., "Frost Investigation 1945-1947. Addendum No. 1 to Report on Frost Investigation 1944-1945", June 1948.

3. Carlson, Harry, "Calculation of Depth of Thaw in Frozen Ground", Highway Research Board Special Report No. 2, 1952, ("Frost Action In Soils, A Symposium"), pp. 192-223.

4. Linell, K. A. and Haley, J. F., "Investigation of the Effect of Frost Action on Pavement Supporting Capacity", Highway Research Board Special Report No. 2, 1952 ("Frost Action in Soils, A Symposium"), pp. 295-325.

5. Haley, J. F. "Progress Report on Cold Room Studies", presented at Highway Research Board Thirty - First Annual Meeting, January 1953.

Soil-Temperature Comparisons Under Varying Covers

GEORGE A. CRABB, JR., Research Hydraulic Engineer,
Soil Conservation Service, U. S. Department of Agriculture, and
JAMES L. SMITH, Hydrologic Research Assistant,
Department of Forestry, Michigan State College

● THE Michigan Hydrologic Research Station was established at East Lansing in 1940 as a cooperative study between the Soil Conservation Service of the U. S. Department of Agriculture and the Michigan Agricultural Experiment Station to study the effect of land use on the hydrology of farm lands under varying types of snow cover and frozen soil. As additional objectives, it was planned for the station to: (1) determine the manner in which freezing and thawing of soils on watersheds with varying types of land use contribute to runoff, erosion, and flood flow under northern winter conditions, and (2) to determine the fundamental hydrologic relationships of typical Michigan soils under varying types of land use, with especial emphasis upon the movement of water through the soil profile during the fall and winter months. In order to accomplish these objectives, one of the most complete hydrologic instrumentations in this country was devised and installed on lands of Michigan State College and the Rose Lake Wildlife Experiment Station, near East Lansing (14).

The multiplicity of climatic and hydrologic factors working together to cause runoff, erosion and flood flow, and controlling the hydrologic relationships of soils requires a broad program of basic research to include investigations in many little known fields of climatology that are of considerable interest to highway engineers, agronomists, agricultural engineers, and many other specialists, as well as hydrologists. One set of relationships which interests both the hydrologist and the highway engineer is the air-soil temperature relationship.

Daily records of soil temperatures at depths up to 60 in., as well as air temperatures, are kept on the watersheds of the Michigan Hydrologic Research Station. These watersheds, three in number, consist of two cultivated watersheds and a wooded watershed. All three watersheds are quite similar in size, slope, soils, and exposure. Their primary difference is a variation in land cover; the two cultivated watersheds being planted to a rotation of corn, wheat, and alfalfa brome, which permits ready comparison between the hydrologic effects of close growing and row crops and wooded cover. Among other differences found in the hydrologic relationships of these watersheds, are soil temperature differences occurring under different vegetal cover. This paper will discuss these differences in some detail, and attempt to present causes for the differences.

Soil temperatures play an important part in determining the hydrologic relations of soils. Soil moisture changes are almost always marked by an accompanying soil temperature change. Soil temperatures also play an important part in the actual measurement of soil moisture. At the East Lansing station, soil moisture on the cultivated watersheds is measured by the Bouyoucos method, with plaster-of-paris electrical-resistance blocks. This method utilizes variations in the electrical resistance of porous units buried in the soil (14). The resistance of such units is directly related to the moisture content and temperature of the blocks. The gathering of daily records of soil moisture content also gives a daily record of soil temperature. This paper will take such a record for several years (1947-51) and show temperature variations in the soil in relation to depth, cover, and air temperature.

LOCATION OF WORK AND DESCRIPTION OF INSTRUMENTS

The studies here reported were conducted near East Lansing, Michigan, which has an average January temperature of 22.9 F., and an average July temperature of 71.1 F. The average date of last killing frost in the spring is May 5, and the average date of first killing frost in the fall is October 10. Average annual precipitation at East Lansing amounts to 31.43 in., while the normal annual amount of insolation received is 102,602 langleys.[1]

The three watersheds upon which this study is based consist of two cultivated areas on the lands of Michigan State College, approximately 3 mi. south of East Lansing, Michigan, and a wooded watershed on the lands of the Rose Lake Wildlife Experiment Station, approximately 10 mi. northeast of East Lansing. These three watersheds, varying in size from 1.3 acres to 1.9 acres, have overall, average, weighted slopes of from 6.0 percent to 6.5 percent. Soils of the two cultivated watersheds are of the Hillsdale, Miami, and Spinks series, while those of the wooded watershed are of the Hillsdale and Miami series. Although these soils differ in characteristics sufficiently to justify separate classification, they are similar. Their major difference is the presence, in certain sections of the cultivated watersheds, of an area of soil underlain at from 30 to 60 in. by a 2- to 8-in. layer of silty clay loam which is relatively impervious. Station A, in Watershed B, is not affected by this layer, whereas deeper readings at Station B, in Watershed A, indicate its presence. Therefore temperatures for Station B are shown only at the 1-in. and 6-in. layers. The soils are generally classified as gray-brown podzolic, and have textures of loamy fine sand and fine sandy loam. Physiographically, they are classed as consisting of undulating and rolling till, moderately good to well drained.

The general instrumentation of the three watersheds basically follows the standard hydrologic instrumentation pattern of the Soil Conservation Service, with facilities for measuring precipitation, runoff, erosion losses, wind movement, and relative humidity. In addition to these basic measurements, comparative precipitation measurements are determined with different types of raingages; evaporation rates with standard and experimental types of equipment; soil moisture at different depths and

[1] A langley is defined as 1 gm. cal. per cu. cm. (13).

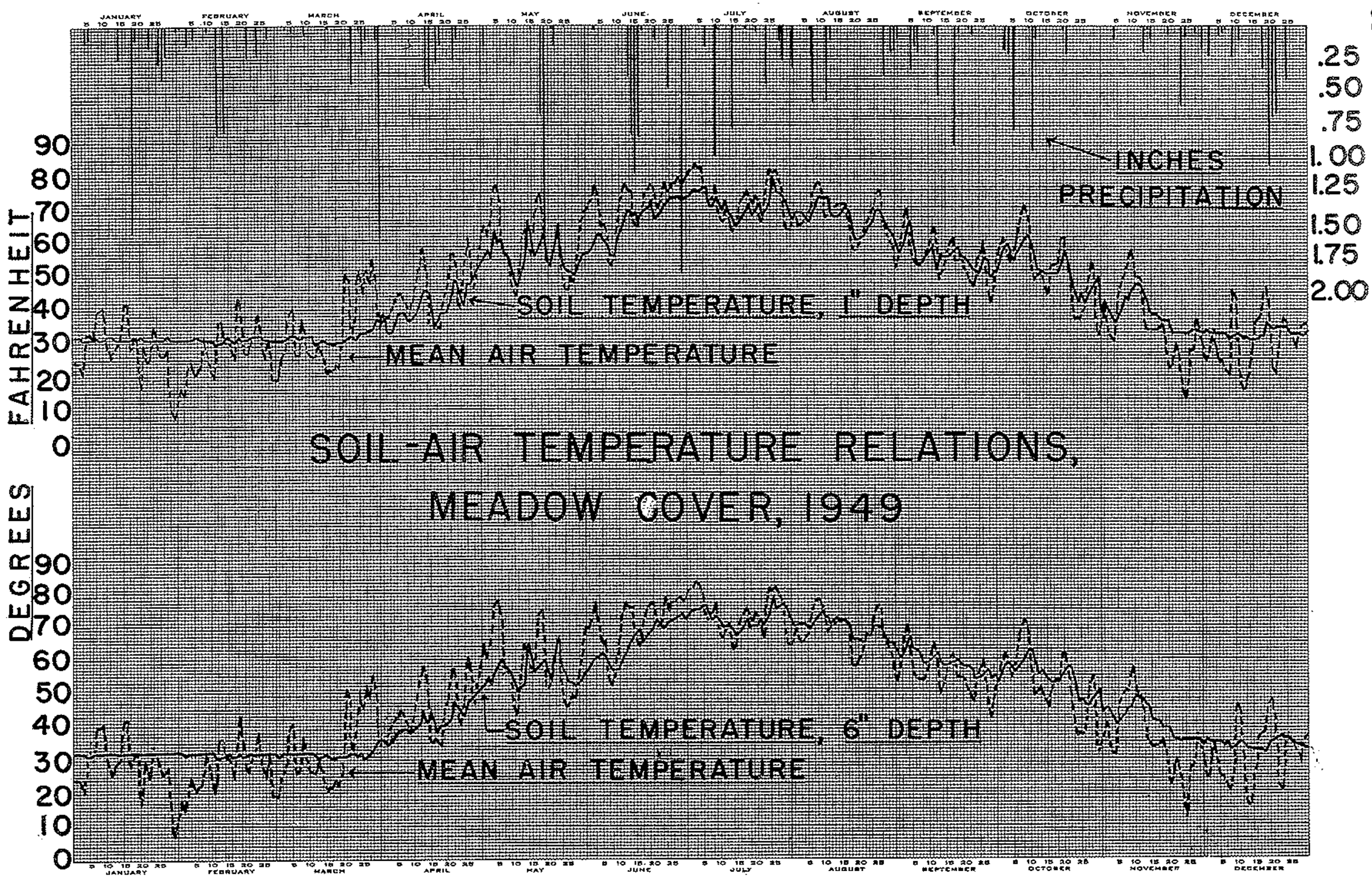


Figure 1. Comparison of mean daily air temperatures with 1- and 6-in. soil temperatures under meadow cover at East Lansing, Michigan, 1949.

under different covers, utilizing the electrical resistance and gravimetric methods; air and soil temperatures by electrical resistance, thermocouples, bimetallic and mercurial thermometers; and insolation. In view of the fact that this paper deals only with variations in soil and air temperatures, specific descriptions will be given only for those instruments which deal with this phase of the study.

Air temperatures are measured at the watersheds by means of standard USWB maximum-minimum thermometer sets, supplemented by mercurial current-reading thermometers, thermographs, and resistance thermometers. Mean air temperature (that used for comparative purposes) is obtained by averaging the maximum and minimum air temperatures of any one day, at the cultivated watersheds. In addition to this record, the instrumentation at each watershed includes a hygrothermograph, which simultaneously records air temperature and relative humidity by means of a bourdon-tube thermal unit and moisture-sensitive hair element.

Soil temperatures at the wooded watershed are recorded automatically by a three-pen, bimetallic, soil thermograph which simultaneously records the temperature at the 1-in. and 6-in. soil depths, and at a point 6 in. above the soil surface. At the cultivated watersheds soil temperatures are measured by thermocouples and resistance thermometers. The thermocouple temperatures are read and recorded manually each day at 8 a. m. The resistance thermometers are connected to a recorder which automatically records, at 15-min. intervals, soil temperatures at each of 14 different locations, and air temperature 3 in. above the soil. For the purposes of this paper, study will be made of the 8 a. m. soil temperatures at all three of the watersheds.

Temperature records are available for both soil and air, at each of the watersheds, continuously since 1942. This paper will deal only with daily records from the years 1947 through 1951 (see Appendix B).

SOIL AND ATMOSPHERIC CLIMATE: DISCUSSION

The atmospheric climate of the East Lansing area of Michigan alternates between continental and semimarine with changing meteorologic conditions (12). The semimarine type of climate is primarily occasioned by the influence of the Great Lakes, which surround the state on three sides. This lake influence is controlled by the force and direction of the winds. During periods of slight wind movement over the area the climate follows the continental pattern, with sharp variation in temperatures, ranging from hot summers to severely cold winters. These extremes, however, may be sharply and quickly modified by a strong wind from the lakes (12).

It has been shown by many technicians that soil climate is largely dependent upon the basic factors of atmospheric climate, such as barometric pressure, temperature, and humidity. Aeration of soils, as influenced by these phenomena, is also a major factor in soil climate. Camp and Walker (5), Harrington (6), Smith (9, 10), and Taylor (11), have demonstrated that atmospheric temperatures affect soil climate, and that this in turn has a pronounced effect on plant growth.

Atmospheric climate is one of the five major factors in soil formation. It affects the characteristics of soils over broad areas (12). Soil climate is modified by the atmospheric climate immediately above it, and vegetation further modifies the soil climate. The effect of vegetation depends to some extent upon its height and density. Wooded cover is generally most effective in modifying the climate of the soil, although the effect of grass cover is also marked. Topography has a modifying effect. Soil climate is particularly affected by direct radiation from the sun, particularly in summer. Soil cover affects this solar modification by interception of the sun's rays. Soil temperature variations from season to season are somewhat dependent upon the angle of the sun's rays to the soil surface, cloudiness, and air temperature. The effect of the latter is much more apparent in the upper layers of the soil. It is generally believed that the average temperature of the surface soil is higher than that of the air above it, but the data at East Lansing indicate this to be true only in cases of little or no cover. The daily fluctuations of soil temperature are generally less than those of air temperature, and soil-temperature changes lag behind atmospheric-temperature changes, especially in the lower soil depths. Daily variations are largely in the surface layers and decrease with depth, so that below approximately 42 in., the soil temperature does not readily reflect daily changes at the surface. There is usually a lag in soil temperature following seasonal variations in the air temperatures. The maximum temperature of the lower horizons is reached many days after the average air temperature has passed the seasonal maximum. The amount of these variations also descreases rapidly with depth, and at a depth of 4 to 10 ft. most soils are nearly constant in temperature (12).

Although some minor differences in the amount of heat absorbed by soils are due directly to the color and conductivity of the soil material, by far the most important differences result from variations in moisture content and organic matter. In order to change the temperature of soil, so much heat is required to change the temperature of the water in it, that other differences in specific heat are relatively insignificant. Porous, well-drained soils, such as sandy soils or those with well-developed porespaces through which the water may pass rapidly, warm up earliest in the spring; that is, they follow more closely the changes in the average air temperature. Soils with poorly developed structure such as massive clays and clay loams, are frequently so moist that they warm very slowly in the springtime (12).

SOIL-MOISTURE VARIATIONS

Soil-moisture determinations were made in all three watersheds at regular intervals. The wooded watershed, subject to much less change in moisture content and being rather difficult of access, was sampled at 2-week intervals for soil moisture determinations, utilizing the gravimetric method. This was accomplished through use of a Veihmeyer Tube for sampling at three depths, 0 to 6 in., 12 to 18 in., and 30 to 36 in. The samples were reduced to oven dryness and the soil moisture percentages were calculated. At the cultivated watersheds, however, a much more intensive study has been made of soil moisture variations at different depths. Here, daily determinations were made at 8 a.m. of soil moisture and temperature at different depths ranging to 60 in. Soil moisture was determined by means of the electrical resistance method (14). In view of the fact that the electrical resistance of plaster-of-paris moisture units is affected by both moisture and soil temperature, soil temperatures were determined through use of copper-constantan thermocouples and a portable potentiometer calibrated in degrees Fahrenheit. The electrical resistance method is one of the most successful yet devised for determination of soil moisture in situ (3, 7).

INTERPRETATION OF FIGURES

Previous studies of soil temperature (10) have tended to utilize data as to sky conditions, cloudiness, etc., in the interpretation of the temperature data. However, in view of the fact that pyrheliometric data, showing actual amounts of solar heat received in the area, are available, this information will be used in interpretation of results.

Precipitation records are available for the period of the life of the study from both areas of record. In the graphic presentation, actual daily precipitation for the watershed in question is plotted above the temperature data. In Appendix B daily amounts of precipitation at the cultivated watersheds are tabulated with each day's temperature record from each watershed so as to provide a measure of this climatic effect on temperature.

TEMPERATURE RECORDS

Temperature records are given in tabular form in Appendix B for the period 1947 through 1951. Similar records are generally available for the period of 1941 to date. In Appendix B, daily entries show air-soil temperature relations for 1-in. depths at Watersheds A and B, and the wooded watershed; 6-in. depths for Watersheds A and B, and the wooded watershed; 12-, 18-, 42-, and 60-in. depths for Watershed B; all in relation to the mean air temperature at the cultivated watersheds for that day. The mean air temperature was used as being most indicative of average daily air temperatures, and that of the cultivated watersheds was accepted as typical for all

TABLE 1

SOIL-AIR TEMPERATURE EXTREMES, 1947-51

Year	Mean Air Temp.	1" A Temp. (°F.)	1"B Temp. (°F.)	1" W Temp. (°F.)	6" A Temp. (°F.)	6" B Temp. (°F.)	6" W Temp. (°F.)	12" A Temp. (°F.)	18" A Temp. (°F.)	42" A Temp. (°F.)	60" A Temp. (°F.)
						MAXIMUM					
1947	84	86	82	71	77	77	71	75	74	69	66
1948	84	87	85	70	86	78	68	75	75	69	65
1949	84	84	75	78	79	79	71	78	76	79	66
1950	80	78	79	68	74	74	65	73	69	67	62
1951	79	75	74	66	70	74	65	70	68	63	60
Max. of period:	84	87	85	78	86	79	71	78	76	79	66
						MINIMUM					
1947	6	23	22	21	28	28	30	28	30	33	36
1948	-3	24	28	22	23	31	25	25	28	33	36
1949	6	27	29	23	29	30	30	31	31	38	43
1950	5	22	26	21	26	30	28	28	30	25	35
1951	2	25	27	17	28	29	28	30	32	35	36
Min. of period:	-3	22	22	17	23	28	25	25	28	25	35
						RANGE					
1947	6-84	23-86	22-82	21-71	28-77	28-77	30-71	28-75	30-74	33-69	36-66
1948	-3-84	24-87	28-85	22-70	23-86	31-78	25-68	25-75	28-75	33-69	36-65
1949	6-84	27-84	29-75	23-78	29-79	30-79	30-71	31-78	31-76	38-79	43-66
1950	5-80	22-78	26-79	21-68	26-74	30-74	28-65	28-73	30-69	25-67	35-62
1951	2-79	25-75	27-74	17-66	28-70	29-74	28-65	30-70	32-68	35-63	36-60
Range of period:	-3-84	22-87	22-85	17-78	23-86	28-79	25-71	25-78	28-76	25-79	35-66

Extremes of period, all depths: 17-87

Extremes of period, mean air: -3-84

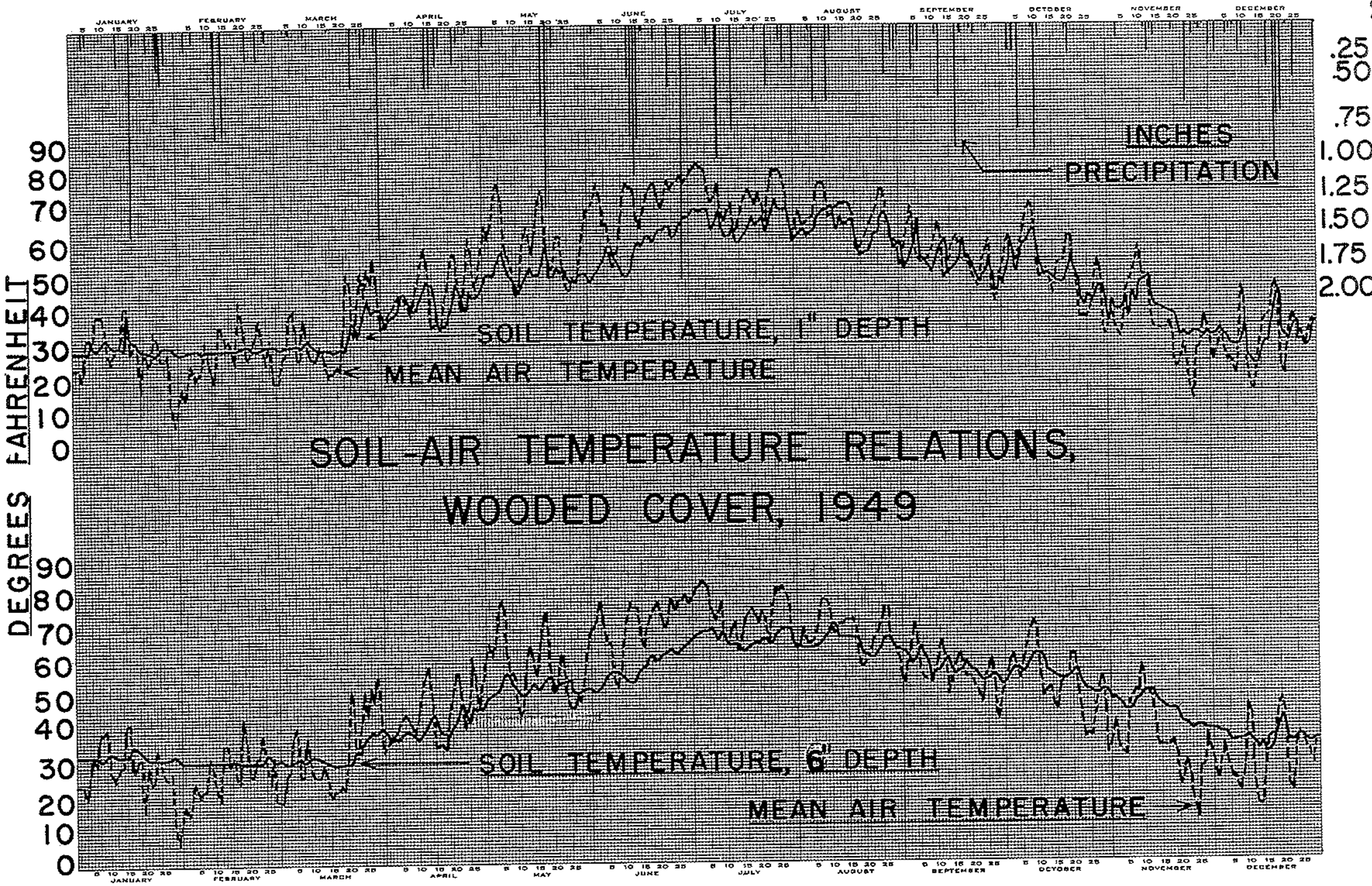


Figure 2. Comparison of mean daily air temperatures with 1- and 6-in. soil temperatures under deciduous forest cover at East Lansing, Michigan, 1949.

watersheds after consultation with climatologists of the U. S. Weather Bureau. In addition, Appendix B shows, for each day, the precipitation received at the cultivated watersheds, and the amount of insolation received, thereby clearly relating the cooling effect of precipitation, and the heating effect of solar radiation.

Temperature extremes, by years, for air and soil are summarized in Table 1. These should be used with caution, as they are undated values. Dates may be obtained by consulting Appendix B.

DAILY THERMOGRAPHS

Daily thermographs have been prepared, graphically presenting temperature fluctuations by 30-min. intervals for 24-hr. periods, at times of seasonal change. Although temperature data from the recording resistance thermometer are available for depths of 1, 4, 10, 12, 18, 21, 27, and 33 in. in Watershed A, 1 in. in Watershed B, and air temperature at a point 3 in. above ground level between the two watersheds, comparison by thermograph was made only for air temperature, and depths of 1, 12, 18, and 33 in.

The most noticeable attribute of the daily thermographs is the relative constancy of the temperatures found at the 18- and 33-in. levels. Almost no hourly variation of temperature was found at these depths, and what little there was occurred in the "dead hours" of predawn, when the heat stored in the soil the previous day tended to dissipate itself to some extent. Temperatures at the 1- and 12-in. levels showed the hourly effect of atmospheric temperatures and insolation but, nonetheless, were surprisingly stable. Analysis of these thermographs points to the conclusion that soil temperature variations, at the lower depths, are not so much the product of hourly, or even daily, air temperatures, but of accumulations of heat gradually stored in the soil profile. Preliminary plottings of thermal data, wherein soil temperatures were plotted cumulatively on an annual basis in comparison with cumulative mean air temperatures and insolation values, illustrate this very clearly. The curve resulting from mean air temperature reflects the insolation curve with remarkable accuracy, and the soil temperature curves follow the mean air curve almost exactly. In fact, the only reason this curve was not used as an illustration for this paper was the lack of separation between the 1-in. and 6-in. soil temperatures when plotted cumulatively and the fact that thermal curves for other depths were so close as to be confusing.

INTERPRETATION OF CHARTS

During January of 1949 at cultivated Watershed A, under meadow cover, the 1-in. depth showed the most stable temperature; the 8 a. m. average reading being 31. 0 F. Watershed B had a slightly higher average temperature under small grain and stubble cover. The average 1-in. soil temperature here was 31. 3 F. The wooded watershed had the lowest average temperature for the period: 30. 3 F. Mean air temperature for the period was 28. 1 F.

Wooded-soil temperatures at the 1-in. depth were more variable than the corresponding cultivated soil temperatures. On days when snow covered the ground, a lag of approximately one day between air and soil temperature changes was noted. However, on days with no snow cover, the lag could be measured in hours. It was noted that the percentage of moisture in the soil was consistently greater under wooded cover than under cultivation.

On January 26, the wooded area had a 4-in. blanket of snow on the surface and a 1-in. soil temperature of 30 F. Air temperature took a slight drop, and very slight rise, and then a sharp drop from 28 F. to 6 F. within 48 hr. One day after the air reached this low temperature, the wooded soil reached a low of 28 F.

An appreciation of the insulating effect of snow upon soil temperature can be gained by a comparison of the data for January with that for late November and December of the same year. In late November, with 8 in. of snow cover, an air temperature drop to 12 F. lowered the wooded soil temperature to 32 F. at the 1-in. level, in a period of 3 days. Previously, an air low of 22 F. without snow cover brought about a soil low temperature of 32 F. within one day. From a rather constant lag of less than a day under snow-free conditions, a change to a lag of three days under snow cover was noted.

The same period under meadow cover in Watershed A showed a low reading of only 33 F., with a time lag of one day. The effect of snow was here minimized by cover. However, soil moisture was greater at the wooded watershed than at Watershed A, where moisture conditions were more favorable for heat transfer. It must also be remembered that under wooded cover, the tree stems deflect and slow down air velocity, and minimize snow blowing. On meadow, however, wind has full play in moving and drifting snow, and at times large areas are blown almost completely clear.

Watershed B during the same period showed an average 1-in. soil depth low temperature of 31 F. This watershed was under small grain stubble and meadow cover. The soil temperature changes were very erratic.

Average monthly temperature for the watersheds for December were: 31.2 F., wooded watershed; 32.2 F., Watershed B; 33.3 F., Watershed A; and 31.1 F., mean air. The wooded watershed, without snow cover, had the most variable temperature, while Watershed A, under a heavy meadow cover, showed the most uniform temperature.

A comparison of the 6-in. depths shows that for the period of rapid temperature drop, the soils of the wooded watershed cooled much slower than those of the two cultivated watersheds. Meadow cover was next, with small grain showing rapid response to a drop in air temperature. The 6-in. low at the wooded watershed for the month of December was 32 F., that for small grain was 32 F., and for meadow 32 F. It is of interest to note that the wooded-watershed temperature reacted more sharply than the cultivated watersheds when snow was not present.

On December 13, a drop in air temperature to 16 F. brought a corresponding drop in 1-in. soil temperature to 23 F. with a time lag of less than a day at the wooded watershed. Small grain registered 28 F., while meadow recorded 31 F. in response to this change.

On December 20, a rise in average air temperature to a peak of 48 F. brought a corresponding increase in 1-in. temperature to 45 F. within one day at the wooded watershed. Small grain cover for the same period showed a lag of less than a day with a peak of 37 F. Meadow cover recorded a peak of 37 F. with a lag of a few hours.

Under small grain cover, for the first 6 mo., temperatures were quite stable for the month of January, and generally more erratic during February than in either of the other two watersheds. The modified cover conditions found there caused a lag of from 1 to 3 days. There was a lag of 3 days in connection with the air temperature drop to 6 F. in late January. This change occasioned a drop of 1 F. in soil temperature, bringing the 1-in. soil temperature to 30 F. under small grain cover. There was a snow blanket at the time. Wooded cover allowed a 2 F. drop to 28 F., while meadow cover permitted a 1 F. drop to 31 F.

After the disappearance of snow at the cultivated watersheds on February 11, a drop in air temperature to 19 F. brought a corresponding change in soil temperature from 30 F. to 26 F. under small grain cover. During this period the wooded watershed showed no reaction to the change in air temperature because of continued snow cover. Meadow cover showed a reduction in soil temperature of 2 F. to 29 F.

The period of March 1 to 20 was one of winter air temperatures. The soil temperature under the small, grain-covered watershed was most erratic, while the wooded watershed was the most stable of the three for this period.

Watershed B, with small grain cover, on March 19, one day after the last snow melt of the winter season, showed the effect of the beginning of spring weather. In two days the air temperature rose from 22 F. to 52 F. The soil temperature at the 1-in. depth rose from a low of 29 F. to 31 F. the same day. There were less radical changes in soil temperature occasioned by air temperature changes than at any time during summer or autumn. A fall in air temperature from 56 F. to 35 F. during this period produced a fall in the slowly rising soil temp-

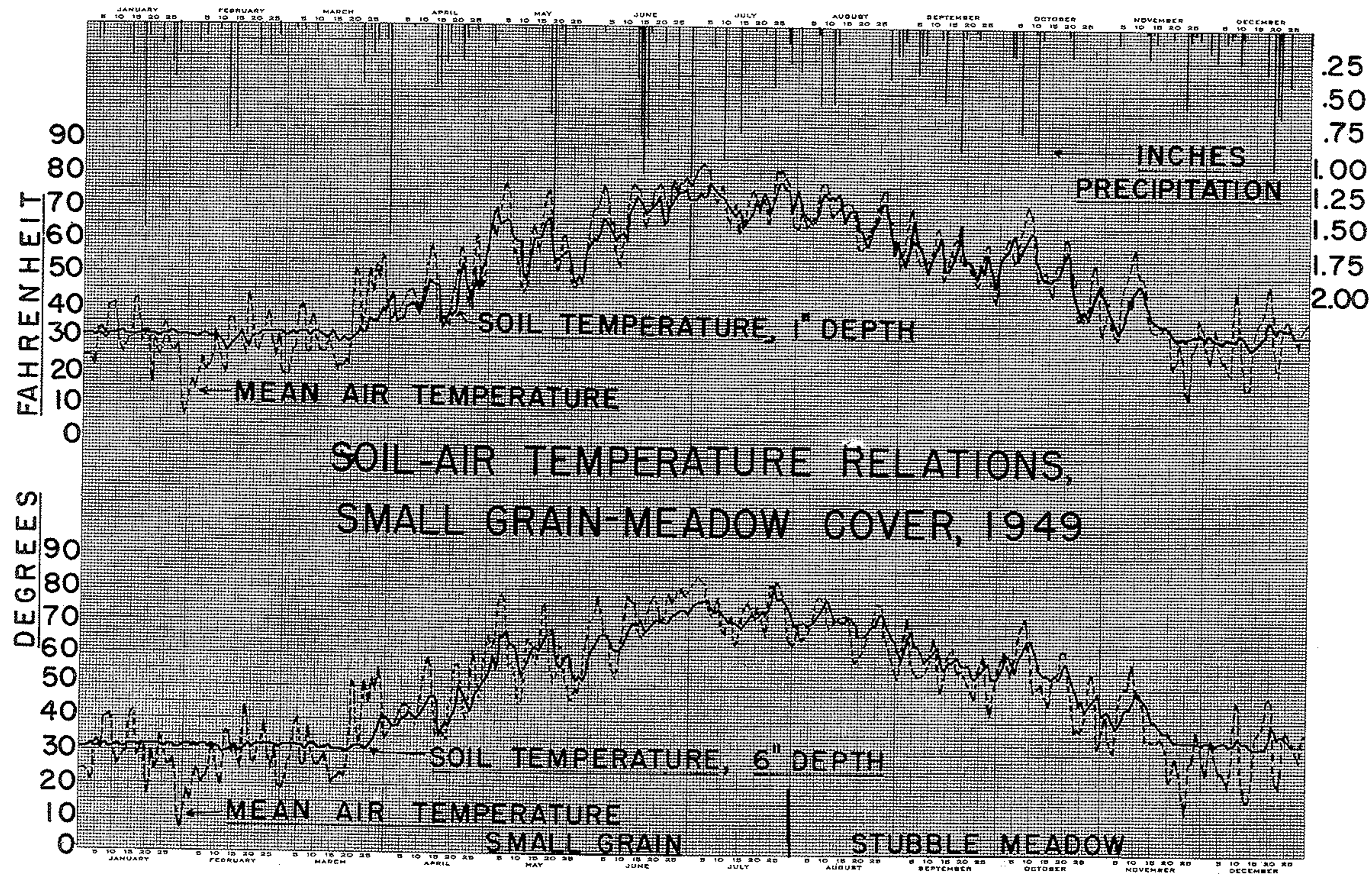


Figure 3. Comparison of mean daily air temperatures with 1- and 6-in. soil temperatures under small grain and stubble-meadow cover at East Lansing, Michigan, 1949.

erature only after a period of three days; that is, the peak for soil temperature lagged three days behind the peak for air temperature. The 6-in. soil depth's reaction to the rise in late March air temperature was a steady rise instead of a series of rises, as was the case at the 1-in. depth. However, the temperature fall at the 6-in. layer only lagged one day behind the air temperature change, showing the effect of the still cool layers below.

Meadow cover on Watershed A at the one-in. depth, for the period March 19 to April 1, showed a rather steady increase, with little fluctuation or response to the rapid rise in air temperature. However, a drop in air temperature of 22 F. over a period of two days occasioned a drop of 6 F. at the 1-in. soil depth, and this occurred after a time lag of 3 days. The peak temperature for the period lagged 3 days behind air temperature.

Under wooded cover during the same period, the response of 1-in. and 6-in. depths to air change was more rapid than under meadow. The peak period under wooded cover was reached 5 days earlier than under either meadow or small grain cover. The peak temperature for both small grain and wooded cover was 44 F., while the peak temperature for meadow was 39 F. This period marked the end of winter and the beginning of spring. The temperature rise of the 6-in. layer in the forest was more nearly coincidental with air than similar depths under other covers.

On April 13, air temperature began a descent from a peak of 59 F. In a 2-day period, it dropped to 35 F. and was followed one day later by the 1-in. soil temperature, which fell to 34 F. The bottom of the trough showed a one day lag. This was under meadow cover. Also under meadow cover, the 6-in. depth showed a lag of two days and dropped to a low of 38 F.

Under wooded cover, the 1-in. depth showed a lag of two days in dropping from a peak of 48 F. to a low of 34 F. The 6-in. depth showed a one day lag in beginning its fall, and in reaching its low of 38 F.

Under small grain, the same time lag was noticed. The lowest temperature at the 1-in. layer was registered under this cover, with wooded cover causing a considerably higher temperature. The same pattern held for the 6-in. depth.

All depths at Watershed B showed the effects of the temperature drop. The lowest depth, 60 in., registered its lowest temperature of the year up to this point. The 42-in. and 60-in. depths had heretofore shown small reaction, if any, to extremes in temperature. They had shown a steady decline in temperature until the latter part of March, then a rapid, steady rise.

The lowest recorded air temperature for 1949 was 6 F. This occurred on January 30. The lowest recorded temperature for the 60-in. layer, 37 F., occurred during the period March 20 to March 28. The lowest recorded temperature for the 42-in. depth was 34 F. This was reached on March 26 and March 27.

The highest recorded air temperature, 84 F., occurred on July 3. The high temperature reading for the 60-in. layer, 66 F., occurred August 19. The 42-in. high of 79 F. occurred on July 30.

An analysis of the temperatures of the 42-in. and 60-in. soil depths leads to the conclusion that soil temperatures at these depths are not the obvious result of daily temperature change but are the result of seasonal accumulations or losses of solar heat.

The next major change in air temperature came about during the period of May 5 to 10. Air temperature dropped during this period from 78 F. to 44 F. The 1-in. wooded temperature dropped from 58 F. to 45 F. within one day. Meadow temperatures for the same period dropped from a 1-in. temperature of 64 F. to 47 F. For the first time, the forest temperature showed the effect of the foliage in shielding the forest floor. Under small grain, the peak temperature for the period was much higher, 70 F., while the low was 48 F. This illustrates the effect of cover in controlling heat absorption and retention by the soil in the spring. Soils under small grain showed greater temperature extremes than either of the other stations.

Under wooded cover, the 6-in. layer rose to 57 F. and dropped to 50 F., while meadow cover reached a peak of

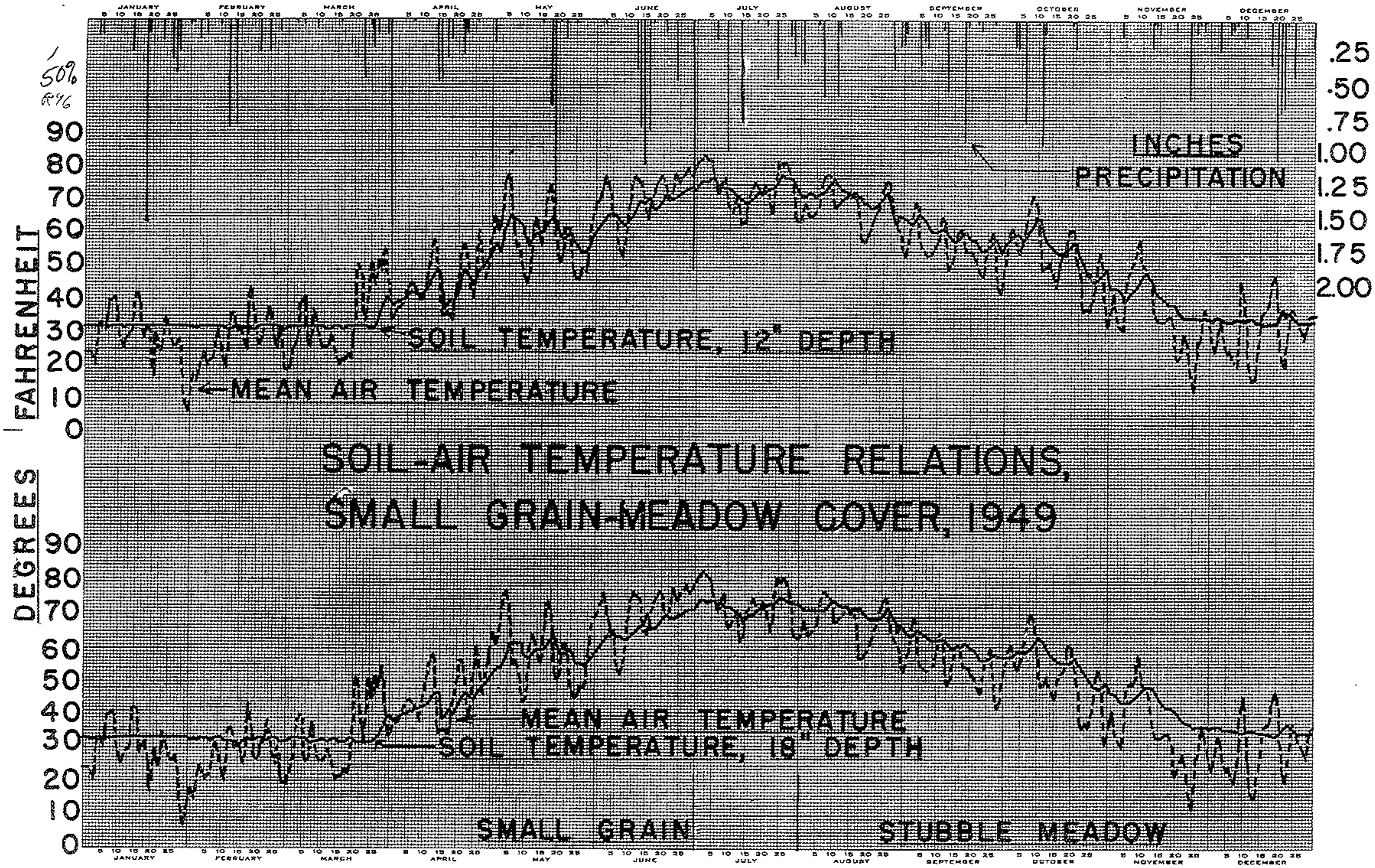


Figure 4. Comparison of mean daily air temperatures with 12- and 18-in. soil temperatures under small-grain and stubble-meadow cover at East Lansing, Michigan, 1949.

60 F. and a trough of 50 F. Under small grain, meanwhile, the soil at 6 in. heated to 67 F., and cooled to 53 F. Thus, it is seen, as the season became progressively warmer temperature peaks and troughs became more extreme in inverse proportion to the amount of cover. At the 60-in. depth, the five-day variation was not apparent.

Inspection of the charts and data thus far indicates that, with warmer weather, one may expect lower soil temperatures under wooded cover than under cultivation, showing the effect of the verdant growth of foliage found at this time of year. Further examination of the charts shows that under small grain, during the period of June 1 to 13, when soil moisture content at the 1-in. depth was 4.5 percent, the soil reacted immediately to air temperature changes. However, wooded cover, with a higher moisture content and a more dense cover, caused a time lag of 3 days for the same temperature change. Under meadow cover the lag was one day. Again, the soil moisture was higher than under small grain.

On June 13 to 17, the area received enough precipitation to bring soil moisture content at the 1-in. depth under small grain to a content of 8.5 percent. The time lag for the moisture rise and the corresponding drop in soil temperature varied from 1 to 2 days. The same lag was noted for the 6-in. depth. Under wodded cover such time lags practically disappeared towards the end of June. However, the soil temperature under this type of cover was still far below that for the other two covers.

July 3 had the highest peak air temperature of 1949, 84 F. The 1949 temperatures and dates for all soil depths were as follows:

in.	Woods	Meadow	Small Grain
1	73 F. July 26	77 F. July 6	78 F. July 5 and 26
6	71 F. Aug. 11	76 F. July 6	81 F. July 26
12			78 F. July 26
18			76 F. July 26
42			79 F. July 30
60			66 F. Aug. 19

Commencing in August, under wooded cover, the differences between air and soil temperature tended to become less and lag greater. This trend was very pronounced in September when time lags of two days were frequent between peaks of rising temperature and lags of one day common between troughs in falling temperature. After the middle of September, these lags disappeared and responses were almost immediate. Soil moisture during this period was relatively stable, within the range of $4\frac{1}{2}$ to 7 percent. In October, rapidly falling air temperatures fell below the more slowly falling soil temperatures at the 1-in. depth. This occurred at the 6-in. wooded depth in mid-August, two months previous to the reversal at the 1-in. depth.

Under meadow cover, the lags in temperature changes became less pronounced about the middle of July.

In July, the soil temperature under small grain showed rapid response to air temperature changes, and continued to vary until mid-November. In late July the small grain was harvested and meadow cover (stubble) remained. Under this cover the fluctuations of soil temperature were marked, and the extremes were nearly as great as those of air temperatures.

Soil temperature was higher than the average air temperature on the following dates:

in.	Wooded Cover	Small Grain Cover	Meadow Cover
1	Oct. 13, Mar. 20	Nov. 15, Mar. 20	Nov. 13, Mar. 20
6	Sept. 19, Mar. 20	July 6, Mar. 20	Aug. 10, Mar. 20

The first below-freezing average air temperature in the fall occurred during the period November 10 to 26. This was preceded by a week's falling temperature, reaching a low of 33 F. Under grain stubble a two day lag of soil temperature was finally overcome and the soil temperature dropped to within two degrees of the low air temperature. This was followed by sharply rising air temperatures to 59 F. Soil temperature responded very slowly and rose to 48 F., where the again-falling air temperature carried it to 31

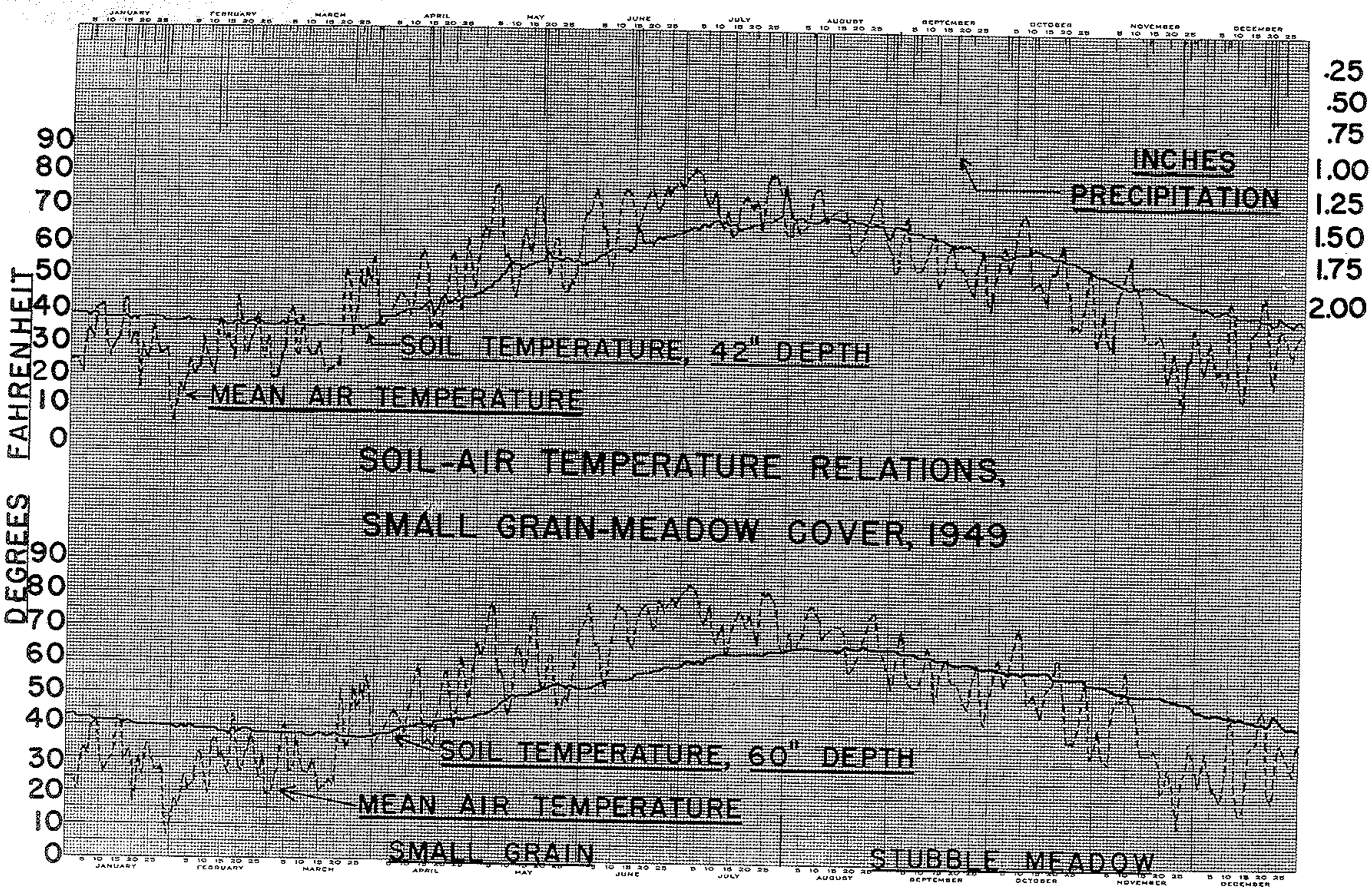


Figure 5. Comparison of mean daily air temperatures with 42- and 60-in. soil temperatures under small-grain and stubble-meadow cover at East Lansing, Michigan, 1949.

F. on November 22. Wooded-soil temperature for the same period showed less fluctuation, but reached the 32 F. temperature on the same day as the stubble covered watershed. Meadow soil temperatures were the most stable for this period, and reached a low of 32 F. at the 1-in. depth on December 8.

The winter season under meadow cover was a period of relative stability. The lowest soil temperature was 31 F., recorded on December 9, 13, 15, 16, and 17, in response to air temperature drops to 12 F. and 16 F. The 6-in. layer recorded a December low of 32 F. on December 20 in response to the 16 F. air low. Under wooded cover, the 1-in. layer reached a low of 23 F. on December 14. The low for the 6-in. layer was 32 F. on December 16.

On December 14, the stubble covered watershed's 1-in. layer reached a temperature of 28 F., while the 6-in. layer had a temperature of 32 F. on December 16. The 12-in. layer at this watershed recorded its lowest temperature on December 16, 33 F.; while the 18-in. layer reached, on December 20, a low of 34 F. The 42-in. depth, meanwhile, registered its low of 38 F. on December 28. The 60-in. layer's low of 42 F. was reached on December 28.

SUMMARY

The most stable period for soil temperatures was found to be the months of January, February, and early March. Meadow cover was most stable for this period, while small grain was most subject to fluctuation. Falling air temperatures during this period were usually accompanied by rains, which helped melt the snow then present on the ground and, in infiltrating, rapidly cooled the 1- and 6-in. layers.

Wooded temperatures in late March and early April were in a state of flux, responding rapidly to changes in air temperatures. As soon as the leaf cover became dense enough to shade the ground, the wooded soil temperatures began to lag behind the rising air temperatures.

Under small-grain cover during the same period, temperature response was slower than under wooded cover, and time lags were greater because of the advanced development of the small-grain crop. After this time, however, soil temperatures followed air temperature more closely than under any other cover. Small-grain soil temperatures during this time were slightly lower than air temperatures.

Response to air-temperature change was slowest for the period of late March and early April under meadow cover. Until early May, the soil temperature response under meadow was slower than under wooded cover. After this, soil temperature more nearly followed air temperature under meadow than under timber.

Bouyoucos (2, 4) observed that heat penetrated uncultivated soil more rapidly than cultivated soil. It was his conclusion that sod-covered soil would be slowest to warm up. The findings of the current study completely substantiate his hypothesis. A comparison of the charts for 1-in. depths will show a sharp rise in soil temperatures of the wooded watershed in late March. Small grain cover gave a slower temperature rise, while meadow showed the slowest rise of the three.

The lowest average soil temperatures under the various soil covers in the summer months were found at the wooded watershed. Here, temperatures were quite low until mid-July. The charts for the 12-, 18-, 42-, and 60-in. depths also indicate that this period marks the peak temperatures for these depths. It should be borne in mind that transpiration has, by this time, removed large quantities of water from the soil, so that the moisture content is near the optimum for heat transfer. After July, the differences between 1-in. soil temperatures and air temperatures were smaller. In September, the falling air temperature and the slowly falling soil temperature were in equilibrium for the first time since early April. This condition was maintained during September and October. In early November, the air temperature, falling rapidly, fell far below the soil temperature and until late January, soil temperatures fluctuated until a state of equilibrium was established between the upper and lower depths. In this area, under wooded cover, the ev-

idence of local records points to approximately 30 F. as the normal winter soil temperature, once it has been exposed to cold air long enough to cool the lower depths.

The situation in the 6-in. wooded soil zone was essentially the same as the 1-in. except for time lags. In mid-September, the air temperature fell below the soil temperature and the 6-in. layer reached its winter equilibrium at approximately the same time as the 1-in. layer. The equilibrium temperature was 31 F.

The 1-in. and 6-in. layers under small grain showed the effects of cover in holding soil temperature to a slow rise in late March. However, summer soil temperatures under this cover were very high in relation to the other two types of cover; and after the grain was cut in late July, soil temperatures at the 1-in. level were higher than the air temperatures. A condition of pronounced soil temperature response to air temperature existed until mid-November, when the soil was cooled rapidly at the 1-, 6-, and 12-in. depths by a sharp drop in air temperature. Because of sudden chilling of its less shallow depths, this watershed reached its equilibrium point of approximately 31 F. in late December.

Meadow cover, consisting of alfalfa and brome grass, was cut twice during the summer of 1949. Cutting dates can easily be located on the 1-in. and 6-in. temperature charts. In May and August, after the cutting of the meadow cover, soil temperatures rose sharply in relation to air temperatures.

There have been many broad statements made concerning the tempering effect upon soil climate of vegetation. It is generally conceded that a forest cover has the greatest effect upon soil climate. The studies at East Lansing indicate that this statement is true in part. The effect of a forest cover upon soil climate will depend upon whether the trees are coniferous or deciduous, their density, depth of leaf mat, etc. The wooded watershed under study, being a hardwood forest, exerts its greatest influence upon soil temperature during the summer, when the foliage tends to screen the soil surface from solar heat. This influence is somewhat lessened by the decrease in soil moisture, through evapotranspiration, to an optimum condition for heat transfer.

Under wooded conditions it was observed that snow covers the ground for longer intervals than is the case under other vegetative cover, and exerts its influence more markedly in ameliorating the effects of extreme temperature drops.

There is, of course, an exchange of air between the surface atmosphere and the pore spaces of the soil. As rain infiltrates the ground, it occupies pore space usually filled with air, thus forcing the air out. As the soil dries, air replaces the moisture. This is one method by which changes in soil temperature are encouraged (4). However, the studies at East Lansing indicate that a greater influencing factor is solar heat. Any vegetal cover tends to reduce the receipt of solar heat in proportion to the density of that cover.

As the various covers were harvested, small grain and meadow, there was greater opportunity for solar heat to exert its warming influence directly upon the soil, and soil temperatures were much higher in relation to air than at other times.

There exists no doubt as to the effect exerted upon soil temperatures by soil moisture, barometric pressure changes, soil color and physical makeup. It is the belief of the authors, however, that the greatest factor in soil temperature is the modification of these various phenomena by vegetative cover. The effect of cover is more widespread than its solar-shielding effect. Vegetal cover also markedly influences each of the following: 1. Moisture content at different soil depths (10). 2. Porosity, permeability, and thus aeration of the soil (10). 3. The color of the soil and organic content (10). 4. The length of time snow will remain on the soil surface (2).

Vegetation exerts then, not only a direct influence upon soil temperature, but also an indirect influence upon almost every other factor affecting soil temperature changes and other hydrologic factors.

REFERENCES

1. Bernard, F., and Betts. C. A., Water and Our Forests, U. S. D. A. Forest

Service Miscellaneous Publication No. 600: 9; 1946.

2. Bouyoucos, G. J., An Investigation of Soil Temperature and Some of the Factors Influencing It, Michigan Agricultural Experiment Station Technical Bulletin 17; 1913.

3. Bouyoucos, G. J., and Crabb, G. A., Jr., Measurement of Soil Moisture by the Electrical Resistance Method. Agricultural Engineering 30 (12): 581-583, 585; 1949.

4. Bouyoucos, G. J. and McCool, M. M., The Aeration of Soils as Influenced by Air Barometric Pressure Changes, Soil Science XVIII (1), 53-63; 1924.

5. Camp, A. F., and Walker, M. N., Soil Temperature Studies with Cotton, Florida Agricultural Experiment Station Bulletin 189: 1-32; 1927.

6. Harrington, E. L., Soil Temperatures in Saskatchewan, Soil Science 25: 183-195; 1928.

7. Kelley, O. J., Hunter, A. S.; Haise, H. R.; and Hobbs, C. H., A Comparison of Methods of Measuring Soil Moisture under Field Conditions, Journal of the American Society of Agronomy 38 (9); 1946.

8. Lutz, H. J., and Chandler, R. F., Forest Soils, 264-265; 300; John Wiley and Sons; 1946.

9. Smith, Alfred, A Contribution to the Study of Inter-Relations Between the Temperature of the Soil and the Atmosphere, and a New Type of Thermometer for Such Study, Soil Science 22: 447-456; 1926.

10. Smith, Alfred, Daily and Seasonal Air and Soil Temperatures at Davis, California, Hilgardia 4: 77-112; 1929.

11. Taylor, E. M., Soil Temperature in Egypt, Journal of Agricultural Science 18: 90; 1928.

12. USDA Yearbook, Climate and Man, Yearbook: 270-291; 1941.

13. U. S. Weather Bureau, Climatological Data — National Summary 1 (1): 23; 1950.

14. White, R. G., Installations for Noting Water and Thermal Relationships in Soils, Agricultural Engineering 27 (1): 21-25; 1946.

Discussion

CARL B. CRAWFORD, Division of Building Research, National Research Council, Ottawa, Canada — The presentation of this paper illustrates the value of cooperation between two normally unrelated sciences. A great many of the unanswered questions concerning soil temperatures have been posed by agriculturalists and many problems have been solved jointly by agriculturalists and engineers.

In this discussion the writer can present some data in support of the author's conclusions. Part of this information has been published by Legget and Crawford (G). These observations have been obtained from a general study of soil temperatures being carried out at Ottawa, by the Division of Building Research of the National Research Council of Canada (F).

The cooling effect in summer of grass-cover is shown in Table A. Although it is thought that grass also has a warming effect in winter, no comparisons are possible since the effects are masked by snow cover.

TABLE A
MAXIMUM SOIL TEMPERATURES OCCURRING UNDER PAVEMENT AND ADJACENT GRASS COVER

Year	Depth	Max. Temp. During Year	
		Pavement	Grass
	ft.	F.	F.
1950	2	82	67
	5	68	60
1951	2	84	68
	5	68	60

As pointed out by the authors, Bouyoucos observed similar effects of grass cover in his work many years ago. Algren (E) found temperatures under sodded ground to be 7.6 F. lower than under bare ground at a depth of 1 ft. in September. At a depth of 16 ft. the difference was

3.6 F. Both Belotelkin (C) and Atkinson and Bay (B) observed considerable differences in frost penetration between pastures and forest covers.

The value of undisturbed snow in reducing frost penetration was quite evident in the Ottawa work.

TABLE B
THE EFFECT OF UNDISTURBED SNOW-COVER ON FROST PENETRATION IN 1950-51

Soil Type	Frost Penetration	
	Snow-Cover in.	No Snow in.
Sand	18	46
Clay	9	29

Table B shows the variation in maximum frost penetration in prepared test pits with and without snow-cover. The average snow cover for the winter was about 1 ft.

In addition to the test-pit measurements a record of frost depths in excavations has been kept by the Ottawa Water Works Department for several years. A study of these records revealed that on the average the frost depth was reduced about 2 ft. for each foot of snow cover. This study has shown a greater effect than that reported by Atkinson and Bay (B) who found that snow reduced frost penetration by an amount equal to its depth.

Thompson (A) studied soil temperatures at Winnipeg, Canada. He found the annual average soil temperature to be 4.7 F. warmer than the average air temperature. Part of this difference was attributed to the insulating effect of snow cover.

In his theoretical studies Berggren (D) estimated that the depth of frost penetration during a given time would be reduced to about one sixth by 4 in. of fresh snow. Many investigators have noticed this marked effect of snow cover, but quite naturally the degree of effect has been variable due to the variety in snow properties.

Of particular interest to many readers of this paper will be the authors' reference to the measurement of soil moisture in situ using the electrical-resistance method. These instruments are an agricultural development which seem to perform adequately their original use which was to follow moisture changes in relatively dry soils. Attempts by the Division of Building Research to use the electrical methods in soils of higher water contents have not been successful. Work is now going on in an effort to devise a similar method which will give satisfactory results.

REFERENCES

A. Thompson, W. A., "Soil Temperatures at Winnipeg, Manitoba", Scientific Agriculture, Canada, Vol. XV, No. 4, pp. 209-217, 1934.

B. Atkinson, H. B. and Bay, C. E., "Some Factors Affecting Frost Penetration", Transactions, American Geophysical Union, Part 3, pp. 935-947, Sept. 1940.

C. Belotelkin, D. T., "Soil Freezing and Forest Cover", Transactions, American Geophysical Union, Part I, pp. 173-175, July, 1941.

D. Berggren, W. P., "Prediction of Temperature --Distribution in Frozen Soils", Transactions, American Geophysical Union, Part 3, pp. 71-77, Nov. 1943.

E. Algren, A. B., "Ground Temperatures as Affected by Weather Conditions", Heating, Piping and Air Conditioning, v. 21, n. 6, pp. 111-116, June, 1949.

F. Legget, R. F., and Peckover, F. L., "Soil Temperature Studies -- A Progress Report", Proceedings, Annual Meeting of the Highway Research Board, pp. 434-445, 1949.

G. Legget, R. F. and Crawford, C. B., "Soil Temperatures in Water Works Practice", Journal, American Water Works Association, Vol. 44, No. 10, pp. 923-939, 1952.

Appendix A

CROP HISTORY, CULTIVATED WATERSHEDS, 1947 THROUGH 1951

1947

WATERSHED A		WATERSHED B	
4-18	Plowed.	4-19	Plowed.
4-19	Plowed & harrowed, oats & alfalfa-brome planted.	6-3 & 4	Disked & planted corn.
8-1	Oats harvested.	6-24 & 25	Cultivated corn.
		9-11	Drilled rye in corn.
		10-5	Harvested corn.

1948

WATERSHED A		WATERSHED B	
6-16	Alfalfa-brome cut.	5-5	Plowed & culti-packed.
8-12	Alfalfa-brome cut.	5-25	Planted corn.
		6-5 & 5-9	Cultivated corn.
		9-23	Corn cut for ensilage.
		10-9	Rye drilled inccorn stubble.

1949

WATERSHED A		WATERSHED B	
6-10	Alfalfa-brome cut.	4-13	Plowed.
7-20	Alfalfa-brome cut.	4-14	Harrowed; planted oats & alfalfa-brome.
		7-15	Oats cut.
		8-10	Oats harvested.

1950

WATERSHED A		WATERSHED B	
5-23	Harrowed, planted corn.	6-22	Alfalfa-brome cut.
6-7,14,& 19	Corn cultivated.	8-23	Alfalfa-brome cut.
7-6	Corn cultivated.	10-30	Alfalfa 6" to 8" tall, thin growth.
8-6	Rye seeded.		
10-23	Corn husked; stocks left in field. Heavy growth of rye.		
12-4	Corn stocks chopped in field.		

1951

WATERSHED A		WATERSHED B	
5-14	Rye 22" high plowed under.	6-19	Alfalfa-brome cut.
5-21	Corn planted.	8-20	Alfalfa-brome cut.
6-17 to 7-17	Corn Cultivated six times.		
10-30	Corn harvested.		
7-17	Rye cover crop seeded.		

Appendix B

DAILY RECORD OF SOIL AND AIR TEMPERATURES, PRECIPITATION, AND INSOLATION, 1947 THROUGH 1951, BY MONTHS

JANUARY 1947

DATE:	TEMPERATURES (°F.)											Total Precip. (In.)	Total Insol. (Lang.)
	Mean Air	Soil Depths in Inches Stations A, B, & W.											
		1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A		
1	11	30	29		31	31		32	34	39	44	-	79
2	24	31	30		31	31		32	33	38	43	.45	30
3	17	31	31		31	31		32	33	38	43	.02	65
4	14	31	30	28	32	31	33	32	34	38	43	-	148
5	13	31	29	29	31	31	33	32	33	38	43	T	177
6	20	31	31	29	32	32	34	32	34	38	43	-	55
7	28	32	31	30	32	32	34	32	34	38	43	-	24
8	23	31	31	30	32	32	34	32	33	38	43	T	112
9	20	31	30	30	32	31	34	32	33	38	43	.01	151
10	26	31	31	30	32	31	34	32	33	38	43	-	62
11	33	32	31	30	32	31	34	32	33	38	42	-	34
12	20	32	31	30	32	32	34	33	34	38	42	-	190
13	30	31	31	30	32	31	34	33	33	38	42	T	26
14	38	32	32		32	32		32	33	38	42	.08	3
15	34	31	31		31	32		32	33	37	41	-	117
16	26	31	31		31	31		32	33	36	41	.01	68
17	30	30	30	28	30	31	34	31	33	36	40	T	155
18	33	29	29	28	31	31	34	32	33	37	41	-	173
19	37	29	30	28	31	31	34	32	33	38	42	-	189
20	30	32	32	29	32	32	34	32	33	37	41	.45	29
21	13	28	27	30	31	30	34	31	32	36	39	T	161
22	11	29	27	27	30	29	36	32	33	37	40	-	182
23	26	30	28	27	31	29	33	31	33	37	40	-	96
24	38	31	31	28	31	31	33	31	32	36	40	T	33
25	38	32	32	28	32	32	32	32	33	37	41	T	75
26	40	32	32	28	32	32	33	32	33	37	41	.01	191
27	44	32	22	30	32	32	33	32	33	37	40	.01	159
28	30	31	31	31	31	31	34	31	32	36	40	-	119
29	26	32	32	31	31	32	33	32	32	36	40	.67	17
30	28	32	32	31	32	32	33	32	33	37	40	1.09	31
31	25	31	32	31	31	32	33	31	32	36	39	.03	118

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

FEBRUARY 1947

DATE:	TEMPERATURES (°F.)											Total Precip. (In.)	Total Insol. (Lang.)
	Mean Air	Soil Depths in Inches Stations A, B, & W.											
		1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A		
1	22	32	32	30	32	32	32	32	33	37	40	.02	100
2	20	31	32	30	32	32	32	32	33	36	40	T	212
3	29	31	31	30	31	32	32	32	33	37	40	-	163
4	12	30	29	30	31	30	32	31	32	36	39	T	263
5	6	29	28	29	30	30	32	32	33	36	39	T	156
6	13	29	28	29	30	29	31	32	33	36	39	.02	133
7	8	29	29	29	30	30	31	31	32	36	40	.02	197
8	8	28	29	28	30	30	31	31	32	36	39	.01	243
9	18	28	30	28	30	31	31	31	33	36	39	-	218
10	22	30	30	28	31	30	31	31	32	37	40	-	183
11	23	29	29	28	30	30	31	31	32	36	39	-	249
12	26	29	30	29	30	30	31	31	32	36	39	-	268
13	32	29	29	29	29	30	31	30	31	35	38	-	195
14	40	30	31	30	31	31	31	31	32	36	39	-	192
15	32	32	31	30	32	31	31	32	32	36	39	.01	39
16	24	32	32	30	32	32	31	32	32	36	39	.04	169
17	26	32	31	30	32	31	31	32	32	36	39	T	117
18	20	31	30	31	31	31	32	31	32	36	39	T	258
19	13	29	29	30	31	29	32	32	33	36	39	-	317
20	15	27	27	29	29	28	31	30	32	35	38	-	328
21	17	28	27	29	29	28	31	30	32	35	38	.01	231
22	18	27	26	28	29	28	31	30	32	36	38	-	291
23	16	26	25	28	28	28	30	30	32	37	39	.02	260
24	27	29	28	28	29	28	30	30	32	36	38	.02	179
25	28	29	29	29	29	29	31	30	31	35	38	-	192
26	26	29	30	29	29	30	31	30	31	35	38	T	339
27	20	28	29	29	28	29	31	29	31	35	38	-	272
28	20	27	29	29	28	29	31	29	32	35	38	-	378
29													
30													
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

MARCH 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F) — Soil Depths in Inches, Stations A, B, & W.												
1	24	26	28	28	28	29	31	29	31	35	38	.03	182
2	26	29	29	28	30	29	31	31	32	35	39	.08	274
3	24	27	29	28	28	29	31	29	31	35	38	-	332
4	27	27	29	29	28	29	31	28	30	34	38	-	328
5	26	27	29	29	28	29	31	29	31	35	38	-	279
6	32	29	30	31	29	30	31	29	30	34	37	-	194
7	24	30	30	29	30	30	31	30	31	35	38	-	237
8	24	28	29	29	29	30	30	29	31	34	37	-	364
9	26	28	30	29	28	30	30	29	30	34	37	-	207
10	27	29	31	29	29	31	31	29	31	34	37	-	435
11	29	30	31	30	30	31	31	30	31	34	37	-	440
12	37	31	31	30	31	31	31	31	31	34	37	-	356
13	38	30	31	30	30	31	31	30	30	34	36	.21	104
14	32	32	31	30	31	31	31	31	32	34	37	T	142
15	32	29	29	29	30	30	31	31	31	34	37	T	260
16	26	29	29	29	30	30	31	31	32	35	38	T	340
17	24	29	29	30	29	29	31	30	31	35	37	T	240
18	25	27	28	29	28	28	31	29	31	34	37	-	402
19	28	26	27	30	28	28	31	29	31	34	37	-	414
20	33	30	31	30	30	31	31	30	31	34	37	-	359
21	32	31	31	30	31	30	30	31	31	34	37	.01	153
22	34	30	31	30	31	31	30	31	32	34	37	-	299
23	46	31	31	31	31	31	32	31	31	34	37	.24	207
24	40	33	32	30	32	32	31	32	32	35	37	.58	32
25	24	32	32	30	32	32	30	32	32	35	37	.04	295
26	24	32	31	30	32	31	30	31	31	34	37	T	395
27	24	32	31	30	32	31	30	31	31	34	37	-	513
28	28	31	32	30	31	32	30	31	31	34	37	.01	211
29	30	32	32	30	32	32	30	32	32	35	37	.12	219
30	27	32	31	30	32	32	30	32	32	34	37	-	532
31	33	32	32	30	32	32	30	32	32	34	37	.01	338

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

APRIL 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, & W.												
1	42	32	32	29	32	31	31	31	32	34	37	.02	192
2	36	33	32	31	32	32	31	32	32	35	37	.97	117
3	36	32	31	30	32	31	31	32	32	34	37	-	518
4	40	32	31	30	32	31	31	31	32	33	36	.20	60
5	58	46	43	43	34	32	35	32	32	34	36	2.57	97
6	46	37	35	44	34	32	40	32	32	34	37	-	72
7	38	38	37	35	33	32	37	32	32	34	36	-	287
8	40	32	32	35	32	32	36	32	32	34	36	-	200
9	43	44	42	38	35	33	38	32	32	33	36	-	323
10	51	38	36	38	34	33	38	32	32	34	36	.35	96
11	52	48	45	50	42	38	43	38	34	34	36	.11	34
12	36	38	35	41	39	34	42	39	38	34	36	.04	88
13	34	34	32	34	35	32	37	37	37	37	37	-	271
14	44	48	44	35	39	35	37	37	36	36	36	-	518
15	42	37	35	37	37	33	39	38	38	36	37	.03	369
16	36	36	34	38	37	34	39	38	38	36	37	.06	282
17	42	45	42	34	39	36	37	37	37	37	38	.09	432
18	40	43	42	39	42	41	38	41	40	38	38	.32	287
19	38	44	43	36	40	38	38	39	39	38	38	.19	430
20	34	37	36	34	38	37	38	39	40	39	39	.34	191
21	38	45	41	32	38	36	36	37	37	38	38	-	520
22	45	39	38	37	39	37	36	39	39	39	39	-	171
23	58	51	48	42	45	42	38	41	39	38	38	-	217
24	54	47	46	45	47	46	44	46	43	39	39	.12	522
25	43	48	45	44	46	44	44	45	44	39	39	-	240
26	50	41	40	40	43	41	42	44	44	40	40	-	527
27	46	47	46	46	47	46	46	47	45	42	40	.03	423
28	43	52	48	37	45	44	42	43	43	41	40	-	602
29	56	47	46	45	45	44	44	44	44	41	40	.05	254
30	56	60	57	52	53	51	49	49	46	41	40	.23	273
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

MAY 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches — Stations A, B, and W.											
1	54	56	54	47	51	49	48	49	47	42	40	1.21	163
2	51	53	51	48	52	50	49	50	49	43	42	.04	206
3	52	51	48	46	48	48	47	49	49	44	42	-	380
4	54	50	49	48	50	50	48	50	50	45	43	.05	246
5	48	52	49	47	48	48	48	47	47	44	42	T	162
6	46	47	46	45	45	46	47	46	47	45	43	.19	390
7	35	40	42	42	42	44	46	43	45	45	43	-	251
8	34	33	37	38	38	40	43	41	44	45	43	-	262
9	38	53	44	36	39	41	41	38	41	43	43	-	663
10	46	43	40	38	39	41	42	41	42	43	43	-	630
11	54	43	43	44	43	43	44	44	45	43	43	-	623
12	66	69	57	49	52	51	48	48	45	42	42	-	513
13	59	61	56	56	54	53	52	52	49	43	42	1.34	371
14	46	52	51	48	51	51	50	51	50	45	43	.03	460
15	59	60	52	48	51	55	49	50	49	46	44	.33	460
16	64	76	63	56	60	57	53	56	52	46	44	-	460
17	54	56	54	52	55	54	52	54	54	47	45	.31	460
18	58	56	56	52	55	54	52	54	53	48	45	.07	460
19	60	71	60	51	58	56	51	54	52	47	44	.09	460
20	52	59	55	51	54	55	53	54	54	48	45	.02	538
21	53	61	53	50	53	52	54	53	53	49	46	.72	343
22	58	60	54	50	52	53	53	52	52	49	46	-	623
23	59	62	58	55	57	56	54	55	54	49	46	.59	204
24	56	61	55	52	55	55	52	54	54	50	47	.02	285
25	52	51	52	50	53	54	53	54	54	50	47	.23	218
26	55	63	57	52	56	55	52	54	53	50	47	.02	529
27	54	54	53	50	53	54	52	52	52	48	47	T	281
28	48	54	53	52	53	53	53	53	52	50	48	.33	78
29	48	51	51	49	49	50	51	50	51	50	48	.29	175
30	48	56	49	47	47	50	50	47	49	50	48	.03	433
31	56	64	54	58	51	52	50	49	49	49	48	-	592

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivate Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

JUNE 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches — Stations A, B, and W.											
1	59	57	55	53	54	54	53	53	52	50	48	.66	92
2	50	52	52	52	53	54	53	53	53	50	48	.21	197
3	50	73	57	58	56	54	51	53	51	50	48	-	681
4	56	51	57	49	51	51	51	52	52	49	48	-	597
5	68	62	58	56	55	55	54	54	53	49	47	-	451
6	71	66	62	58	60	59	56	58	55	50	48	.15	345
7	64	72	63	56	62	60	56	60	57	51	48	.70	236
8	67	68	62	58	62	61	57	61	58	52	49	.33	457
9	68	77	68	57	65	64	57	62	60	52	49	-	621
10	79	79	71	64	68	67	60	65	61	53	49	-	584
11	66	66	66	64	67	66	61	67	63	55	50	.21	526
12	52	71	60	54	61	60	57	61	61	55	51	-	414
13	62	60	58	54	59	59	56	60	60	56	51	.43	296
14	54	57	59	56	59	61	57	60	60	56	52	.01	124
15	54	51	55	52	55	57	55	56	58	55	52	-	149
16	56	69	61	52	58	59	55	57	56	55	52	-	651
17	58	60	59	54	58	59	55	57	57	55	52	-	267
18	59	71	62	53	59	60	55	57	56	55	52	-	607
19	59	74	62	54	60	60	55	59	58	55	52	-	553
20	60	73	63	53	62	61	55	59	58	55	53	-	639
21	64	72	63	55	61	61	55	60	59	55	53	-	671
22	67	61	60	56	61	59	57	61	61	56	53	-	645
23	68	67	63	56	63	61	57	63	62	57	53	-	615
24	63	64	61	57	63	61	57	64	63	56	53	T	266
25	68	74	67	58	65	63	58	63	61	57	53	.31	516
26	69	68	65	59	65	63	58	64	63	58	54	-	548
27	74	67	65	61	65	64	59	65	63	58	54	-	485
28	75	70	67	62	67	65	60	67	64	58	54	-	604
29	75	74	70	64	70	67	62	69	65	57	53	-	470
30	71	82	72	61	71	68	61	69	67	60	55	-	578
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

JULY 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Mean Air; Soil Depths in Inches, Stations A, B, and W.												
1	66	76	70	63	71	67	63	70	68	60	55	.14	556
2	64	70	67	59	67	65	60	67	67	61	56	-	574
3	66	69	66	58	65	63	59	66	66	60	55	-	600
4	67	70	64	59	66	62	59	66	66	60	55	.22	374
5	72	67	66	61	65	65	61	65	65	60	55	.83	351
6	69	68	66	62	67	65	63	67	66	61	57	-	242
7	66	74	70	60	68	67	61	66	65	61	57	-	650
8	65	69	67	58	64	64	60	64	65	61	57	-	624
9	68	70	66	60	66	64	60	66	65	61	57	-	345
10	69	69	67	62	67	65	62	66	65	61	57	-	563
11	68	66	64	60	67	65	61	67	66	61	57	.08	385
12	72	66	64	60	66	63	60	67	66	61	57	-	566
13	74	82	72	62	72	67	62	70	67	62	58	-	417
14	74	76	72	64	72	68	63	71	69	62	58	.05	308
15	70	77	72	64	71	68	63	69	68	62	58	.24	273
16	73	74	70	64	70	67	64	69	68	63	58	.16	257
17	72	75	71	64	70	67	64	69	68	63	58	-	532
18	69	71	69	66	71	69	65	71	70	63	59	.26	226
19	59	60	62	58	65	65	62	67	69	64	59	.01	284
20	60	57	58	56	61	61	60	64	65	63	59	.27	376
21	58	68	66	58	64	63	60	64	65	63	59	.13	447
22	56	62	61	54	60	60	59	61	63	62	59	-	462
23	60	66	64	55	61	61	58	61	63	62	59	-	545
24	66	67	64	58	63	62	59	63	63	62	59	-	542
25	70	63	62	60	64	63	60	65	65	61	59	-	573
26	72	69	66	62	67	65	62	67	66	61	59	-	365
27	74	73	71	65	70	68	63	69	68	62	59	.17	470
28	72	82	75	63	71	70	63	69	68	63	60	-	519
29	75	75	71		69	68		69	68	63	59	-	545
30	78	79	74		72	70		71	69	63	59	T	334
31	67	76	71		71	69		70	69	63	60	-	598

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

AUGUST 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (Inc.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Mean Air; Soil Depths in Inches, Stations A, B, and W.												
1	59	70	66	63	67	65	63	68	68	64	60	-	478
2	70	72	68	66	68	66	65	68	68	64	60	-	400
3	78	73	69	64	69	68	65	69	68	64	61	-	434
4	78	86	79	57	74	72	62	72	69	64	50	.63	463
5	80	84	80	60	75	74	61	72	70	65	61	-	448
6	82	83	80	64	76	75	63	74	72	65	61	-	508
7	80	79	79	64	76	76	64	75	73	65	61	.34	307
8	70	70	70	67	72	71	66	73	73	66	61	.01	383
9	68	70	69	69	69	68	68	70	71	66	61	-	323
10	71	66	66	70	67	67	68	69	70	66	62	-	557
11	76	79	79	66	72	73	66	70	69	66	62	-	432
12	80	77	77	62	73	73	65	72	70	66	62	-	424
13	82	80	80	61	75	75	64	73	72	66	62	T	475
14	82	82	81	63	75	76	65	74	72	66	62	.06	431
15	70	71	72	68	73	74	67	74	73	66	62	-	386
16	68	73	72	70	70	71	68	71	71	67	63	-	452
17	78	72	72	70	71	71	69	71	71	67	63	-	479
18	84	84	82	68	75	76	68	74	72	67	63	T	453
19	83	81	80	62	76	76	65	75	73	67	63	.07	276
20	80	82	80	68	75	75	69	74	73	67	63	.71	416
21	77	78	77	70	75	75	70	75	74	68	64	.01	380
22	76	75	74	69	74	74	69	74	74	68	64	-	437
23	80	75	74	69	73	73	69	74	73	68	64	-	530
24	82	76	76	71	75	75	71	75	74	68	64	.86	351
25	78	79	79	70	77	77	71	75	74	69	65	.04	310
26	69	72	71	68	72	72	69	73	73	68	64	.59	534
27	68	69	69	68	69	70	67	70	71	68	64	-	641
28	72	72	72	68	72	72	67	71	71	68	65	.30	233
29	70	70	69	68	70	69	67	70	70	68	64	.55	240
30	74	70	69	68	70	69	67	70	69	68	64	.06	360
31	65	70	69		69	69		69	68	67	64	.02	677

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

SEPTEMBER 1947

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches — Stations A, B, and W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	66	71	70		69	69		68	68	67	64	.05	370
2	70	71	71		68	68		68	67	66	64	-	505
3	71	72	72		68	69		68	67	66	64	-	
4	72	73	73		69	70		68	68	66	64	-	
5	70	70	69		69	69		68	68	66	65	.06	
6	71	67	66		68	68		69	68	66	66	-	
7	74	68	69		68	69		69	69	66	65	-	
8	74	70	69		69	70		70	70	66	64	-	
9	77	73	71		72	70		71	70	66	64	-	
10	74	77	74		73	71		72	71	66	64	-	
11	74	74	73		72	71		72	71	66	64	.20	
12	72	71	71		71	71		72	72	67	64	3.43	
13	70	70	69		69	70		71	71	67	64	-	
14	71	69	67		67	68		70	70	67	64	.04	
15	58	66	65		68	68		70	70	68	65	.22	
16	56	62	61	64	64	65	65	67	68	67	65	-	
17	61	57	57	68	60	61	67	63	66	66	64	-	
18	70	62	61	68	63	63	67	65	66	66	64	-	
19	72	67	66	68	67	66	67	67	67	65	64	-	
20	72	68	67	68	68	67	66	68	66	65	63	-	
21	62	63	62	66	64	64	66	65	66	65	63	1.74	
22	44	58	57	63	60	61	66	63	65	66	62	.07	
23	47	54	53	62	55	56	65	58	62	65	64	-	
24	53	60	57	54	58	57	52	58	60	64	63	-	
25	41	50	50	48	54	55	56	57	60	64	63	-	
26	44	50	49	48	50	53	54	54	58	63	63	-	
27	46	48	49	48	51	52	54	54	57	62	63	-	
28	50	51	52	50	53	53	54	54	57	61	62	.21	
29	46	55	55	54	55	55	55	55	56	60	61	.12	
30	40	48	47	46	50	51	43	52	55	60	61	-	
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

OCTOBER 1947

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches — Stations A, B, and W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	42	50	47	45	47	49	51	50	53	59	61	-	402
2	47	49	48	47	48	49	51	50	52	58	60	-	265
3	61	49	49	51	50	51	52	52	53	58	60	-	312
4	68	59	56	58	55	54	57	54	53	56	58	.04	283
5	64	61	57	57	56	55	57	55	54	56	57	-	318
6	66	64	59	57	57	56	58	56	55	55	56	-	313
7	68	61	59	60	59	58	59	59	58	56	57	-	294
8	52	61	58	57	60	59	59	60	60	57	58	-	260
9	49	56	53	51	55	54	56	56	59	58	59	-	301
10	50	52	49	48	51	51	54	54	57	58	59	-	329
11	56	52	49	49	51	50	54	53	55	58	59	-	266
12	64	55	53	54	53	52	56	54	55	57	57	-	236
13	56	58	56	56	56	55	58	56	55	55	56	-	267
14	54	52	50	50	53	53	55	55	58	57	58	-	288
15	67	62	55	56	54	52	57	54	54	54	54	-	237
16	64	62	56	56	56	54	57	55	55	54	54	-	264
17	68	62	58	60	58	56	60	57	56	54	55	1.50	240
18	62	61	59	60	60	58	60	59	58	56	56	-	
19	62	59	56	58	57	56	60	57	57	56	55	-	332
20	59	57	52	54	54	53	58	55	56	55	54	-	201
21	64	55	52	56	53	53	58	55	56	56	55	-	188
22	66	61	56	58	55	53	59	54	54	53	53	-	209
23	51	56	51	57	53	52	59	54	55	56	55	-	262
24	49	50	46	51	51	50	56	54	57	58	58	-	216
25	56	52	49	52	52	50	55	54	56	56	56	-	132
26	63	55	52	55	53	51	56	53	54	54	55	T	134
27	63	53	54	58	53	52	59	53	52	52	53	.23	136
28	52	53	54	56	56	56	58	57	58	57	58	.15	109
29	48	50	50	54	53	53	56	55	57	58	58	.81	24
30	50	49	49	53	50	51	55	52	54	57	57	T	28
31	49	50	48	52	50	51	55	52	54	57	58	T	44

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

NOVEMBER 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, and W.												
1	48	48	45	51	49	48	55	51	53	56	57	T	93
2	46	46	44	48	46	46	53	48	50	55	57	-	221
3	48	44	42	49	43	44	53	45	48	54	56	T	103
4	51	47	45	52	47	47	53	48	49	54	57	.02	19
5	51	48	48	52	48	48	54	48	49	53	56	.11	22
6	47	45	46	52	47	48	54	48	49	53	55	.02	27
7	46	41	42	50	43	45	53	45	48	53	55	.08	36
8	36	30	33	46	35	39	51	39	45	52	55	-	18
9	31	23	28	44	25	34	49	29	35	48	52	-	42
10	36	32	23	42	33	29	48	36	40	50	53	.32	45
11	36	41	42	46	42	44	49	43	45	52	55	.25	110
12	30	37	38	40	39	41	47	41	44	51	54	T	89
13	26	35	37	41	38	39	46	40	43	51	54	-	161
14	30	33	35	37	36	38	43	38	42	50	54	-	172
15	34	33	35	40	36	38	44	38	41	49	54	.10	
16	32	34	36	40	36	38	43	38	41	48	53	.08	
17	32	35	36	38	36	38	42	38	40	47	52	-	96
18	32	36	36	40	37	38	42	38	40	47	52	-	53
19	33	33	34	36	35	37	42	37	40	46	51	-	189
20	36	35	35	39	36	37	42	37	40	46	51	-	125
21	39	36	36	40	36	37	42	37	39	46	50	-	134
22	40	39	39	44	39	39	43	39	39	45	49	-	17
23	34	37	37	40	38	38	43	39	39	45	49	T	138
24	31	35	34	40	37	37	42	38	39	44	49	.42	48
25	27	34	34	40	36	36	42	37	39	45	48	T	76
26	23	33	33	40	35	36	41	36	39	45	48	-	181
27	24	33	33	38	35	36	41	36	38	45	48	.02	80
28	21	33	33	38	34	35	40	36	38	44	48	.07	139
29	22	32	32	38	34	34	40	36	38	44	48	-	191
30	18	32	32	36	33	34	39	36	38	44	46	-	236
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

DECEMBER, 1947

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, and W.												
1	28	32	32	37	33	34	39	35	37	43	47	-	250
2	39	32	32	38	34	34	39	35	37	43	47	.06	101
3	38	37	32	40	35	34	39	35	37	43	47	.25	
4	28	33	32	34	35	34	38	36	37	42	47	.12	
5	34	33	32	36	34	33	38	35	37	42	46	.36	
6	32	33	32	36	34	34	38	35	36	41	46	-	
7	42	33	33	36	35	34	38	36	37	41	46	.23	
8	38	34	34	39	37	35	40	38	38	41	45	T	
9	24	32	33	33	34	34	38	35	37	41	45	-	
10	22	32	33	32	34	34	36	35	37	41	55	.08	
11	24	32	32	34	33	33	36	34	36	41	45	-	
12	24	31	32	34	33	34	36	34	36	41	45	T	
13	25	31	32	34	33	33	36	34	35	40	44	-	
14	30	31	32	34	33	33	36	34	35	40	43	-	
15	33	31	31	34	32	33	36	33	34	39	43	.32	
16	26	32	32	34	33	33	36	33	34	40	44	.03	
17	27	31	29	35	31	30	36	32	34	39	43	-	
18	22	28	31	33	29	33	36	30	32	37	40	-	
19	17	34	35	33	36	36	36	36	38	42	46	-	
20	22	34	35	32	36	36	35	36	38	42	46	-	
21	26	33	34	32	35	36	35	35	37	42	46	-	
22	24	33	34	32	35	36	35	35	37	42	46	-	
23	23	33	34	33	35	36	35	35	37	42	46	-	
24	24	33	34	33	35	36	35	35	37	42	46	-	
25	22	34	34	33	34	35	35	35	37	42	45	-	
26	28	34	34	34	34	35	35	35	37	42	45	-	
27	30	29	28	34	29	30	35	30	32	36	40	-	
28	34	30	30	34	31	31	35	32	33	38	41	-	
29	18	31	32	34	33	33	35	34	35	40	42	-	
30	26	33	32	34	33	34	35	34	35	40	43	-	
31	26	34	33	34	34	35	35	35	36	40	44	-	

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

JANUARY 1948

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches — Stations A, B, & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	26	32	32	34	32	33	35	33	34	38	42	.82	*
2	25	32	32	34	32	33	35	33	34	38	42	T	*
3	28	32	32	33	32	33	35	33	34	38	41	-	*
4	30	32	32	33	32	33	35	33	34	38	41	.08	*
5	29	32	32	33	32	33	35	33	34	38	41	-	71.9
6	24	32	32	33	32	33	35	33	34	38	41	-	177.3
7	24	32	32	33	32	33	35	33	34	38	41	-	146.7
8	32	32	32	33	32	33	35	33	34	38	41	-	70.7
9	32	31	32	33	32	33	35	33	34	37	41	-	63.6
10	18	31	32	32	32	33	34	33	34	37	41	-	198.6
11	22	31	32	30	32	33	33	33	34	37	41	.01	146.7
12	30	32	32	30	32	33	33	34	34	38	41	-	88.7
13	16	31	32	32	32	33	33	33	33	37	40	-	125.3
14	6	31	32	32	32	33	33	34	34	37	40	-	20.2
15	16	31	32	31	32	33	32	34	34	37	40	T	83.9
16	18	31	32	30	32	33	32	34	34	37	40	-	124.5
17	7	30	32	29	32	33	31	33	33	37	40	-	164.6
18	2	30	32	28	32	33	30	33	33	37	40	T	231.7
19	13	29	32	28	31	33	30	33	33	37	40	T	141.8
20	20	30	32	28	31	33	30	32	33	37	40	-	210.1
21	22	30	31	28	31	33	30	32	32	36	40	.02	144.7
22	6	30	31	28	31	32	30	32	33	36	39	-	189.0
23	-3	26	31	27	30	32	30	32	33	36	39	-	261.2
24	2	26	31	26	29	32	30	31	32	36	39	.01	122.7
25	10	27	31	26	29	32	30	31	32	36	39	-	249.0
26	14	28	31	26	30	32	29	31	32	36	39	T	183.6
27	9	28	31	26	29	32	29	30	32	36	39	-	146.0
28	10	26	31	26	28	32	29	30	32	36	39	-	262.6
29	15	26	31	26	28	32	29	29	32	36	39	T	206.9
30	6	26	32	26	28	32	29	29	32	35	39	-	297.4
31	7	25	31	25	28	32	29	29	32	36	39	-	241.8

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

FEBRUARY 1948

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches — Stations A, B, & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	8	25	31	25	28	32	29	29	32	36	39	-	203.8
2	22	26	31	26	27	32	29	29	31	35	39	-	235.0
3	14	25	31	26	27	32	29	28	31	35	38	.03	197.7
4	13	26	31	27	28	32	29	29	31	35	38	.04	223.4
5	10	27	31	27	28	32	29	29	31	34	38	-	262.6
6	14	27	31	27	28	32	29	29	31	35	38	-	229.9
7	22	27	31	27	28	32	29	29	31	35	38	T	135.5
8	14	26	31	27	28	32	29	29	31	35	38	-	325.7
9	6	25	31	25	27	32	29	28	30	34	37	-	320.9
10	8	24	31	25	25	32	29	27	30	34	37	-	261.7
11	18	25	31	26	26	32	29	27	30	34	38	.07	99.1
12	23	26	31	27	27	32	29	28	30	34	37	-	272.0
13	27	27	31	27	28	32	29	29	30	34	37	.36	69.8
14	20	30	32	28	30	32	29	30	31	34	37	.04	211.1
15	20	30	32	28	30	32	29	30	31	34	37	-	243.6
16	38	30	31	28	29	32	29	30	31	34	37	-	259.2
17	39	32	32	28	31	32	29	31	31	34	37	-	251.4
18	37	32	32	28	31	32	29	31	32	34	37	-	249.7
19	32	32	30	29	31	32	30	31	31	34	37	-	143.1
20	14	28	30	28	27	32	29	29	31	33	36	-	249.6
21	13	24	30	24	23	32	29	25	29	33	36	-	248.1
22	17	24	30	22	23	32	29	25	29	33	36	-	349.2
23	26	24	29	22	23	32	29	25	28	34	36	-	282.5
24	40	30	31	27	28	32	29	29	30	34	37	T	279.2
25	38	32	32	28	31	32	30	31	31	34	37	.01	121.0
26	39	32	31	30	31	32	29	31	31	33	36	-	274.2
27	33	32	31	29	31	31	29	31	31	33	36	.88	89.5
28	36	32	32	30	32	32	29	31	31	34	37	.33	61.7
29	28			29			29					T	191.1
30													
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

MARCH 1948

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, & W.												
1	20	31	31	28	31	31	29	31	31	33	44	.34	86.6
2	24	32	32	28	31	32	29	32	31	34	44	.48	70.1
3	24	32	31	26	32	31	29	32	32	34	45	-	232.4
4	12	31	31	27	32	31	29	31	31	33	46	-	438.2
5	11	31	31	28	31	31	29	32	32	33	46	-	424.7
6	22	31	31	28	31	32	29	31	31	34	46	.03	235.4
7	30	31	31	28	31	32	29	31	31	34	46	.06	129.8
8	27	30	32	27	31	32	29	31	31	33	46	-	252.3
9	24	31	32	26	31	32	29	31	31	33	46	-	375.0
10	16	30	31	25	31	32	25	31	31	34	47	-	332.0
11	8	28	31	26	30	32	29	31	31	33	46	-	405.4
12	14	26	30	27	28	32	29	29	31	33	46	-	411.3
13	24	26	30	30	27	32	30	29	30	33	46	-	420.8
14	34	28	31	30	29	32	30	30	30	33	45	-	400.7
15	45	31	32	29	31	32	29	31	[illegible]	34	46	.03	110.7
16	44	32	32	29	31	32	29	31	32	34	46	.07	59.6
17	36	32	31	29	31	32	29	31	31	33	47	T	107.6
18	38	34	32	33	32	32	32	32	32	34	47	-	324.3
19	52	37	32	30	32	32	29	32	32	34	47	2.48	72.6
20	48	34	32	37	32	32	31	32	32	34	46	-	391.7
21	58	37	34	37	34	35	31	32	32	34	47	.11	84.5
22	46	40	37	35	36	38	32	33	32	33	46	-	248.1
23	45	37	36	32	33	36	32	32	32	33	47	-	420.9
24	46	44	40	33	35	38	34	33	32	33	48	-	436.5
25	44	33	36	33	34	38	35	34	32	33	48	-	428.4
26	50	37	39	38	36	39	37	35	32	33	48	.04	123.0
27	38	38	41	39	41	42	39	40	35	35	49	.27	97.5
28	28	36	38	32	37	39	35	37	34	35	48	-	486.1
29	40	32	35	32	32	36	34	33	33	34	49	.04	216.8
30	36	44	41	31	35	38	34	33	33	34	49	-	457.5
31	46	37	38	37	36	38	36	35	34	34	50	.34	69.2

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Water shed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

APRIL 1948

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, & W.												
1	39	40	41	40	40	41	39	38	36	34	36	-	66.0
2	38	33	37	34	33	38	36	36	36	34	36	-	287.3
3	36	40	38	34	43	38	36	35	36	35	36	-	425.7
4	48	42	41	34	44	40	36	37	37	35	36	-	432.4
5	56	44	44	44	45	42	41	40	38	35	36	.38	210.8
6	50	51	47	42	53	45	42	42	40	36	36	-	441.8
7	58	46	46	45	46	45	43	45	42	37	37	T	250.1
8	46	49	49	47	49	47	47	47	44	38	37	-	359.2
9	34	36	39	40	35	43	42	42	43	38	38	T	312.0
10	42	35	37	36	35	40	39	39	41	39	38	.02	414.3
11	54	38	40	45	38	42	44	41	42	39	38	.74	129.0
12	43	41	43	42	41	44	43	43	43	39	38	-	218.9
13	42	42	41	40	42	42	42	42	42	40	39	-	118.7
14	39	40	40	41	40	42	42	41	42	40	39	.03	40.9
15	50	41	41	39	41	40	40	40	41	40	40	-	471.7
16	48	47	46	49	47	45	46	44	42	40	39	-	466.3
17	39	36	39	39	36	42	42	43	43	40	40	-	593.5
18	45	42	42	42	40	43	42	43	43	40	40	.06	100.9
19	66	48	46	49	44	44	45	43	42	41	40	-	372.4
20	60	55	53	53	51	50	50	49	45	41	40	-	433.5
21	49	46	47	46	48	49	46	49	48	42	40	-	593.1
22	50	45	46	45	46	47	47	47	47	42	41	-	488.9
23	55	54	50	48	49	48	49	48	47	43	41	.47	194.1
24	64	57	55	53	52	53	50	52	49	45	42	-	201.7
25	70	57	55	55	54	54	51	53	50	45	42	-	602.9
26	70	58	56	56	56	55	53	55	52	44	42	.15	426.6
27	66	59	57	55	57	56	54	56	53	45	42	.45	265.0
28	50	53	53	50	55	54	52	55	54	47	43	.02	335.3
29	50	52	51	50	53	52	51	53	53	47	44	.01	451.0
30	52	48	50	48	51	51	50	52	52	48	44	-	586.8
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

MAY 1948

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches			Stations A, B, & W.								
1	53	50	51	49	51	51	50	51	52	48	44	-	457.8
2	52	50	50	48	51	51	50	51	52	48	44	.16	231.9
3	54	49	49	48	51	50	50	51	51	48	45	-	571.0
4	52	51	50	48	51	50	50	52	52	48	46	T	186.0
5	58	50	50	52	51	51	52	52	51	49	46	-	509.5
6	56	54	53	48	54	53	51	54	52	48	46	.46	64.6
7	44	48	49	44	52	51	48	52	52	49	46	.51	115.6
8	44	41	44	47	46	48	49	48	50	49	46	-	559.7
9	48	45	45	45	47	47	48	48	49	49	46	1.32	162.7
10	48	49	46	47	48	46	48	47	48	48	47	1.81	156.9
11	46	49	47	47	48	47	47	48	49	48	46	.21	73.8
12	50	48	47	49	48	47	49	48	48	47	46	.11	205.8
13	54	52	49	50	49	48	50	49	48	47	46	.04	271.4
14	58	62	54	50	54	51	50	52	49	47	45	-	439.0
15	56	52	50	52	52	51	51	52	51	47	46	-	155.1
16	64	53	52	50	52	52	52	53	52	47	46	.80	485.0
17	58	54	54	50	53	53	51	54	53	48	47	-	374.8
18	56	52	53	50	53	53	51	53	53	49	47	-	480.0
19	52	61	55	50	56	52	51	54	53	49	47	-	504.8
20	60	55	53	54	53	52	54	53	53	49	46	.05	514.9
21	54	55	54	50	56	54	52	56	49	49	47	-	575.8
22	52	50	50	51	52	51	52	53	53	49	46	.01	554.5
23	54	51	50	50	53	51	51	53	53	50	47	.07	566.4
24	50	52	50	50	54	52	51	54	54	51	48	-	523.4
25	52	56	52	50	53	51	51	54	54	51	48	-	557.4
26	58	52	51	54	54	52	54	54	54	50	48	-	623.1
27	62	59	55	50	57	53	52	56	55	51	49	-	613.0
28	65	57	54	52	57	54	52	58	56	51	48	-	554.1
29	54	58	56	50	59	56	51	59	58	52	49	-	650.8
30	56	58	54	50	59	55	51	59	58	52	49	-	605.9
31	60	57	52	50	59	53	51	60	58	53	50	-	613.2

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

JUNE 1948

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches			Stations A, B, & W.								
1	64	65	57	53	60	55	53	60	59	53	50	-	576.2
2	68	61	57	55	61	56	55	61	59	53	50	-	526.6
3	70	67	61	58	64	58	56	63	61	54	50	-	547.7
4	72	65	59	59	65	58	57	65	67	55	56	.13	545.6
5	58	65	61	57	63	59	56	64	63	55	51	-	667.1
6	56	67	58	52	62	58	54	63	63	56	51	-	324.0
7	62	69	56	53	61	56	54	62	62	57	52	.36	283.0
8	56	57	57	54	59	57	55	60	61	57	53	.27	134.1
9	62	56	56	53	58	56	55	59	60	57	53	-	465.5
10	64	61	59	55	59	57	55	59	59	56	53	-	551.7
11	64	67	60	57	62	58	55	62	60	56	53	.26	231.8
12	60	66	60	58	62	59	56	62	61	56	53	.14	113.2
13	62	63	59	54	61	58	55	61	61	56	53	-	542.0
14	62	59	57	54	59	57	55	60	60	56	53	-	376.3
15	59	62	58	55	60	57	56	60	60	57	54	-	482.4
16	57	66	59	53	60	57	50	60	59	56	53	-	649.3
17	60	61	57	56	60	56	56	61	60	56	53	-	559.6
18	64	68	62	54	65	58	55	63	62	57	54	.20	294.0
19	54	60	57	50	61	57	49	62	62	57	54	.09	68.2
20	59	61	58	56	62	58	56	62	62	57	54	-	599.6
21	64	63	60	59	63	59	55	63	62	57	54	.06	179.6
22	72	71	66	64	65	61	61	62	61	57	54	1.22	259.0
23	78	75	71	65	69	66	64	67	64	57	54	.07	427.5
24	72	71	69	62	70	68	64	69	66	58	54	-	344.9
25	71	73	71	61	68	67	61	67	66	59	54	-	567.2
26	71	71	69	64	67	67	63	67	66	59	55	-	465.1
27	73	74	72	64	70	68	63	68	67	60	55	.40	219.1
28	76	78	75	65	73	70	64	70	68	61	56	.74	410.5
29	70	70	71	65	70	69	64	69	68	61	56	.03	189.2
30	64	67	68	62	67	67	63	67	67	61	56	-	526.1
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

JULY 1948

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches — Stations A, B, & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	60	64	64	58	64	65	61	65	66	62	57	-	662.9
2	68	64	63	58	64	64	60	65	65	61	57	.64	308.0
3	79	70	69	62	68	67	64	67	66	61	57	-	567.8
4	78	71	70	67	69	68	64	69	67	61	57	-	532.9
5	78	73	72	65	71	70	65	71	69	62	57	-	472.0
6	72	74	73	66	72	71	64	71	69	62	57	-	491.2
7	69	75	70	64	72	69	64	71	69	62	57	-	535.8
8	68	70	67	60	69	67	62	69	69	63	58	-	627.7
9	72	78	72	61	71	67	61	70	69	63	58	-	578.4
10	79	81	74	63	76	68	64	71	69	63	58	.13	383.0
11	80	84	75	65	81	70	64	72	70	64	58	T	499.0
12	78	87	77	67	86	72	65	73	71	64	59	-	458.0
13	66	75	71	64	74	70	65	74	72	65	60	-	144.9
14	66	70	67	62	70	67	63	70	71	65	60	-	432.3
15	65	68	66	59	68	66	63	69	70	65	60	-	555.2
16	77	74	70	63	72	68	66	71	70	65	60	.08	334.5
17	78	69	68	64	70	68	64	71	70	64	60	-	492.6
18	74	72	69	66	70	68	65	71	70	64	60	-	407.7
19	73	75	71	63	71	69	64	71	70	65	61	.11	480.2
20	74	73	69	67	70	67	65	70	70	65	60	-	395.2
21	74	73	70	66	72	69	65	71	70	65	61	.88	219.1
22	74	76	72	67	73	70	66	72	71	66	61	.13	244.4
23	62	69	69	63	70	69	65	71	70	65	61	.05	181.2
24	65	66	65	60	66	66	62	67	68	65	61	-	512.3
25	70	69	68	60	67	67	64	67	68	65	61	-	373.9
26	76	73	71	64	69	68	65	68	68	65	61	.02	523.8
27	74	72	69	64	70	67	64	69	69	65	61	-	414.5
28	70	75	69	62	68	67	63	68	68	64	61	-	499.1
29	73	67	68	62	66	66	63	66	66	64	60	-	478.0
30	74	79	75	69	75	72	66	73	71	66	63	.08	483.6
31	70	69	68	65	70	68	65	70	71	66	62	-	586.4

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

AUGUST 1948

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches — Stations A, B, & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	68	71	68	62	69	67	64	70	70	67	62	-	497.2
2	66	70	67	60	68	66	64	69	69	68	62	-	437.6
3	68	72	67	60	69	66	62	69	69	66	62	T	237.3
4	64	68	66	60	68	66	62	69	69	66	63	.01	170.0
5	60	67	65	57	66	64	61	66	68	66	63	-	567.6
6	62	75	70	55	70	66	60	69	68	66	63	-	488.0
7	67	67	64	59	67	64	60	68	68	66	63	-	407.7
8	66	68	65	58	67	64	60	68	68	66	63	T	388.3
9	66	69	66	56	66	64	60	67	67	65	62	-	506.5
10	72	69	66	60	67	65	61	67	67	65	62	-	332.7
11	71	70	66	62	69	66	63	69	68	66	62	.84	279.7
12	68	70	68	63	69	67	63	68	68	65	62	-	362.8
13	64	70	66	60	68	66	62	68	69	66	63	-	289.8
14	66	65	65	60	66	65	61	67	68	65	63	-	484.6
15	68	69	69	59	68	67	61	67	68	65	63	-	431.1
16	68	74	73	60	70	70	61	68	67	65	63	T	442.9
17	73	71	70	60	68	67	61	68	68	65	62	-	388.6
18	70	71	70	62	69	68	63	69	68	65	62	-	351.2
19	68	73	71	60	69	68	62	68	68	65	62	-	442.1
20	67	68	68	60	66	67	61	67	67	65	62	-	502.3
21	72	66	66	60	67	67	61	68	69	65	63	-	479.1
22	76	69	71	62	69	69	63	69	69	65	63	-	444.8
23	78	73	76	64	71	71	64	70	69	65	62	-	385.4
24	82	77	77	66	73	72	65	73	71	66	64	-	422.2
25	84	75	75	70	74	73	67	74	72	65	63	-	451.6
26	83	78	78	69	75	74	67	74	73	66	63	-	330.4
27	84	84	85	70	78	78	68	75	73	67	64	-	349.8
28	83	78	79	70	76	75	68	75	73	67	63	-	346.8
29	78	76	75	68	75	74	68	75	74	68	64	-	453.9
30	67	73	71	64	74	73	66	75	75	69	64	T	313.7
31	63	71	71	60	70	69	64	71	72	68	64	-	416.0

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

SEPTEMBER 1948

DATE	TEMPERATURES (°F.)											Total Precip. (In.)	Total Insol. (Lang.)
	Mean Air	Soil Depths in Inches Stations A, B, & W.											
		1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A		
1	60	68	68	56	67	66	64	68	70	68	64	-	290.1
2	71	70	70	61	69	68	62	69	69	68	64	-	279.9
3	70	72	72	62	70	68	63	69	69	67	64	-	379.9
4	74	69	69	61	69	68	63	70	70	67	64	-	433.0
5	74	72	72	62	71	69	63	71	70	67	64	-	330.5
6	76	76	75	66	73	71	65	72	71	67	64	.05	210.2
7	74	74	73	66	71	70	65	71	70	67	64	-	195.3
8	66	70	69	64	70	69	64	70	70	67	64	.93	222.6
9	62	61	66	60	62	66	62	69	69	67	64	-	427.5
10	60	64	64	57	65	65	61	67	68	67	64	.08	362.1
11	66	61	60	58	63	62	60	65	67	67	64	-	323.3
12	74	64	64	62	65	64	62	66	67	66	64	-	399.4
13	70	67	68	64	67	67	64	67	67	66	63	-	367.3
14	60	63	65	57	64	64	62	65	66	65	63	-	390.7
15	58	63	63	58	63	64	61	65	66	67	64	.23	72.5
16	70	63	62	58	63	62	60	64	66	67	65	-	323.9
17	73	62	62	61	64	64	62	65	65	65	63	-	267.7
18	74	66	64	65	66	65	64	66	65	65	63	T	199.5
19	78	68	66	65	67	67	65	68	66	64	63	-	294.1
20	65	72	69	66	69	69	67	69	67	64	63	.05	92.0
21	58	65	64	58	66	64	63	66	67	65	63	-	178.3
22	55	62	62	54	62	61	60	63	65	65	63	-	327.4
23	54	57	58	54	59	59	53	61	63	64	62	T	170.0
24	54	58	58	55	59	59	58	59	62	63	62	-	115.0
25	56	57	58	52	57	57	57	58	61	63	62	-	298.8
26	58	61	60	52	58	57	57	58	61	62	62	-	381.8
27	58	65	62	51	59	57	56	59	61	62	62	-	349.8
28	60	64	61	52	60	58	56	60	61	62	62	-	283.5
29	62	60	58	55	60	58	57	61	62	62	62	.15	170.4
30	62	62	60	59	62	60	59	62	62	62	61	.14	114.8
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

OCTOBER 1948

DATE	TEMPERATURES (°F.)											Total Precip. (In.)	Total Insol. (Lang.)
	Mean Air	Soil Depths in Inches Stations A, B, & W.											
		1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"E	60"A		
1	66	65	64	55	62	61	59	62	62	61	61	.01	229.8
2	48	58	58	49	61	61	55	63	63	62	61	-	74.1
3	48	54	55	47	54	57	54	56	59	62	61	-	355.1
4	49	57	51	47	54	53	54	55	58	61	61	-	271.4
5	52	55	54	48	54	53	54	55	58	61	61	-	241.5
6	49	53	51	49	53	53	54	55	57	60	61	-	148.2
7	50	55	54	52	55	54	54	56	57	60	61	.26	46.2
8	48	53	53	49	53	52	56	54	56	60	61	.05	146.8
9	50	52	52	49	51	51	53	52	54	59	60	-	249.6
10	48	51	50	48	51	50	52	52	54	59	60	-	309.0
11	46	49	48	54	50	49	52	51	54	59	60	.10	51.7
12	48	51	52	48	50	50	52	50	52	59	60	.01	163.0
13	45	49	49	49	50	50	54	51	53	57	59	.01	38.9
14	46	50	49	46	49	49	51	51	53	58	60	-	192.3
15	48	50	49		49	49		50	52	57	59	-	273.8
16	55	50	49		50	51		51	52	56	58	-	56.2
17	38	47	46		48	49		50	52	56	58	T	79.7
18	34	44	43		46	46		48	52	57	58	-	238.8
19	39	46	46		46	46		47	50	55	57	.04	129.9
20	40	45	42	44	45	45	49	46	49	55	57	-	267.6
21	44	47	45	44	45	45	49	47	48	54	57	-	171.6
22	44	45	43	43	45	45	49	46	49	54	57	-	134.9
23	51	48	47	49	48	48	50	48	49	54	56	.03	111.1
24	48	50	48	49	48	48	50	48	50	54	56	-	63.7
25	44	53	50	43	49	48	49	49	51	54	56	-	205.9
26	52	53	50	46	49	47	50	49	50	54	56	-	222.9
27	54	49	46	46	49	47	50	50	52	54	56	-	203.7
28	52	53	51	46	50	48	50	49	51	53	55	-	184.7
29	52	50	47	46	48	47	51	49	51	53	55	-	201.9
30	54	48	47	47	49	48	51	50	51	53	55	-	171.5
31	54	52	51	56	51	50	52	51	51	53	55	.08	13.5

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

NOVEMBER 1948

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, & W.												
1	52	55	55	50	54	53	52	53	52	53	54	-	113.3
2	52	53	52	50	52	51	52	52	53	52	54	-	87.5
3	52	52	51	50	52	51	52	52	53	54	55	.23	5.5
4	58	52	51	50	50	48	56	49	47	48	49	.18	96.7
5	61	54	54	53	53	54	54	53	53	53	54	.50	31.4
6	54	50	51	52	52	52	54	53	53	53	54	.01	4.6
7	46	47	47	47	48	48	52	59	52	53	54	-	218.3
8	42	44	43	44	44	45	50	46	51	53	54	-	152.4
9	50	44	47	46	43	46	50	44	45	50	51	.17	47.6
10	40	44	45	45	45	46	50	46	48	52	54	.22	108.7
11	40	41	43	43	41	43	49	43	46	51	53	-	149.5
12	40	41	41	43	41	42	48	42	45	52	54	.05	22.4
13	36	42	42	44	43	43	49	43	45	51	53	-	75.7
14	36	44	43	40	43	43	46	42	44	50	53	.02	73.9
15	42	47	44	43	42	43	47	41	43	49	52	.03	139.1
16	48	45	45	40	43	43	45	42	44	50	53	.26	114.7
17	42	40	42	44	42	43	48	41	44	49	52	-	180.2
18	46	44	43	42	42	42	46	41	44	49	51	-	158.8
19	47	44	44	46	43	44	48	43	44	48	52	.70	1.7
20	41	40	41	44	42	43	48	43	45	48	51	.01	26.7
21	40	40	41	43	42	43	47	42	44	48	51	.03	35.9
22	36	40	41	43	41	42	46	41	43	48	51	.01	18.7
23	34	38	39	40	39	41	45	40	42	48	51	-	8.1
24	32	38	39	40	39	40	45	39	41	48	51	-	56.6
25	39	35	36	40	37	38	44	38	46	47	50	-	49.7
26	46	49	44	44	41	42	45	40	41	47	50	.08	93.9
27	35	38	39	42	40	41	45	41	42	47	50	-	46.5
28	34	38	38	40	39	40	44	40	41	47	50	-	37.3
29	32	37	36	38	37	38	43	38	40	46	49	-	145.2
30	34	34	34	36	36	37	41	37	39	45	49	-	32.5
31													

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

DECEMBER 1948

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depth in Inches, Stations A, B, & W.												
1	30	34	34	37	35	37	41	37	39	46	49	-	116.5
2	36	32	33	34	34	35	40	36	38	45	49	-	132.4
3	41	37	35	36	35	35	40	35	37	45	48	-	125.6
4	46	40	38	38	37	37	40	37	38	41	48	-	130.8
5	44	38	37	42	37	37	42	37	39	42	48	.17	7.6
6	36	35	36	39	37	38	42	38	40	44	47	-	66.2
7	33	37	36	36	36	36	40	37	39	44	48	-	117.9
8	27	33	33	35	34	35	40	35	38	43	47	-	55.9
9	28	32	33	32	34	35	37	35	37	43	47	-	90.4
10	22	31	32	30	33	34	36	34	36	43	46	T	22.6
11	29	31	31	33	32	33	37	33	35	42	46	-	110.4
12	38	31	31	32	32	33	37	33	35	42	46	.10	20.4
13	32	31	32	32	32	33	37	33	35	42	46	T	16.2
14	28	32	33	32	33	33	36	34	35	42	46	.21	68.7
15	32	32	32	34	33	33	37	33	35	42	46	.68	0.5
16	36	32	33	32	33	33	37	33	35	41	45	.09	118.3
17	24	32	32	30	33	33	35	33	34	40	45	T	33.2
18	22	30	32	30	32	33	34	33	34	40	44	-	82.2
19	26	31	32	29	32	33	35	33	34	40	44	.05	102.2
20	29	32	32	32	33	33	35	33	34	41	45	.05	61.2
21	36	32	32	34	32	33	36	33	34	40	44	.06	90.9
22	28	31	31	30	32	33	34	33	34	39	44	-	63.0
23	22	32	32	30	32	33	33	33	34	40	44	-	121.5
24	22	31	31	29	32	33	32	33	34	39	43	-	91.8
25	13	30	30	26	33	33	32	33	35	40	45	T	164.4
26	12	29	30	27	32	32	32	33	34	39	45	-	159.8
27	25	28	29	27	30	31	32	32	33	39	44	T	20.0
28	32	30	30	27	30	31	31	31	33	39	43	.28	56.9
29	30	32	31	28	32	31	31	32	33	38	43	.58	3.2
30	17	32	32	28	32	32	31	32	33	39	43	-	139.1
31	18	32	32	29	32	32	31	32	33	38	43	-	184.1

Note: Mean air temperature is average daily maximum and minimum temperatures.
All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

JANUARY 1949

Date	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
		TEMPERATURES (°F.)											
		Soil Depths in Inches						Stations A, B, & W					
1	24	31	32	29	31	32	33	32	33	38	43	-	110
2	24	31	32	29	31	32	33	32	33	38	43	-	154
3	20	30	31	29	32	32	33	32	33	38	42	-	172
4	32	31	31	28	31	31	33	32	33	38	42	.11	22
5	33	31	31	31	31	31	33	32	33	37	42	.10	58
6	30	29	31	32	31	32	34	32	33	38	42	-	143
7	40	31	32	29	32	32	32	32	33	38	42	-	26
8	40	31	31	31	31	32	32	32	33	37	41	-	140
9	41	31	31	33	31	32	34	32	33	37	41	-	118
10	29	31	32	33	31	32	34	32	33	37	41	-	28
11	25	32	32	31	32	32	34	32	33	37	41	-	41
12	28	31	32	30	31	32	33	31	33	37	41	-	18
13	30	31	31	30	31	32	33	32	33	37	41	-	175
14	30	31	31	30	32	32	33	32	33	37	41	.25	23
15	42	31	31	29	32	32	33	32	33	37	41	-	5
16	42	31	31	40	32	32	37	32	33	37	41	-	44
17	28	31	31	33	31	32	36	32	33	36	40	-	7
18	32	32	32	31	32	32	35	32	33	37	41	1.53	T
19	32	31	31	31	32	32	34	32	33	36	40	.10	44
20	16	31	32	29	32	32	33	32	33	37	40	-	118
21	30	31	31	29	32	32	32	32	33	37	40	-	43
22	24	30	31	29	32	32	32	32	33	37	40	-	179
23	26	31	31	28	32	32	32	32	33	37	40	.16	38
24	35	31	31	28	32	32	32	32	33	37	40	-	14
25	30	31	31	29	31	31	32	32	32	37	40	-	7
26	26	32	31	30	32	32	32	32	33	37	40	.30	46
27	26	31	31	30	32	32	32	32	33	36	40	.41	50
28	31	32	30	31	32	33	32	33	36	36	40	.24	41
29	12	31	31	30	31	32	33	32	33	36	40	-	156
30	6	31	31	29	31	32	32	32	33	36	40	-	234
31	12	31	31	28	32	32	31	32	33	36	40	.03	135

Note: Mean air temperature is average daily minimum and maximum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

FEBRUARY 1949

Date	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
		TEMPERATURES (°F.)											
		Soil Depths in Inches						Stations A, B. & W					
1	18	31	31	28	32	32	31	32	33	36	39	.01	225
2	14	30	31	28	31	31	31	31	32	36	39	-	63
3	20	30	31	29	32	32	31	32	33	37	40	.15	203
4	25	31	31	29	31	32	31	32	32	36	39	-	189
5	20	31	32	29	32	32	31	32	33	36	40	-	198
6	22	31	32	29	32	32	31	32	33	36	40	.10	132
7	22	31	31	28	31	32	31	32	32	36	39	-	251
8	32	31	31	29	32	32	31	32	33	36	39	9	190
9	26	31	31	29	31	32	31	32	33	36	39	-	263
10	22	30	31	29	31	32	31	32	33	36	39	.03	91
11	19	27	29	29	29	31	31	31	32	36	39	-	274
12	36	29	30	29	30	31	31	31	32	36	39	.82	163
13	36	29	30	29	30	31	31	31	32	36	39	-	46
14	30	31	31	29	31	31	31	32	32	35	38	.80	26
15	32	32	32	29	32	32	31	32	32	35	38	-	60
16	28	30	31	29	30	31	31	31	31	35	38	T	117
17	24	28	30	29	30	31	31	31	32	36	37	-	272
18	44	31	32	30	31	32	31	32	33	36	39	-	302
19	35	31	31	30	31	31	31	31	32	35	38	-	208
20	27	31	31	30	31	31	31	31	32	35	38	-	92
21	26	32	31	29	32	32	31	32	33	36	39	.23	69
22	32	32	32	29	32	32	31	32	33	36	39	-	33
23	32	32	32	29	32	32	31	32	33	36	39	-	96
24	39	32	32	30	32	32	31	32	32	35	38	.15	62
25	29	32	32	30	32	32	33	32	33	36	38	-	98
26	24	32	31	30	32	32	32	32	32	35	38	-	295
27	32	32	31	30	32	32	32	32	32	35	38	.09	137
28	19	31	31	30	31	32	31	31	32	35	38	T	259

Note: Mean air temperature is average daily minimum and maximum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

MARCH 1949

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (IN.)	Total Insol. (Lang.)
1	19	31	31	29	32	31	31	32	32	35	38	–	329
2	26	32	31	30	32	32	30	32	33	36	38	–	69
3	28	31	31	30	32	32	31	32	33	35	38	.03	223
4	39	32	32	30	32	32	31	32	33	36	38	–	118
5	41	32	32	30	32	32	32	32	33	36	38	.04	166
6	26	32	32	30	32	32	32	32	33	36	38	–	241
7	26	31	31	29	31	32	31	32	32	35	38	–	396
8	38	32	32	30	32	32	31	32	32	35	38	–	113
9	30	32	32	32	32	32	32	32	32	35	38	.07	55
10	26	32	32	30	32	32	32	32	32	35	38	–	204
11	26	31	32	30	31	32	32	32	33	35	37	–	279
12	26	30	29	29	31	31	32	31	32	35	37	–	315
13	30	31	30	29	31	31	31	31	32	35	37	–	404
14	25	32	31	29	32	31	31	32	33	35	38	–	270
15	20	30	30	29	31	32	30	32	33	35	38	–	233
16	22	29	30	29	31	31	30	32	32	35	38	.02	215
17	22	30	29	28	31	30	30	31	32	35	37	–	436
18	24	30	30	29	31	31	30	32	32	35	37	T	229
19	22	29	30	29	30	31	30	32	33	35	38	–	272
20	32	30	30	28	30	31	30	32	33	35	38	–	282
21	52	31	31	30	31	31	30	32	32	35	37	–	298
22	46	33	32	37	32	32	33	32	32	35	37	–	119
23	32	32	32	34	32	32	35	32	32	35	37	.43	111
24	40	32	31	32	32	31	33	32	32	35	37	–	289
25	52	36	33	37	31	32	37	31	32	35	37	.03	439
26	44	35	33	40	32	30	38	31	32	34	37	.22	61
27	53	35	33	44	33	31	40	33	33	34	37	.11	190
28	48	36	34	39	35	32	39	35	34	35	37	–	488
29	56	39	34	40	38	33	40	38	36	35	37	–	418
30	45	41	37	41	41	36	41	41	39	35	37	.12	259
31	34	38	36	39	40	36	40	40	40	36	37	1.58	41

Note; Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

April 1949

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	36	44	39	35	40	36	38	38	38	38	38	–	353
2	38	35	33	33	38	35	37	39	39	38	38	–	488
3	38	36	33	34	38	35	38	39	39	38	38	–	522
4	41	36	34	34	38	36	37	40	40	38	38	–	513
5	44	40	37	36	40	38	39	40	40	38	38	–	220
6	45	40	39	40	41	39	40	42	41	39	39	–	300
7	44	41	39	40	42	39	40	42	41	39	39	.01	220
8	42	39	38	38	41	39	39	42	42	40	40	–	409
9	38	37	36	35	40	38	39	41	42	40	40	–	561
10	43	39	38	35	41	39	37	42	42	40	40	–	515
11	50	41	40	37	42	40	39	43	43	40	40	–	514
12	56	40	42	40	44	41	41	45	44	40	40	–	494
13	59	48	46	44	47	45	43	47	46	41	41	–	465
14	5–	47	46–	43	49	41	45	49	47	42	41	.45	430
15	35	46	45	43	47	45	44	48	47	43	41	.46	102
16	36	33	34	38	35	36	40	37	39	38	36	–	558
17	36	35	36	35	37	38	39	38	40	40	39	.28	217
18	34	38	39	35	39	40	39	40	42	43	42	.15	42
19	44	37	39	35	38	40	38	39	40	42	42	–	561
20	49	38	39	38	40	41	40	41	42	42	42	–	534
21	57	47	44	43	43	43	43	44	43	42	42	–	528
22	57	53	49	48	50	48	47	49	46	43	42	.27	443
23	48	49	48	45	48	47	47	48	47	42	42	.10	422
24	40	44	45	42	45	45	45	46	46	43	42	–	286
25	48	39	41	40	42	43	42	44	45	44	43	–	423
26	62	52	48	46	48	47	47	48	46	44	42	.03	188
27	56	45	48	44	49	48	46	49	48	44	43	–	561
28	46	51	50	44	51	49	47	50	49	44	43	–	589
29	54	57	52	45	53	50	46	52	50	45	43	–	573
30	61	63	54	48	55	51	49	54	51	45	43	–	435

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

May 1949

Date	Mean Air	Soil 1"A	Soil 1"B	Soil 1"W	Soil 6"A	Soil 6"B	Soil 6"W	Station 12"A	Station 18"A	Station 42"A	Station 60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)												
1	66	68	56	50	57	53	50	56	53	46	44	.15	223
2	61	70	58	50	59	55	51	57	58	47	44	-	575
3	67	65	55	49	55	52	51	54	54	47	44	-	574
4	77	84	64	54	66	57	53	61	56	49	45	-	460
5	78	66	60	57	65	58	55	63	59	49	46	-	444
6	72	66	61	58	67	60	57	66	62	51	46	-	515
7	56	61	57	54	63	58	55	64	62	51	46	-	440
8	57	60	56	50	63	57	53	64	62	53	48	-	463
9	52	60	55	50	62	55	53	63	62	55	50	-	126
10	44	50	49	47	55	52	51	58	59	54	49	-	608
11	46	48	47	45	53	50	50	56	58	54	50	-	512
12	60	55	51	49	57	52	51	58	57	53	49	-	448
13	65	56	53	50	59	53	52	60	59	53	50	T	508
14	62	61	67	53	62	66	54	60	60	54	50	-	471
15	56	61	61	50	62	61	52	60	60	54	50	.03	243
16	65	61	56	50	61	56	52	61	60	55	50	-	405
17	74	67	59	52	64	57	54	64	61	55	51	-	356
18	75	66	61	57	66	59	55	65	63	55	51	.66	368
19	58	67	63	60	66	60	56	65	64	56	51	1.65	92
20	51	53	54	50	58	57	53	61	63	58	53	-	583
21	53	55	53	50	56	54	52	58	59	56	52	.02	362
22	62	57	59	53	57	60	54	59	59	56	52	.15	107
23	62	57	66	51	59	67	54	60	59	56	53	-	477
24	50	57	57	52	60	58	54	60	60	55	53	-	416
25	46	48	52	50	55	55	55	57	59	56	53	.01	223
26	46	47	51	48	52	53	51	55	56	56	53	-	500
27	50	49	51	49	53	53	51	54	56	55	52	-	263
28	48	47	50	48	52	52	51	54	55	55	53	-	604
29	54	55	53	50	54	53	52	55	56	55	53	-	597
30	63	62	56	51	57	54	52	57	57	54	52	÷	464
31	70	61	57	51	60	56	52	60	58	54	52	-	560

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

JUNE 1949

Date	Mean Air	Soil 1"A	Soil 1"B	Soil 1"W	Soil 6"A	Soil 6"B	Soil 6"W	Station 12"A	Station 18"A	Station 42"A	Station 60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)												
1	70	60	57	48	62	58	51	62	60	55	52	-	526
2	72	63	59	50	64	59	51	63	61	55	52	-	487
3	78	67	62	52	66	61	53	65	63	56	52	.03	337
4	72	66	63	53	66	62	54	66	64	57	53	-	584
5	65	64	62	56	66	62	56	66	64	57	53	-	616
6	66	63	60	59	65	61	57	66	65	58	54	-	501
7	55	60	58	59	63	59	57	64	64	58	54	-	633
8	52	62	56	56	61	57	57	63	64	59	54	-	599
9	58	62	56	54	61	56	56	62	63	59	55	-	547
10	66	60	56	52	63	57	55	64	63	59	55	-	500
11	75	68	62	50	65	60	54	65	64	50	55	-	518
12	78	71	65	50	67	62	54	67	65	59	55	-	474
13	76	74	69	52	70	65	54	70	66	58	55	.38	346
14	76	72	70	57	69	67	56	69	67	69	55	.82	280
15	66	68	68	60	69	68	58	69	67	60	55	1.11	28
16	64	70	69	59	71	69	58	71	71	66	61	.84	89
17	71	68	66	62	67	65	60	67	66	61	57	.03	217
18	74	70	69	62	68	66	62	67	66	61	57	-	421
19	77	71	70	60	69	68	60	68	67	61	57	-	463
20	78	72	71	62	71	70	60	70	68	60	57	-	479
21	74	74	73	64	72	72	62	72	70	62	57	.10	270
22	70	65	67	64	71	70	62	71	70	63	58	-	570
23	72	66	68	65	69	69	63	70	69	62	58	-	498
24	79	71	70	65	70	70	64	71	69	63	58	-	498
25	75	72	72	62	72	72	63	72	70	63	59	.46	239
26	78	74	73	62	72	72	62	72	70	63	59	-	439
27	78	75	74	65	73	73	64	73	71	64	59	-	421
28	80	75	74	67	74	73	65	74	72	64	59	-	485
29	77	76	74	68	74	74	65	74	72	64	59	1.90	294
30	79	73	73	68	72	72	66	73	72	65	59	-	546

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

JULY 1949

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Station A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	82	73	74	70	75	74	67	75	73	65	60	-	502
2	82	75	76	70	76	75	68	76	75	66	61	-	498
3	84	74	76	69	76	75	69	76	75	66	61	-	494
4	82	74	75	70	76	75	69	76	74	65	60	-	464
5	82	78	76	70	77	76	69	77	75	67	66	-	451
6	75	76	77	70	77	76	70	77	75	67	61	.15	236
7	72	75	71	64	74	73	68	74	73	66	60	-	164
8	74	74	71	66	73	72	66	74	74	68	62	-	381
9	78	73	74	70	74	73	69	74	73	68	62	.99	227
10	68	72	72	64	73	72	68	74	73	68	62	-	628
11	66	71	70	62	72	70	65	73	73	67	63	-	542
12	70	69	68	62	70	70	65	72	72	68	63	-	240
13	72	68	69	62	70	70	65	71	71	67	63	-	524
14	63	70	68	60	70	69	65	70	71	67	63	.78	162
15	64	64	65	60	77	67	63	69	69	67	63	-	585
16	71	65	66	62	68	68	63	70	70	66	63	-	541
17	74	67	68	63	70	69	63	71	70	66	63	-	494
18	76	69	70	66	71	70	65	72	71	66	63	.01	427
19	74	73	72	68	73	72	66	73	72	66	63	-	533
20	71	69	68	65	71	70	65	72	72	67	63	-	346
21	75	74	70	67	72	70	67	73	72	67	63	.04	192
22	71	75	73	68	74	72	67	74	73	67	63	-	546
23	66	68	68	63	72	70	65	74	74	68	63	-	556
24	76	71	70	67	75	72	65	75	74	68	63	.49	355
25	82	75	73	71	76	74	68	76	74	68	63	-	437
26	81	76	75	73	81	79	69	78	75	68	64	-	432
27	82	78	75	70	77	75	70	77	76	69	64	-	464
28	80	76	75	70	78	76	70	78	76	69	64	.10	417
29	76	76	75	70	77	77	70	77	76	70	64	.27	257
30	65	69	72	65	75	75	69	75	75	79	64	-	282
31	64	73	70	60	72	73	65	73	74	74	64	-	517

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

AUGUST 1949

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Station A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	64	76	67	62	69	70	64	71	73	69	65	.32	335
2	70	70	69	63	70	70	64	71	72	69	65	-	428
3	65	68	69	63	79	71	65	72	72	69	65	-	467
4	66	67	69	62	70	71	64	72	72	69	65	-	369
5	67	66	67	63	69	70	64	71	72	68	65	-	475
6	68	67	66	64	70	69	64	72	72	68	65	.03	293
7	75	70	69	67	71	71	65	72	72	68	65	.57	401
8	78	74	72	69	73	73	67	73	72	68	65	-	492
9	78	75	74	70	74	74	68	74	73	68	64	-	479
10	75	73	73	70	76	75	69	76	76	69	65	-	433
11	68	74	74	71	77	74	71	77	75	69	65	.62	206
12	69	73	74	70	74	74	70	74	74	69	65	.53	157
13	71	75	68	64	71	71	67	73	73	69	65	-	451
14	71	70	68	68	71	72	67	73	73	69	65	-	455
15	72	66	69	65	71	73	67	73	73	69	65	-	429
16	72	69	70	66	70	71	67	71	71	68	64	-	437
17	72	70	71	67	72	72	67	73	73	69	65	-	187
18	68	70	70	67	71	71	67	71	72	69	65	-	408
19	58	64	67	60	70	70	65	71	73	69	66	-	451
20	58	59	61	56	66	66	62	69	71	68	65	-	454
21	60	59	61	57	66	66	62	69	70	68	65	-	488
22	63	59	62	57	66	66	61	68	69	68	65	-	464
23	66	63	63	58	67	65	61	68	69	67	65	-	433
24	68	66	66	63	69	68	63	69	69	68	66	-	277
25	71	67	66	63	69	67	64	70	70	67	65	-	397
26	76	72	70	68	72	70	67	72	71	68	65	-	350
27	76	72	70	69	73	70	67	73	73	67	65	-	199
28	66	69	68	68	71	69	67	72	72	67	65	.36	54
29	65	66	66	62	68	67	64	70	70	68	65	-	277
30	61	57	64	58	61	66	63	63	65	63	60	.19	115
31	60	61	63	58	65	65	63	66	68	67	65	.18	276

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

SEPTEMBER 1949

Date	Mean Air	TEMPERATURES (°E.) Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Station A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	53	54	60	60	62	63	63	65	67	67	65	.09	384
2	59	53	57	52	59	60	61	61	65	67	65	-	457
3	65	56	60	53	61	62	59	63	64	66	64	-	397
4	71	60	63	58	64	64	60	65	65	66	64	-	337
5	60	67	67	63	68	67	62	67	66	65	64	.33	209
6	56	59	61	67	63	63	65	65	66	65	64	.15	269
7	54	59	60	55	63	63	61	64	65	65	64	.20	10
8	54	55	58	55	60	61	60	62	64	65	64	-	371
9	54	51	55	52	58	59	53	61	63	64	63	-	444
10	57	55	57	51	59	59	57	61	63	64	63	-	405
11	59	58	58	54	60	60	57	61	63	64	63	-	131
12	66	60	60	58	62	61	59	62	63	63	63	.07	150
13	61	62	51	60	63	62	60	63	63	63	63	.54	89
14	49	52	57	61	58	59	61	60	62	63	62	-	205
15	54	52	56	50	56	58	57	58	60	63	62	-	386
16	58	53	56	52	58	58	56	59	61	62	62	-	361
17	61	55	57	54	58	59	57	59	61	62	62	-	348
18	62	60	58	55	59	59	57	60	61	62	62	.92	115
19	55	66	59	61	60	60	60	61	62	61	61	.05	201
20	55	54	56	55	57	58	59	59	61	62	61	-	290
21	55	55	56	56	57	58	57	58	60	61	61	-	143
22	52	53	55	54	57	58	57	58	60	61	61	.01	149
23	49	49	53	50	54	57	56	56	58	61	61	.07	247
24	47	47	52	48	53	54	54	55	57	60	61	-	276
25	55	49	52	50	54	54	54	55	57	60	61	-	334
26	57	51	53	51	55	55	55	56	57	60	60	-	349
27	61	57	56	56	57	56	56	58	58	59	60	.01	242
28	47	54	55	51	58	57	56	59	59	59	60	-	198
29	42	47	50	45	53	54	54	56	58	59	60	-	357
30	50	47	52	48	53	55	53	54	58	59	60	-	364

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

OCTOBER 1949

Date	Mean Air	TEMPERATURES (°F.) Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	53	56	52	47	53	53	54	57	58	59	60	-	352
2	60	58	52	52	56	55	55	58	58	59	60	-	335
3	62	60	59	60	60	58	57	59	58	58	59	.19	57
4	59	62	60	60	60	59	58	60	59	58	59	.21	95
5	54	63	56	51	59	58	57	60	60	58	59	-	311
6	58	55	55	55	56	56	56	58	59	59	58	.78	42
7	64	58	58	59	59	58	57	59	59	59	59	-	279
8	69	60	59	60	61	60	60	61	60	59	59	-	310
9	72	62	61	63	63	61	62	63	61	59	59	-	261
10	70	64	63	64	65	63	62	65	63	59	58	.02	320
11	59	62	62	60	65	63	62	65	64	60	59	.93	60
12	49	54	58	54	61	60	61	62	63	60	59	.09	348
13	51	50	52	50	56	56	57	58	61	60	59	-	338
14	52	50	52	51	55	57	57	57	59	60	59	-	248
15	48	48	51	50	54	55	56	56	58	59	59	-	323
16	45	49	51	46	54	54	55	55	57	59	59	-	316
17	53	50	51	49	53	53	54	54	56	59	59	-	224
18	54	50	51	48	54	53	54	55	56	58	59	-	252
19	54	52	51	48	53	53	55	55	56	58	58	-	286
20	62	54	54	52	55	55	56	56	56	58	58	.03	234
21	62	58	58	58	58	57	58	58	57	57	58	.20	51
22	53	48	55	52	57	58	58	58	58	57	57	-	252
23	48	44	50	50	53	55	55	55	56	57	57	-	158
24	37	41	46	44	49	51	53	51	54	57	57	-	253
25	38	38	42	41	45	47	51	48	52	56	57	-	263
26	37	40	45	44	47	48	51	49	51	56	57	-	300
27	41	37	42	40	43	46	50	46	49	55	57	-	280
28	48	40	43	43	44	46	50	46	49	55	57	-	257
29	55	44	46	47	46	48	51	47	48	54	56	-	254
30	49	46	48	47	47	50	50	48	49	54	56	-	176
31	32	48	50	45	49	51	51	50	50	53	56	-	91

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

NOVEMBER 1949

Date	Mean Air	Soil 1"A	Soil 1"B	Soil 1"W	Soil 6"A	Soil 6"B	Soil 6"W	Sta. 12"A	Sta. 18"A	Sta. 42"A	Sta. 60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)												
1	36	43	39	37	42	44	48	44	48	53	55	-	265
2	42	40	43	43	43	45	49	44	47	53	55	-	88
3	34	38	41	40	43	45	48	44	47	52	55	-	31
4	32	37	40	40	41	43	47	42	45	52	55	.10	63
5	31	33	36	33	38	40	45	40	44	51	54	-	252
6	45	35	38	40	39	41	45	41	44	51	54	-	153
7	49	37	40	38	41	43	45	42	44	50	53	-	196
8	51	44	44	45	44	45	48	44	45	50	53	-	215
9	50	41	43	42	44	45	48	45	46	49	53	-	209
10	59	46	46	48	46	46	50	46	47	49	53	-	153
11	50	48	48	50	48	49	51	49	48	50	52	-	86
12	50	48	48	49	48	48	50	48	49	49	52	.02	30
13	48	44	46	50	47	48	51	48	49	49	52	.21	27
14	38	40	44	42	46	47	50	47	49	50	52	.03	34
15	34	37	41	40	43	45	48	44	47	50	52	.09	77
16	34	37	39	40	40	42	47	42	45	50	52	-	32
17	34	36	39	40	40	41	46	41	44	50	52	-	68
18	34	35	38	39	39	41	45	40	43	49	52	-	109
19	36	35	37	39	37	39	45	39	42	48	52	-	35
20	32	34	37	39	37	39	45	39	42	48	52	.06	72
21	22	33	37	37	37	39	43	39	41	48	51	-	129
22	24	31	33	32	35	36	41	37	40	47	51	-	150
23	30	32	33	33	34	36	41	36	39	47	51	-	92
24	26	31	33	32	34	35	40	35	38	46	50	.58	21
25	18	32	33	32	34	36	39	35	38	46	50	-	113
26	12	32	33	33	34	36	40	35	37	45	50	.08	89
27	28	32	33	33	34	36	40	35	37	45	50	.02	69
28	28	32	34	33	34	36	40	35	37	44	49	.06	80
29	38	32	34	32	34	36	39	35	37	44	48	.02	117
30	34	33	34	33	34	36	39	35	37	44	48	-	97

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

DECEMBER 1949

Date	Mean Air	Soil 1"A	Soil 1"B	Soil 1"W	Soil 6"A	Soil 6"B	Soil 6"W	Sta. 12"A	Sta. 18"A	Sta. 42"A	Sta. 60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)												
1	30	31	33	32	33	34	39	34	36	43	47	.17	99
2	24	33	34	32	34	36	39	35	37	44	48	-	227
3	29	32	33	33	34	35	38	35	37	43	47	.23	159
4	35	31	33	34	34	35	38	35	37	43	47	-	82
5	28	31	33	30	33	35	38	34	36	42	46	-	161
6	24	30	33	31	34	35	35	34	36	42	47	.09	56
7	25	32	33	29	34	34	36	34	36	43	47	.05	174
8	21	31	33	29	34	35	36	35	36	43	47	.02	116
9	20	31	32	29	33	33	36	34	36	42	46	-	161
10	28	31	31	30	33	33	36	34	35	42	46	.24	17
11	47	32	32	35	34	34	37	34	35	42	46	.12	29
12	43	34	34	26	36	35	35	35	36	41	46	-	131
13	24	32	33	24	34	34	34	35	56	41	45	-	139
14	16	30	32	23	34	33	33	34	36	41	46	-	69
15	16	28	32	23	33	33	35	34	35	41	45	-	61
16	26	27	31	25	32	33	32	33	35	41	45	-	139
17	36	29	31	30	32	33	32	33	35	41	45	-	153
18	37	30	31	30	32	33	33	33	35	41	45	.34	19
19	38	32	32	36	32	32	35	33	34	40	44	-	36
20	46	32	32	43	32	32	40	33	34	40	44	1.05	15
21	48	37	37	45	35	35	43	34	34	40	44	.68	10
22	42	43	42	32	40	39	39	38	36	39	43	.67	14
23	22	33	34	31	35	36	36	36	37	39	44	.01	88
24	20	35	35	30	36	37	35	37	38	42	47	-	150
25	34	35	35	35	36	36	36	36	37	41	46	.42	72
26	38	34	35	36	35	36	37	35	36	40	45	-	24
27	36	34	35	30	34	35	37	34	35	39	43	-	22
28	34	32	33	30	33	34	36	34	35	38	42	-	155
29	32	32	33	28	33	34	35	34	35	39	43	-	153
30	28	32	33	30	33	34	35	34	35	39	43	-	122
31	36	32	32	35	33	33	36	34	35	39	42	.20	34

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

JANUARY 1950

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	42	47	46	36	42	40	36	40	38	39	42	-	33
2	47	47	46	41	42	40	38	40	38	39	42	-	30
3	54	47	46	47	42	40	45	40	38	39	42	.13	16
4	36	40	41	40	42	42	40	42	41	39	42	.82	16
5	23	32	34	30	36	36	38	38	39	40	42	.27	87
6	23	32	33	28	34	35	36	35	37	40	42	-	26
7	20	31	32	26	33	34	34	34	36	42	42	-	51
8	20	31	32	22	33	34	36	34	34	41	42	-	175
9	38	31	32	27	33	33	34	34	35	40	42	-	122
10	40	31	32	36	32	33	35	33	35	39	42	.14	60
11	20	30	32	25	33	33	38	33	35	39	42	-	192
12	32	29	32	25	32	33	36	33	34	38	41	-	134
13	48	32	32	32	32	33	35	33	34	38	41	.96	16
14	36	31	32	30	32	33	36	33	34	38	42	.03	104
15	33	29	32	25	32	33	31	33	34	38	42	.12	12
16	19	26	32	23	32	33	35	33	34	38	41	-	192
17	27	27	32	22	32	33	34	33	34	38	41	-	59
18	21	27	32	24	32	32	34	33	34	38	41	-	54
19	13	23	30		31	32		32	33	37	40	-	146
20	15	23	29		29	32		32	33	37	40	.13	112
21	27	28	31		31	32		32	34	37	40	-	50
22	34	30	31		31	32		32	34	37	40	-	30
23	29	32	32		32	32		32	33	37	40	-	28
24	42	31	31	28	31	31	31	31	32	36	39	.33	21
25	54	32	32	32	32	32	34	32	33	37	40	.36	50
26	31	32	32	32	32	32	32	32	33	37	40	-	41
27	18	29	31	22	32	32	32	32	33	37	40	-	226
28	30	30	32	23	32	32	30	32	33	36	39	-	136
29	29	28	32	30	32	32	30	32	33	36	39	-	25
30	12	26	31	22	32	32	30	32	33	36	39	-	105
31	22	29	31		32	32		32	33	36	39	.05	200

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

FEBRUARY 1950

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	19	29	30	25	31	32	30	32	33	36	39	-	229
2	23	29	31	24	31	32	38	32	33	36	39	-	100
3	24	25	29	25	30	32	30	32	33	36	39	-	255
4	28	26	29	24	30	32	30	32	33	36	39	-	271
5	32	29	30	24	31	32	30	32	33	36	39	-	107
6	34	32	32	24	32	32	30	32	33	36	39	-	28
7	27	32	32	30	32	32	30	32	33	36	39	-	259
8	29	28	31	26	31	32	30	32	33	36	39	-	108
9	31	32	32	25	32	32	30	32	33	36	39	.32	77
10	33	31	31	29	32	31	30	32	33	36	38	-	122
11	30	32	31	27	32	32	30	32	32	36	38	.03	161
12	26	31	31	27	32	32	30	32	32	36	38	-	109
13	28	29	31	25	31	32	30	32	33	36	38	.80	51
14	33	31	31	25	32	32	30	32	33	36	39	.29	22
15	30	32	32	29	32	32	30	32	33	36	39	.63	93
16	26	31	32	28	32	32	30	32	33	36	39	T	131
17	28	31	32	28	32	32	30	32	33	36	38	-	277
18	33	31	31	27	31	32	30	32	32	35	38	.06	148
19	15	30	31	27	31	32	30	32	32	35	38	-	182
20	7	29	31		32	32		32	33	36	38	-	290
21	20	29	30		31	32		32	33	36	38	.06	58
22	17	29	31		31	31		31	32	35	37	.15	100
23	19	30	31	25	31	31	30	32	33	36	38	-	300
24	13	31	31	27	32	32	30	32	33	36	38	.03	328
25	9	30	31	26	31	31	30	32	32	35	38	-	349
26	13	30	31	25	31	31	30	32	32	35	38	-	373
27	17	29	31	26	31	32	29	32	32	35	38	-	367
28	30	31	31	24	31	31	30	32	32	35	38	.52	91

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

MARCH 1950

Date	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches						Stations A, B, & W					
1	17	29	31	28	31	31	31	31	32	35	37	-	261
2	7	27	31	26	31	31	29	32	33	35	38	-	342
3	13	25	31	26	29	32	30	31	32	35	38	-	351
4	26	26	30	26	28	31	30	30	32	35	37	-	234
5	36	26	30	30	29	31	31	30	32	35	37	-	363
6	26	26	31	27	30	32	30	31	32	35	37	-	371
7	38	27	31	27	29	32	30	30	32	35	37	.04	311
8	29	32	32	30	31	32	30	31	32	34	37	-	139
9	17	20	26	23	28	31	30	30	32	34	37	-	300
10	22	22	26	21	26	30	29	28	32	35	37	.02	379
11	31	31	31	27	31	31	30	31	32	35	37	.17	73
12	16	31	31	26	31	31	28	31	32	35	37	-	313
13	22	31	31	26	31	31	28	31	32	35	37	-	369
14	24	28	30	25	30	31	29	31	32	35	37	-	405
15	26	25	29	25	29	31	29	30	31	34	36	-	415
16	24	26	29	25	29	31	29	30	31	34	36	-	196
17	27	28	29	26	29	31	29	30	32	34	37	.08	104
18	20	28	30	24	30	31	29	31	33	35	38	-	469
19	22	29	30	22	30	31	29	31	33	35	38	-	433
20	34	30	31	25	30	31	29	31	32	35	37	-	259
21	36	31	31	30	31	32	29	31	31	34	36	.02	88
22	37	31	31	30	30	31	30	30	30	33	35	.23	28
23	38	32	32	30	32	32	30	32	32	35	37	-	130
24	37	32	32	29	32	32	29	31	32	34	37	.20	115
25	39	32	32	28	32	32	29	32	32	35	37	-	381
26	38	31	32	29	32	32	29	32	32	34	37	.28	33
27	50	39	31	36	31	31	31	31	31	33	36	.40	58
28	35	45	32	32	32	32	32	32	32	34	37	-	56
29	28	32	32	28	32	32	32	32	32	34	36	-	372
30	30	32	32	27	32	32	30	32	32	34	35	-	405
31	39	32	32	28	32	32	30	32	32	35	37	.17	185

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

APRIL 1950

Date	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches						Stations A, B, & W					
1	37	35	32	36	32	31	34	32	32	34	36	.39	77
2	37	37	32	28	32	31	33	32	32	34	36	.26	179
3	51	38	33	41	33	32	34	32	32	34	37	.24	301
4	38	37	34	37	35	32	37	32	32	34	36	.73	57
5	29	32	32	30	32	32	35	32	32	34	36	-	147
6	28	31	32	24	32	32	33	32	32	34	36	-	527
7	38	32	32	25	32	32	32	32	32	34	36	-	342
8	32	32	32	26	33	32	36	33	33	34	36	-	418
9	31	32	32	24	33	32	31	33	33	34	36	-	206
10	43	32	32	27	32	32	32	32	32	34	35	.43	173
11	44	37	35	36	38	31	37	37	35	34	36	.10	61
12	27	32	32	32	34	32	35	34	34	34	36	-	213
13	21	31	32	28	33	32	33	33	34	34	36	-	268
14	29	31	32	27	32	32	32	32	33	34	35	-	165
15	38	32	32	27	32	32	32	33	33	35	36	-	584
16	45	38	36	38	35	33	32	35	34	35	36	-	486
17	57	44	40	43	39	35	38	38	35	34	36	.08	406
18	58	46	40	46	43	40	42	42	39	35	36	-	369
19	48	45	45	44	46	44	43	45	42	36	36	.11	243
20	40	38	40	39	42	42	41	42	42	37	37	-	174
21	39	36	38	36	39	39	39	39	40	38	37	-	272
22	45	34	36	34	38	38	38	39	40	38	38	-	467
23	52	38	39	45	41	40	44	41	41	38	38	.07	393
24	43	42	42	40	44	43	42	44	43	38	37	1.31	117
25	47	41	42	42	43	42	42	43	43	39	38	.82	144
26	40	38	41	40	42	42	42	43	43	40	39	-	302
27	36	37	39	36	40	41	41	41	42	40	39	.23	259
28	40	35	37	37	37	38	39	38	40	40	39	-	362
29	44	40	40	40	41	41	41	41	41	40	39	-	245
30	44	40	40	40	41	41	42	41	41	40	39	.01	130

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

MAY 1950

Date	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
		TEMPERATURES (°F.)											
		Soil Depths in Inches						Stations A, B, & W					
1	44	40	41	40	42	42	42	42	41	40	39	-	372
2	44	39	39	39	41	41	41	42	42	40	39	-	606
3	55	43	43	43	43	43	43	44	43	40	39	-	523
4	64	55	51	53	51	49	49	49	46	41	40	-	315
5	66	54	53	52	52	51	49	51	48	41	40	-	299
6	60	49	51	51	53	51	50	53	50	42	41	-	525
7	47	46	48	47	50	49	49	51	50	43	41	-	582
8	45	43	45	43	47	47	47	49	49	44	41	-	570
9	58	46	46	48	48	47	48	48	48	44	42	.15	140
10	52	48	48	50	50	49	49	50	49	45	42	-	519
11	50	46	46	48	48	48	48	49	49	45	43	-	391
12	59	48	47	50	49	48	48	49	49	45	43	-	538
13	61	54	52	53	52	51	51	52	51	45	43	-	497
14	62	54	52	49	53	51	50	53	52	45	43	-	365
15	61	54	53	52	54	52	51	54	52	46	43	-	577
16	54	51	51	55	54	52	50	54	53	46	43	-02	582
17	56	53	52	57	55	52	52	55	53	47	44	-	587
18	52	51	50	49	53	51	50	54	53	47	44	-	487
19	55	49	49	50	52	50	50	53	52	47	44	-	630
20	57	52	51	50	54	51	50	55	53	48	45	-	636
21	63	54	52	53	55	52	51	55	53	48	45	-	615
22	63	56	54	53	56	53	52	55	54	48	45	.43	314
23	65	55	54	54	56	54	56	56	55	49	46	-	517
24	70	59	57	60	58	56	55	57	55	49	46	.09	338
25	75	61	59	60	59	57	56	58	56	50	46	.67	489
26	58	62	61	58	61	59	56	60	58	51	47	-	129
27	57	56	56	51	58	57	55	58	57	52	48	-	530
28	58	56	56	54	58	57	54	58	57	52	48	-	657
29	62	56	57	55	57	57	54	58	57	52	48	-	618
30	67	59	58	55	59	58	55	59	57	52	48	-	455
31	64	62	62	59	61	60	57	60	58	52	48	-	389

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

JUNE 1950

Date	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
		TEMPERATURES (°F.)											
		Soil Depths in Inches						Stations A, B, & W					
1	62	60	59	55	60	59	55	60	58	53	48	1.83	636
2	64	57	56	56	59	58	55	59	58	54	49	.40	111
3	55	59	58	53	60	60	56	59	57	53	50	-	389
4	55	59	59	50	59	59	54	58	57	53	50	-	640
5	67	59	60	55	57	57	56	57	56	52	49	-	567
6	71	59	60	57	59	59	56	58	57	53	50	-	625
7	72	61	65	62	60	62	58	60	58	53	50	-	619
8	75	63	67	61	62	65	59	61	59	53	50	-	616
9	73	66	69	63	64	68	60	63	60	54	50	.35	301
10	64	65	68	60	64	66	60	64	61	54	51	.10	642
11	61	63	67	55	62	64	53	62	61	54	51	.01	610
12	69	60	65	57	60	62	57	60	60	55	51	-	551
13	65	61	63	59	62	65	58	62	60	55	51	.73	129
14	69	61	62	63	61	62	60	61	60	56	52	-	494
15	73	64	67	64	63	65	61	62	60	55	51	.07	426
16	68	67	70	53	65	66	58	63	61	56	52	-	443
17	56	58	60	51	62	64	56	63	62	56	52	-	598
18	54	58	62	52	60	63	55	61	61	56	52	.01	161
19	57	59	65	55	58	61	56	58	59	57	53	-	242
20	63	56	58	57	58	59	57	58	59	57	53	T	490
21	65	58	61	62	59	62	58	59	59	56	53	T	632
22	74	62	65	65	61	65	60	61	59	56	53	-	578
23	80	68	69	65	66	68	64	65	62	56	53	.03	413
24	74	70	70	66	68	68	64	68	65	56	53	.91	450
25	77	71	71	68	71	70	64	70	64	57	53	-	649
26	74	73	72	60	74	72	64	73	63	58	54	-	642
27	62	62	64	60	69	69	60	70	60	59	54	-	462
28	63	59	60	60	66	65	60	67	67	60	55	.26	465
29	63	61	62	58	65	65	59	66	66	60	55	.05	574
30	59	58	59	53	64	63	57	65	65	60	55	.08	331

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

JULY 1950

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	59	56	58	60	58	58	57	60	62	59	55	-	548
2	67	67	68	53	62	62	58	62	62	59	55	-	462
3	63	78	79	58	66	66	59	64	63	59	56	-	448
4	70	70	73	61	67	67	60	66	65	59	56	-	578
5	66	68	68	59	67	67	59	67	66	60	56	T	401
6	64	61	62	58	66	66	58	67	66	60	56	-	606
7	67	61	63	58	66	67	58	67	66	60	57	-	647
8	70	64	67	58	66	67	57	67	66	60	56	-	590
9	71	65	67	60	67	68	58	68	67	60	56	-	621
10	73	66	68	60	69	70	59	70	68	61	56	-	558
11	75	67	69	62	70	71	61	71	68	61	57	-	569
12	78	69	71	65	72	73	62	72	69	61	57	-	550
13	64	67	70	62	73	74	62	73	70	62	57	.68	404
14	60	58	58	56	65	64	59	68	68	62	57	-	667
15	68	67	69	59	65	66	59	66	66	62	57	-	641
16	77	68	70	63	68	69	61	68	67	62	57	-	441
17	75	70	71	68	71	72	64	70	68	62	58	1.85	312
18	66	65	65	60	71	71	62	71	69	63	59	-	640
19	65	67	66	62	70	69	62	70	69	62	58	1.07	149
20	60	62	61	60	65	65	61	67	67	67	58	.15	158
21	63	58	57	57	63	62	60	65	66	63	59	-	612
22	69	63	63	61	65	65	60	65	65	62	58	-	512
23	72	65	65	61	66	67	60	66	66	62	58	-	501
24	69	67	68	61	68	70	61	68	67	62	59	.24	466
25	67	63	63	61	67	67	61	68	67	62	58	-	460
26	68	66	66	61	67	67	61	67	67	62	58	-	452
27	72	64	65	63	67	68	61	67	67	62	58	-	563
28	72	66	68	64	67	69	64	68	67	62	58	-	515
29	74	67	69	64	68	69	63	68	67	62	59	-	570
30	76	68	70	65	68	70	63	68	67	62	59	.38	402
31	76	70	72	68	69	71	65	69	68	62	58	.84	312

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

AUGUST 1950

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	73	69	72	68	70	71	65	70	68	63	59	.12	396
2	64	68	68	65	69	69	65	69	69	64	60	-	308
3	61	62	62	60	66	66	62	67	67	63	60	-	439
4	62	60	60	59	64	64	61	65	66	63	59	-	551
5	65	61	61	58	63	64	60	64	65	63	59	-	592
6	67	61	62	60	63	65	60	64	65	62	59	-	605
7	68	61	63	60	64	66	60	65	65	62	60	-	578
8	72	63	65	61	65	68	61	66	65	63	60	-	462
9	74	66	68	64	66	69	63	66	65	62	59	-	380
10	73	66	68	63	66	68	63	66	66	62	60	.28	392
11	61	64	63	58	66	67	61	67	66	63	60	.04	461
12	58	57	58	53	62	62	58	64	65	62	59	-	579
13	61	57	59	54	62	62	58	64	64	62	59	-	594
14	65	58	60	56	61	62	59	63	63	62	59	-	506
15	74	65	67	63	63	65	61	63	63	61	59	-	485
16	75	65	67	64	66	68	62	66	64	61	59	-	505
17	77	71	72	68	67	68	64	67	65	61	59	-	499
18	61	66	67	61	69	69	63	68	67	62	59	-	121
19	64	64	64	60	65	66	61	65	65	61	58	-	427
20	55	62	61	55	64	64	60	64	65	61	58	-	552
21	57	59	58	53	62	61	58	64	65	62	59	-	542
22	65	67	64	58	64	63	58	64	64	62	59	.20	269
23	71	59	66	60	63	63	59	64	64	61	59	-	488
24	72	62	62	62	66	65	61	66	65	61	59	-	513
25	69	67	65	63	68	66	62	68	66	62	59	-	329
26	69	65	64	60	68	65	61	69	67	62	60	.99	304
27	76	68	66	67	69	67	62	69	67	62	60	.07	312
28	76	71	69	67	71	69	65	70	68	63	60	1.08	333
29	66	68	68	66	71	69	65	70	69	63	60	.87	292
30	63	64	63	60	68	66	63	69	69	63	60	-	182
31	70	71	68	62	68	67	63	68	68	64	60	.75	147

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

SEPTEMBER 1950

Date	Mean Air	Soil 1"A	Soil 1"B	Soil 1"W	Soil 6"A	Soil 6"B	Soil 6"W	Stations 12"A	Stations 18"A	Stations 42"A	Stations 60"A	Total Precip. (In.)	Total Insol. (Lang.)
		TEMPERATURES (°F.)											
		Soil Depths in Inches						Stations A, B, & W					
1	65	68	67	66	69	68	64	69	68	64	60	.21	96
2	61	61	61	58	65	65	62	67	68	64	60	-	383
3	64	60	60	57	65	64	60	67	67	64	60	-	428
4	57	58	59	55	64	63	60	66	66	64	61	-	495
5	55	57	56	53	61	60	59	63	65	63	60	-	504
6	57	57	57	52	61	58	57	62	64	63	60	-	496
7	61	57	56	54	61	59	57	63	64	62	60	-	444
8	67	63	60	60	63	61	59	64	64	62	60	-	229
9	69	63	62	60	64	62	60	64	64	62	60	-	390
10	68	65	64	62	65	63	61	65	65	62	60	.70	162
11	69	68	66	65	66	65	63	66	66	63	60	.93	217
12	65	67	66	64	67	66	63	67	66	62	60	.13	70
13	61	64	64	61	66	65	62	66	66	63	60	1.21	52
14	58	61	61	60	64	63	61	65	65	63	61	.09	54
15	59	60	60	57	62	61	59	63	64	63	60	.02	218
16	54	58	57	53	62	60	58	63	64	63	61	-	197
17	55	58	57	52	61	59	57	62	63	63	61	-	427
18	63	58	57	54	59	57	56	60	62	62	60	.28	356
19	62	62	61	57	62	62	59	62	62	61	60	-	348
20	61	58	58	55	62	60	58	62	63	62	60	-	385
21	58	59	58	58	61	60	60	62	62	61	62	.25	93
22	60	59	58	55	60	59	58	61	61	61	60	-	282
23	47	56	56	52	60	59	57	60	61	61	60	-	454
24	39	55	53	47	57	56	54	58	59	61	60	-	100
25	55	53	50	50	53	52	53	55	57	61	60	-	372
26	61	53	52	50	55	54	49	56	57	60	60	-	391
27	63	56	56	55	57	57	55	57	58	59	59	-	159
28	65	59	59	58	58	58	57	58	58	59	59	-	179
29	71	60	61	60	60	60	58	59	59	59	59	-	333
30	66	60	59	59	60	60	58	60	60	58	58	-	241

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

OCTOBER 1950

Date	Mean Air	Soil 1"A	Soil 1"B	Soil 1"W	Soil 6"A	Soil 6"B	Soil 6"W	Stations 12"A	Stations 18"A	Stations 42"A	Stations 60"A	Total Precip. (In.)	Total Insol. (Lang.)
		TEMPERATURES (°F.)											
		Soil Depths in Inches						Stations A, B, &W					
1	70			60	61		60	61	61		58	-	265
2	68	63	62	53	63	62	59	62	62	59	59	.03	302
3	56	57	58	60	62	62	60	62	62	60	59	-	340
4	46	56	55	50	58	56	56	59	60	60	59	-	255
5	47	56	49	49	56	54	54	57	59	60	59	-	342
6	53	55	51	51	56	54	54	56	57	60	60	-	165
7	63	55	54	56	55	55	55	56	57	59	59	.28	235
8	56	55	55	54	56		56	57	57	59	59	-	146
9	55	56	55	54	57	57	56	58	58	58	58	.27	341
10	55	55	55	53	56	56	55	57	57	58	58	.37	55
11	54	53	52	52	56	54	55	56	57	58	58	-	99
12	49	51	51	50	54	54	55	56	57	57	58	.07	153
13	48	48	49	48	53	52	54	54	55	57	58	.07	319
14	50	51	51	50	52	52	53	53	55	57	58	.29	200
15	49	51	50	46	52	51	54	53	55	57	58	-	296
16	58	50	49	49	51	51	53	53	54	57	58	-	285
17	67	54	53	56	54	53	55	54	54	56	57	-	281
18	68	55	55	57	56	56	56	56	55	55	56	-	299
19	65	57	56	57	57	58	57	57	56	56	57	-	288
20	47	51	51	51	56	55	56	57	57	56	56	-	322
21	51	48	47	50	53	51	54	54	56	56	56	-	307
22	48	48	48	50	53	51	54	54	55	56	56	-	62
23	45	49	49	49	52	51	53	53	54	55	56	T	45
24	47	48	48	48	50	49	54	52	53	56	56	-	74
25	43	46	45	47	49	48	54	51	52	55	56	-	240
26	42	40	36	43	47	46	50	48	52	55	56	-	287
27	51	45	46	47	48	47	52	48	50	54	55	.24	60
28	55	49	49	50	49	49	50	50	51	53	55	-	55
29	56	49	49	49	50	50	52	51	51	53	55	-	204
30	62	49	49	49	51	51	52	52	52	53	55	-	240
31	67	55	55	53	54	55	54	54	53	53	55	-	183

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

NOVEMBER 1950

Date	Mean Air	Soil Depths in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	67	58	58	56	56	56	56	55	54	53	54	-	246
2	47	50	50	51	55	55	56	56	56	54	54	-	104
3	39	47	45	49	51	49	53	53	54	54	55	-	47
4	31	46	40	44	48	46	51	50	52	54	55	T	47
5	32	43	39	40	46	43	48	48	50	54	55	-	98
6	49	40	39	43	44	42	48	45	48	53	54	-	209
7	43	41	39	44	45	43	48	46	48	53	54	.46	53
8	44	44	43	45	45	45	49	45	48	52	54	.12	79
9	42	44	44	45	47	46	49	47	48	51	54	.37	10
10	31	38	37	42	43	41	47	44	47	51	53	-	78
11	25	37	36	40	41	40	45	42	45	51	54	.08	132
12	27	36	35	39	40	39	44	41	44	50	53	-	127
13	30	35	34	37	39	38	44	40	43	49	52	-	63
14	38	33	34	36	37	37	42	39	42	48	52	.01	150
15	50	42	42	43	40	41	44	41	42	48	52	.80	15
16	48	48	48	48	45	46	48	44	44	48	51	-	54
17	39	38	38	41	42	42	46	43	44	47	51	-	182
18	39	37	36	40	40	39	45	41	44	47	51	-	101
19	45	37	37	42	42	40	45	42	43	47	50	.25	8
20	35	35	38	36	40	41	43	41	43	47	50	.50	32
21	29	33	34	36	38	38	44	39	42	46	50	-	54
22	29	33	34	35	37	37	41	38	41	46	50	-	61
23	22	33	34	32	36	36	40	37	40	46	50	.09	62
24	5	32	34	30	35	36	38	37	39	45	49	-	192
25	16	30	33	31	35	36	38	36	38	45	49	.19	35
26	25	31	33	31	35	35	37	36	38	44	49	.10	119
27	21	32	33	32	34	35	37	35	37	43	48	.06	100
28	24	32	33	33	34	35	38	35	37	43	48	-	117
29	28	32	33	33	34	35	38	35	37	43	47	-	21
30	26	32	33	33	34	35	38	35	36	43	48	-	78

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

DECEMBER 1950

Date	Mean Air	SOIL DEPTHS in Inches 1"A	1"B	1"W	6"A	6"B	6"W	Stations A, B, & W 12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	26	32	34	31	34	35	38	35	36	42	47	-	113
2	40	32	34	36	33	35	38	34	36	41	46	.52	27
3	39	32	33	30	33	35	36	34	36	41	46	-	4
4	27	32	33	21	34	35	35	35	36	41	46	-	11
5	28	32	33	30	34	34	35	35	36	41	46	-	33
6	33	32	32	33	34	34	36	34	36	41	45	.24	15
7	26	32	33	30	34	34	36	34	36	41	45	.67	1
8	19	32	33	30	34	34	35	34	36	40	45	-	41
9	24	32	33	30	34	34	35	34	36	40	45	.02	71
10	25	32	33	30	34	34	35	34	36	40	46	-	52
11	25	32	32	30	33	34	35	34	35	40	44	-	93
12	27	32	32	30	34	34	35	34	36	40	44	T	77
13	25	31	32	31	33	33	35	33	34	39	43	.02	43
14	19	32	32	30	33	34	35	34	35	39	43	-	129
15	19	32	32	30	33	34	35	34	35	39	43	.08	120
16	19	32	32	30	33	33	34	34	35	39	43	-	68
17	16	31	32	29	33	33	33	34	35	39	43	-	87
18	15	31	32	29	33	33	33	34	35	39	43	-	142
19	16	31	32	30	33	33	33	33	35	39	42	-	120
20	20	31	32	30	33	33	33	33	35	38	42	-	131
21	21	31	32	30	32	33	33	33	34	38	42	.03	134
22	27	31	31	30	32	32	34	33	35	38	42	.04	44
23	30	31	31	30	32	33	34	33	34	38	42	-	31
24	26	31	31	30	32	33	34	33	34	38	42	T	58
25	13	31	31	29	32	33	33	33	34	38	42	.04	76
26	6	31	31	29	32	33	33	33	34	38	42	.04	173
27	10	30	31	29	32	33	32	33	34	38	41	-	150
28	15	30	31	29	32	32	32	33	34	38	41	-	162
29	21	31	31	29	32	32	32	33	34	38	41	-	76
30	26	31	31	29	32	33	32	33	34	38	41	-	30
31	27	31	31	29	32	33	32	33	34	38	41	-	117

Note: Mean air temperature is average daily maximum and minimum temperature. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed. "T" indicates trace, or amount too small for measurement. Blank spaces indicate incomplete record for that day and station.

JANUARY 1951

DATE	Mean Air	Soil Depths in Inches, Stations A, B, & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)												
1	30	31	31	29	32	32	33	33	34	38	41	-	132
2	40	32	32	29	32	33	33	33	34	38	41	1.10	12
3	39	32	32	29	32	33	33	33	34	38	41	.49	2
4	30	32	32	31	32	33	33	33	34	38	41	-	62
5	30	32	32	31	32	32	33	33	34	38	40	t	64
6	25	32	32	29	32	32	32	33	34	38	40	-	25
7	16			22			31			38		-	106
8	18	28	29	26	32	32	29	33	34	37	40	-	119
9	26	27	27	27	32	32	31	32	34	37	40	-	153
10	36	31	30	26	32	32	29	32	34	37	40	-	73
11	30	31	32	26	32	32	28	33	34	37	40	-	84
12	27	30	30	25	32	32	30	32	33	37	40	-	175
13	25	28	27	25	32	32	30	33	33	37	40	-	55
14	29			24			30			37		.20	3
15	30	31	31	26	31	32	30	32	33	37	40	.01	89
16	29	30	31	29	32	32	31	32	33	37	40	-	115
17	34	31	31	29	32	32	31	33	34	36	40	-	86
18	36	32	32	29	32	32	29	32	33	36	39	-	88
19	38	32	32	33	32	32	33	32	33	36	39	-	140
20	32	32	32	32	32	32	32	32	33	36	39	.25	2
21	17			26			31			36		-	156
22	17	30	32	23	32	32	31	32	33	36	39	-	86
23	30	31	32	25	31	32	29	32	33	36	39	.05	21
24	21	29	32	27	31	32	31	32	33	36	39	-	127
25	21	29	30	27	31	32	31	32	33	36	39	-	65
26	21	29	31	27	31	32	30	32	33	36	39	.08	121
27	15	31	31	27	32	32	30	32	33	36	39	.12	150
28	13			26			30			36		-	82
29	8	30	31	26	31	32	30	32	33	36	39	.04	136
30	3	29	31		31	32		32	33	36	39	-	220
31	5	30	30		32	32		32	33	37	39	.11	71

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

FEBRUARY 1951

DATE	Mean Air	Soil Depths in Inches, Stations A, B, & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)												
1	10	30	31		31	32		32	33	36	39	.06	94
2	2	31	31	25	31	32	29	32	33	36	39	-	254
3	9	30	31	25	31	32	29	32	33	36	39	-	212
4	19			23			29					.02	136
5	22	31	31	25	31	32	29	32	32	36	38	-	98
6	26	31	31	25	31	32	29	32	33	36	38	.21	23
7	19	32	32	27	32	32	30	32	33	36	39	.01	156
8	4	29	30	26	31	32	29	32	32	36	38	-	224
9	2	28	28		31	31		32	33	36	39	-	261
10	16	28	28		30	31		32	33	36	38	-	167
11	37											-	179
12	34	32	32		31	32		32	33	36	38	.30	20
13	32	29	30	26	31	32	29	32	32	36	38	.09	53
14	12	26	28	25	30	30	29	31	32	36	38	-	292
15	18	25	27	24	29	29	29	31	33	36	39	-	304
16	25	27	28	24	28	29	29	30	32	36	38	.22	51
17	34	31	31	29	31	31	29	31	32	35	38	-	83
18	37			29			29					.02	182
19	40	31	32	29	31	31	30	31	32	35	37	.29	16
20	36	32	32	29	31	31	28	32	32	35	37	-	67
21	35	32	32	29	32	32	29	32	32	35	38	-	42
22	33	32	32	28	32	32	28	32	32	35	37	-	200
23	33	32	32	26	32	32	28	32	32	35	38	-	213
24	38	32	32	24	32	32	28	32	32	35	37	-	266
25	43			28			29					-	90
26	47	33	34	32	32	32	34	32	32	35	37	.11	54
27	31	32	32	28	32	32	32	32	32	35	37	-	97
28	26	32	32	28	32	32	32	32	32	35	3	.06	158

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 A.M. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

MARCH 1951

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang)
		Soil Depths in Inches						Stations A, B, & W.					
1	33	32	32	30	32	32	32	32	32	35	37	.08	341
2	27	32	32	30	32	32	32	32	32	35	37	.04	107
3	44	32	32	29	32	32	31	32	32	35	37	.33	39
4	32			32			33					-	349
5	38	32	32	30	32	32	32	32	32		37	-	346
6	50	32	32	31	32	32	36	32	32	35	37	-	272
7	43	32	32	34	32	32	36	32	32	35	37	-	363
8	30	32	32	32	32	32	35	32	32	35	37	-	111
9	24	32	32	29	32	32	36	32	32	35	37	-	358
10	26	32	32	26	32	32	32	32	32	35	37	-	352
11	30	32		26			30					-	346
12	35	32	32	26	32	32	31	32	32	35	37	-	210
13	38	32	32	32	32	32	34	32	32	35	37	.29	37
14	34	32	32	32	32	32	33	32	32	35	37	.18	53
15	32	32	32	30	32	32	33	32	32	35	36	.12	154
16	31	32	32	29	32	32	32	32	33	35	37	-	185
17	32	32	32	26	32	32	33	32	32	35	37	-	344
18	33			28			33					-	83
19	26	32	32	27	32	32	33	32	33	35	37	-	67
20	23	32	32	26	32	32	32	32	33	35	37	t	321
21	20	30	32	28	32	32	31	32	33	35	37	t	131
22	28	30	31	26	32	32	30	32	33	35	37	-	255
23	38	32	32	31	32	32	30	32	33	35	37	-	61
24	28	32	32	27	32	32	30	32	33	35	37	-	204
25	27			24			30					-	366
26	28	30	32	24	32	32	29	32	33	35	37	-	468
27	46	32	32	30	32	32	30	32	33	35	36	-	236
28	49	33	37	40	32	32	34	32	33	35	36	-	44
29	54	39	42	42	35	36	37	34	34	35	37	.40	87
30	43	42	43	44	40	41	41	39	36	35	37	.06	134
31	33	34	35	39	39	38	40	39	38	36	38	.04	71

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

APRIL 1951

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
		Soil Depths in Inches						Stations A, B, & W.					
1	36	34	35	36	37	36	35			36		.19	131
2	35	34	34	30	36	35	35	36	36	36	38	.02	104
3	34	34	33	32	36	35	34	36	36	36	38	.02	59
4	40	34	34	30	35	35	35	36	36	36	38	-	164
5	44	33	33	30	36	35	36	37	37	37	38	-	506
6	47	37	35	42	38	37	40	39	38	37	37	-	331
7	57	43	42	42	41	41	40	41	39	37	37	-	277
8	44	40	40	36	41	40	38					.56	28
9	44	38	38	35	40	39	37	31	31	38	38	-	359
10	43	40	39	36	42	40	40	43	42	39	39	-	356
11	47	41	41	39	44	42	40	44	43	40	39	-	331
12	42	42	41	43	44	43	44	44	43	39	39	.16	244
13	36	40	40	38	43	41	40	43	43	40	39	.17	88
14	41	37	37	32	41	39	38	42	42	41	39	.20	131
15	38	36	37	37	40	38	38					.07	132
16	35	35	36	31	39	38	37	39	41	41	40	-	198
17	34	34	34	32	38	37	37	39	40	41	40	-	223
18	40	35	33	34	37	36	37	38	39	40	40	.15	88
19	40	35	35	34	38	37	37	39	39	40	40	-	335
20	39	34	34	31	38	37	36	39	40	40	40	-	574
21	47	39	39	38	41	40	37	41	41	40	40	.17	363
22	43	37	37	44	40	39	42					.36	79
23	42	36	36	33	39	38	38	41	41	40	40	-	566
24	46	41	41	41	42	40	41	42	42	40	40	.41	61
25	54	43	43	42	42	41	42	42	42	41	40	.34	94
26	49	43	43	42	44	43	45	44	43	41	41	-	532
27	52	43	43	42	46	44	46	46	45	41	41	-	543
28	66	52	52	50	48	48	48	47	45	41	41	-	415
29	66	52	53	55	50	50	50					.35	418
30	59	53	63	50	53	53	50	52	49	42	41	-	334

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches / Stations A, B, & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (Inc.)	Total Insol. (Lang.)
1	66	51	52	50	52	51	50	52	49	43	41	-	523
2	70	56	56	54	55	55	53	54	51	45	42	.07	446
3	62	59	59	59	56	56	54	55	52	44	41	.04	422
4	55	53	51	50	55	54	54	55	53	46	43	-	485
5	49	49	48	46	53	51	50	54	53	47	44	-	461
6	48	48	47	49	51	50	45					-	435
7	50	46	47	42	50	49	45	51	51	48	45	-	486
8	59	49	50	50	51	50	46	51	51	48	45	-	610
9	59	53	53	50	53	52	49	52	51	48	45	-	356
10	44	50	49	49	52	51	47	52	52	48	46	1.03	60
11	44	47	45	43	49	47	45	50	51	49	47	.31	72
12	53	46	46	45	48	46	44	49	49	49	46	-	549
13	49	47	48	45	49	48	44					-	652
14	61	48	49	50	50	50	45	50	50	48	45	-	595
15	70	52	53	53	52	52	49	51	49	47	46	-	595
16	68	56	58	56	55	56	53	54	52	48	45	.37	566
17	54	55	55	50	55	56	51	55	53	48	46	-	132
18	66	56	57	52	55	56	51	55	53	49	46	-	538
19	67	56	59	53	57	57	53	56	54	49	47	-	527
20	74	58	61	57	58	58	55					.03	433
21	69	61	63	56	59	60	55	58	56	50	47	-	463
22	56	59	61	55	60	61	57	58	56	51	47	.30	80
23	53	52	54	50	55	55	55	56	56	51	48	-	678
24	62	53	54	50	55	56	55	56	55	51	48	-	495
25	66	55	57	54	56	57	55	56	55	51	48	-	609
26	64	58	59	54	57	58	54	57	56	52	49	.27	363
27	54	56	57	51	56	57	52					.47	190
28	56	54	55	52	55	56	52	55	55	52	49	.29	151
29	60	54	55	52	55	55	52	54	55	52	49	-	545
30	64	56	57	52	56	57	51	56	55	52	49	-	590
31	66	57	59	54	57	59	54	57	55	52	49	.02	474

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

DATE	TEMPERATURES (°F.) Mean Air	Soil Depths in Inches / Stations A, B. & W. 1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
1	75	61	64	58	59	62	56	58	56	52	49	.52	506
2	68	62	64	59	62	64	57	61	58	53	50	.02	265
3	70	61	62	60	62	63	58					-	303
4	55	60	60	54	61	62	56	61	59	53	50	-	214
5	55	56	56	51	57	57	54	58	58	53	50	-	280
6	57	53	55	52	56	57	52	57	57	54	51	-	585
7	61	54	57	52	56	58	52	57	56	54	51	-	585
8	63	56	58	54	57	60	55	57	56	54	51	.11	183
9	64	58	60	54	58	60	55	57	56	54	51	-	221
10	63	56	60	52	57	60	55					-	579
11	63	55	59	52	57	60	54	57	57	54	51	-	533
12	68	57	61	54	58	62	55	58	57	54	51	.08	332
13	65	58	61	54	58	62	56	58	57	54	51	.61	282
14	63	58	60	56	58	61	55	58	58	54	52	-	629
15	64	55	59	57	58	60	54	58	57	54	51	-	644
16	68	58	51	58	59	62	57	58	57	54	52	-	522
17	71	60	65	59	60	64	57					-	596
18	74	62	67	60	61	67	57	60	58	54	51	.02	527
19	73	65	69	60	63	68	60	62	60	54	52	.57	256
20	70	65	67	61	63	66	61	62	60	55	52	-	416
21	64	58	60	58	60	61	58	60	59	54	50	.08	328
22	58	59	59	57	61	62	58	61	60	56	53	.84	64
23	67	60	61	57	60	62	56	60	59	56	52	-	454
24	73	65	65	59	63	64	59	63	60	56	53	-	447
25	65	62	63	58	64	64	59	64	62	56	53	-	672
26	71	63	63	58	65	65	58	66	63	56	53	-	433
27	71	65	64	60	66	65	60	66	64	57	53	.10	426
28	68	65	67	60	67	67	63	67	65	57	53	-	265
29	65	60	62	59	65	65	60	66	65	58	54	-	653
30	68	63	64	60	67	66	60	66	65	58	54	.01	538

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement
Blank spaces indicate incomplete record for that day and station.

JULY 1951

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches						Stations A. B. & W.					
1	66	65	66	58	68	67	60	67	67	60	56	-	561
2	67	62	62	57	64	64	59	65	65	59	56	-	634
3	69	65	66	59	66	67	59	66	65	59	56	-	203
4	67	67	67	59	65	66	61	65	64	59	55	.01	457
5	63	60	63	58	64	66	59	66	65	59	55	.02	683
6	68	62	64	57	64	66	58	65	65	60	55	--	649
7	72	64	66	59	66	68	60	66	65	60	55	-	595
8	73	66	67	60	67	68	63					.13	154
9	72	68	68	61	68	68	63	67	66	60	56	.38	405
10	75	68	67	62	68	68	64	67	66	60	56	-	513
11	63	66	66	60	68	69	63	69	67	61	56	-	109
12	66	63	63	60	65	65	61	66	66	61	57	.03	453
13	68	64	65	58	65	66	58	65	66	61	57	-	596
14	72	66	68	59	66	69	61	66	66	61	57	-	280
15	73	65	68	60	66	69	62	67	65	60	56	-	571
16	76	68	70	60	68	71	65	68	66	61	57	-	465
17	71	67	70	61	68	72	63	69	67	61	57	-	405
18	72	67	71	60	68	71	62	68	67	63	57	-	369
19	65	66	68	59	68	71	64	68	67	61	57	-	496
20	64	62	64	56	65	69	60	67	67	62	57	-	624
21	72	63	69	60	66	71	61		67	62	58	.22	161
22	75	65	68	63	67	71	64	67				-	292
23	68	66	67	60	67	70	63	68	66	62	58	-	262
24	73	64	66	61	66	68	63	67	66	62	57	-	542
25	75	66	69	62	68	71	64	68	67	62	58	-	567
26	79	68	71	63	69	73	65	67	67	61	58	-	557
27	75	70	73	66	70	74	65	70	68	62	58	1.27	372
28	68	69	71	63	70	72	65	69	68	62	58	-	215
29	70	69	72	57	68	72	64					-	605
30	76	70	74	61	67	71	63	67	67	62	58	-	581
31	76	69	72	66	69	72	64	68	67	62	58	.06	233

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.

"T" indicates a trace, or amount too small for measurement.

Blank spaces indicate incomplete record for that day and station.

AUGUST 1951

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.)	Soil Depths in Inches						Stations A. B. & W.					
1	68	66	67	62	68	71	65	69	68	62	59	-	604
2	71	64	67	60	67	70	63	68	67	62	59	-	516
3	64	69	72	63	69	73	65	69	67	63	59	.05	595
4	59	60	65	54	65	70	60	67	66	62	59	-	625
5	62	62	66	54		70	59					-	446
6	63	63	68	56	65	70	59	66	65	62	59	.01	106
7	67	64	67	60	65	68	61	65	65	62	59	-	148
8	69	63	66	59	65	68	61	65	65	62	59	-	463
9	67	65	68	61	66	70	63	66	65	62	59	-	342
10	65	62	65	57	65	68	61	65	65	61	59	-	512
11	71	63	67	59	65	70	61	65	65	61	59	-	457
12	71	64	68	60		70	64					-	428
13	69	65	68	59	67	71	62	67	66	62	59	.12	395
14	67	63	66	57	66	69	61	66	65	62	59	-	417
15	65	64	66	61	66	69	63	66	65	62	59	.96	163
16	66	65	66	59	65	68	62	66	65	62	59	-	270
17	60	62	63	56	63	66	60	65	65	62	59	.16	237
18	66	62	64	58	64	66	58	64	64	62	59	-	338
19	67	62	64	58		66	60					-	422
20	67	63	65	57	65	67	61	65	64	61	59	.22	258
21	65	64	67	61	66	69	63	65	64	61	59	.26	522
22	61	60	62	56	64	65	62	64	64	61	59	-	503
23	57	56	58	53	62	63	57	63	64	61	59	-	547
24	59	55	57	51	62	62	55	63	64	61	59	-	553
25	63	60	60	53	62	64	57	64	64	61	59	-	517
26	67	62	63	58		65	59					.02	133
27	70	66	65	59	65	65	61	64	64	60	59	-	104
28	74	67	66	61	66	65	62	66	64	60	57	.05	361
29	76	68	67	63	68	67	63	68	65	60	57	-	439
30	76	69	62	62	69	68	65	69	67	60	58	-	311
31	75	75	62	66	69	69	67	69	67	60	57	.81	359

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.

"T" indicates a trace, or amount too small for measurement.

Blank spaces indicate incomplete record for that day and station.

SEPTEMBER 1951

Date	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
		Temperatures (°F.) — Soil Depths in Inches — Stations A, B, & W.											
1	58	63	65	60	67	68	64	69	68	61	58	-	71
2	59	61	63	56	65	66	60					-	190
3	60	59	61	54	63	64	57	64	65	62	59	-	449
4	58	56	58	54	63	63	57	64	65	62	59	-	494
5	63	59	59	60	63	62	61	64	65	63	60	.12	368
6	66	64	64	53	65	64	58	65	65	63	60	.29	366
7	55	55	60	51	62	63	53	64	64	62	59	-	441
8	54	54	55	50	59	59	54	61	63	62	60	-	410
9	60	58	58	50	61	61	54					-	477
10	63	61	61	52	62	63	57	62	63	62	60	.56	49
11	71	60	61	58	62	62	60	62	62	61	59	-	444
12	74	64	64	62	64	65	63	64	64	61	59	-	441
13	63	64	66	60	66	67	63	66	65	61	59	.19	180
14	64	58	59	55	61	63	59	65	64	61	59	.04	348
15	58	56	58	54	60	62	57	62	63	61	60	-	258
16	54	54	56	51	58	60	55					-	350
17	58	52	54	50	56	58	53	58	59	60	59	-	383
18	56	51	54	50	56	59	54	58	59	60	59	-	440
19	64	55	57	52	58	60	55	59	60	60	59	-	372
20	68	59	59	55	60	61	57	60	61	60	59	-	342
21	72	61	61	59	62	63	61	61	61	60	59	-	377
22	60	66	65	61	64	65	63	64	62	60	59	.31	124
23	56	62	62	51	62	63	55	63	62	60		-	409
24	60	57	59	54	60	61	56	61	61	60	59	.08	191
25	54	57	59	53	59	61	55	60	61	60	59	-	250
26	60	54	56	50	58	59	53	59	60	60	59	.66	81
27	56	55	58	54	59	61	57	59	59	60	59	-	282
28	45	47	51	48	53	55	52	55	58	59	59	-	230
29	44	43	46	41	50	53	47	53	57	59	59	-	413
30	53	49	51	47	53	55	48					.29	154

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

OCTOBER 1951

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
		Temperatures (°F.) — Soil Depths in Inches — Stations A, B, & W.											
1	64	56	56	50	55	57	51	55	56	58	59	.42	303
2	71	60	60	56	59	60	56	58	57	58	58	-	295
3	73	62	61	60	61	62	60	61	60	58	58	-	268
4	76	63	63	60	63	64	60	63	62	58	58	-	322
5	64	66	65	61	65	65	64	64	62	58	58	-	155
6	51	59	61	55	63	63	60	63	63	59	58	.14	39
7	42			50			54					1.34	22
8	41	47	49	46	52	53	46	53	57	59	58	-	156
9	45	46	47	44	50	51	47	51	54	59	58	-	253
10	43	43	46	44	49	50	46	51	53	58	58	-	324
11	47	44	46	46	48	50	47	50	52	57	58	-	314
12	52	46	47	45	49	51	47	51	52	56	58	-	298
13	54	47	47	48	50	51	47	51	53	56	58	-	302
14	55			51			52					-	280
15	61	52	52	52	52	53	52	53	53	56	57	-	318
16	64	52	53	52	53	54	52	53	53	55	56	-	278
17	60	54	55	53	55	56	54	55	55	55	57	-	254
18	62	53	54	52	55	55	54	55	55	55	56	-	261
19	43	49	52	51	55	55	53	56	56	56	56	.10	199
20	42	44	45	45	50	51	48	52	54	55	56	-	173
21	59			47			48					-	268
22	60	53	55	53	54	54	53	53	53	55	56	-	93
23	48	53	54	51	55	55	53	55	55	55	56	1.80	26
24	44	50	51	48	51	52	50	52	54	55	56	.40	29
25	49	44	45	46	48	49	47	49	51	54	56	-	272
26	53	47	48	48	49	50	48	50	51	55	56	-	150
27	42	46	49	48	51	52	49	51	52	54	55	-	127
28	37			40			46					-	43
29	39	38	39	40	44	45	43	45	48	53	55	-	255
30	51	44	44	44	45	46	45	46	47	53	55	-	243
31	40	41	44	44	46	48	46	48	48	52	54	-	170

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.
"T" indicates a trace, or amount too small for measurement.
Blank spaces indicate incomplete record for that day and station.

NOVEMBER 1951

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, & W.												
1	34	37	39	40	43	44	44	45	47	52	54	-	226
2	23	36	39	40	42	43	42	44	46	52	54	-	85
3	20	33	35	31	39	40	39	41	45	51	54	.01	154
4	23			32			43					-	191
5	19	32	34	30	37	38	36	38	41	50	53	-	241
6	21	32	33	31	36	37	37	37	40	49	52	.36	34
7	29	33	34	31	35	37	37	36	39	48	52	.57	11
8	27	33	33	31	35	36	36	37	38	47	52	-	108
9	31	34	34	31	35	37	36	36	38	47	51	-	189
10	37	34	35	29	36	37	36	37	49	47	51	-	220
11	34			29			36					-	209
12	43	35	35	33	36	37	36	37	38	45	50	.17	42
13	53	42	42	40	38	40	40	38	38	45	49	.71	4
14	49	43	45	38	43	45	39	43	41	45	49	-	129
15	39	38	39	36	41	42	38	42	42	45	49	-	180
16	32	36	38	34	39	41	38	40	41	45	48	.13	70
17	29	34	36	22	38	39	36	39	41	45	49	-	116
18	24			20			35					-	103
19	23	32	34	26	35	36	33	37	39	45	48	-	182
20	23	30	32	27	35	35	33	35	38	44	48	-	159
21	34	31	32	34	34	35	36	36	37	44	48	-	166
22	42		34	33			37					.36	6
23	30	33	34	30	34	35	35	35	37	43	47	-	43
24	22	32	33		34	35		35	36	42	47	-	190
25	24											.21	58
26	28	32	33		34	34		35	36	42	47	.01	61
27	20	31	33	17	34	35	36	35	37	42	47	-	195
28	32	31	33	28	33	34	36	34	36	41	45	-	50
29	39	32	33	28	33	34	33	34	36	41	45	-	125
30	44	32	33	30	33	34	34	34	35	41	45	-	152

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.

"T" indicates a trace, or amount too small for measurement.

Blank spaces indicate incomplete record for that day and station.

DECEMBER 1951

DATE	Mean Air	1"A	1"B	1"W	6"A	6"B	6"W	12"A	18"A	42"A	60"A	Total Precip. (In.)	Total Insol. (Lang.)
	TEMPERATURES (°F.) — Soil Depths in Inches, Stations A, B, & W.												
1	47	32	33	33	33	34	37	34	35	40	45	-	150
2	50			38			34					-	130
3	53	38	40	40	38	39	39	37	37	40	44	.20	138
4	46	43	45		42	43		40	38	40	44	.35	111
5	37	35	37	43	39	39	41	40	40	40	44	.02	81
6	49	38	38	34	39	39	38	39	39	41	45	-	86
7	52	42	44	38	43	43	37	42	40	41	45	.16	130
8	37	37	38	42	40	40	44	41	41	42	44	.03	24
9	33			38			40					.03	30
10	32	34	35	35	37	37	38	38	40	42	45	-	144
11	28	33	34	32	36	36	36	37	39	42	45	-	75
12	17	33	34	31	35	36	36	36	38	42	45	.02	60
13	14	32	33	31	35	35	35	36	38	42	45	-	133
14	15	31	33	27	34	35	38	35	37	41	45	.10	20
15	8	32	32	26	34	34	36	35	37	41	44	.03	137
16	4			26			35					t	154
17	6	31	32		33	34		34	36	40	44	.07	127
18	12	32	32	26	34	34	35	34	36	40	44	.12	93
19	5	32	33		34	34		35	36	40	44	-	121
20	23	32	32		34	34		34	36	40	44	.36	34
21	20	32	32		34	34		34	35	40	43	.30	16
22	7	32	33		34	34		35	36	40	43	-	144
23	16											.02	86
24	17	32	32		33	33		34	35	39	42	.03	121
25	20			26			32					.32	35
26	15	33	33	27	34	34	34	34	36	39	43	.02	165
27	15	32	32	28	33	34	34	34	35	39	43	-	154
28	21	30	31	28	31	32	34	32	33	37	40	-	62
29	31	33	33	27	34	34	34	35	30	40	43	-	55
30	31											-	68
31	39	32	31		33	32		33	34	38	41	-	35

Note: Mean air temperature is average daily maximum and minimum temperatures. All other temperatures are as of 8:00 AM. Station A is located in Cultivated Watershed B, Station B is in Cultivated Watershed A, and Station W is in the Wooded Watershed.

"T" indicates a trace, or amount too small for measurement.

Blank spaces indicate incomplete record for that day and station.

Calculation of Depth of Freezing and Thawing Under Pavements

HARRY CARLSON, Chief, Permafrost Division, St. Paul District, Corps of Engineers, and MILES S. KERSTEN, Associate Professor, Civil Engineering, University of Minnesota

Test installations of thermocouples measuring ground temperatures beneath runway pavements at three sites in Alaska are described. Data obtained from these installations over a period of several years are utilized to determine depths and rates of penetration of frost and thaw. A theoretical method of calculating frost and thaw penetration utilizing soils data, air temperature data, and predetermined thermal conductivity values and surface correction factors is explained. Results of calculations by this method are compared with the frost and thaw depths indicated by the thermocouple readings. In certain instances frost conditions obtained by borings and test pits are available for comparisons with the theoretical results. It is concluded that the theoretical method is a useful tool for making estimates of frost conditions in runway sections. The depth of frost and thaw penetration may be computed with a resulting error of 1 to 3 ft. in soils where actual penetration is from 6 to 15 ft., provided adequate soil and air temperature data are available.

● THE performance of roads and runways in any northern climate is affected greatly by frost action. In arctic and subarctic regions the effects of frost action may be particularly severe. The presence of permafrost in such regions may bring about special problems which must be considered.

In order to meet problems introduced into road or runway design and construction by frost action, a knowledge of the rate and depth of frost penetration and the rate and depth of thawing is highly desirable. As a part of a comprehensive investigation of the design and construction of airfields in arctic and subarctic regions being conducted by the St. Paul District, Corps of Engineers, Department of the Army, field measurements of temperatures in runway sections are being made. These observations have been accompanied by theoretical studies of frost penetration and thawing. Comparisons between the depth of frost or depth of thaw as determined by the temperature observations and those calculated by theoretical methods can be made. Although this work is still continuing, it is felt that the results obtained thus far are of sufficient value and interest to be reported. Results to date indicate that if one has adequate information on the soils materials, principally the water contents of the various strata, and also the climatological data, it is possible to make calculations for the location of the frost line with a reasonable degree of accuracy needed for stability considerations of the pavement section.

The investigations reported were conducted by the Permafrost Division, St. Paul District, Corps of Engineers, U. S. Army. Colonel A. H. Bagnulo is the district engineer. Acknowledgement is made of the assistance of D. E. Johnson of the Permafrost Division for assistance in calculations and preparation of data.

THEORETICAL CALCULATION METHODS

In attempting to select a method of calculation for frost depths, a review of both foreign and American literature was made (1). Study of the various methods indicated that an adaptation of the so-called Stefan equation was the most promising. This equation is essentially predicated on the hypothesis that the latent heat of fusion is the only heat that need be conducted to or from a point in the process of thawing or freezing. Heat quantities involved in change of temperature above or below the freezing point are considered of minor importance, and are ignored. The flow of heat during the freezing or thawing process is between the ground surface and the freeze or thaw line. Modifications of the "Stefan" equation used in these calculations include: (1) use of a correction factor to convert degree days of air temperature to degree days of surface temperature and (2) calculation of freezing or thawing by increments based on soil strata of varying physical characteristics.

Restricting our discussion for the moment to a freezing action, or penetration of frost, the equations utilized in this method are as follows:

For a uniform soil (nonstratified),

$$h = \sqrt{\frac{48kF}{L}}$$

h = depth of frost penetration in feet
k = thermal conductivity of frozen soil in Btu. per square foot per degrees Fahrenheit per foot per hour
F = surface freezing index in degree days Fahrenheit
L = latent heat of fusion in Btu. per cubic foot

For a layered system of soil, such as a pavement section which might consist of a bituminous concrete pavement, a gravel base course, and a subgrade (which might be layered in itself), the following method is utilized:

The partial-freezing index required to freeze the top layer may be calculated by a rearrangement of the above equation

$$F = \frac{L_1 h_1^2}{48\,k} = \frac{L_1 h_1}{24} \cdot \frac{h_1}{2k} = \frac{L_1 h_1}{24} \cdot \frac{R_1}{2}$$

in which R_1 is termed the thermal resistance of the soil layer and is equal to its thickness divided by the thermal conductivity.

In freezing the second layer of soil, of thickness h_2, the heat must travel through all of Layer 1, represented by the thermal resistance R_1, and through some part of Layer 2. For the freezing of all of Layer 2, an average resistance in that layer of $R_2/2$ is utilized. The partial-freezing index required for freezing of this layer is

$$F_2 = \frac{L_2 h_2}{24} (R_1 + \frac{R_2}{2})$$

Likewise, for the nth layer, the partial freezing index would be

$$F_n = \frac{L_n h_n}{24} (R_1 + R_2 + \ldots R_{n-1} + \frac{R_n}{2})$$

$$= \frac{L_n h_n}{24} (\Sigma R + \frac{R_n}{2})$$

in which ΣR is the summation of the thermal resistances of all layers above Layer n. Knowing the total degree-days of freeze for any season, or particular time period, the depth of freezing may be determined by selecting those layers whose sum of partial freezing indexes equals the total of the period.

To calculate thawing in soil, similar equations are used except I, the surface-thawing index, is utilized instead of F, and the k value should be the thermal conductivity of thawed rather than frozen soil, since in this instance the heat required to thaw the ice is travelling from the surface to the point of melting through thawed soil.

Each of the factors in these equations is discussed more fully in the following paragraphs.

F, the surface-freezing index, is determined by a summation of degree-days below 32 F. at the pavement surface. Since air temperatures are usually available and surface temperatures are not, a study has been made from data obtained at Corps of Engineers installations in Alaska to determine the relation between a freezing index calculated from air temperatures and from different types of pavement surfaces. A surface correction factor of 0.6 has been found for bituminous, portland-cement-concrete, and gravel surfaces, i.e.,

Surface F = 0.6 x F based on air temperatures.

For the thawing index, I, which is a summation of degree-days above 32 F., the correction factor is 1.4 for the same three types of surfaces, i.e.,

Surface I = 1.4 x I based on air temperatures.

These correction factors are based on more complete temperature data than those previously reported (1). It is emphasized that the correction factors may be different for other climates or localities and for other types of surfaces.

L, the latent heat of fusion in Btu. per cubic foot is calculated by the formula

$$L = 143.4 \frac{wd}{100} = 1.434 \text{ wd}$$

in which w = water content of soil in percent of the dry weight

d = dry density in pound per cubic foot.

Values for k, the coefficient of thermal conductivity have been obtained from charts derived from tests of thermal properties made at the University of Minnesota under a contract with the St. Paul District, Corps of Engineers (2, 3).

An example of a calculation of depth of thaw for an actual pavement section is given later.

FIELD TEMPERATURE MEASUREMENTS

General

In this report temperature - measurement installations at three different Alaskan sites will be considered. Two of these were in actual airfield runways and the third in a series of specially constructed runway test sections with a variety of base-course thicknesses.

Northway Airfield

Investigational work at Northway Airfield, about 230 mi. southeast of Fairbanks, was initiated in 1945 to collect basic physical data on soil characteristics, ground water, foundation designs, ground temperatures, and other factors affecting facilities at the site, with particular reference to permafrost. During 1945, ground-temperature-measuring equipment consisting of mercury-thermometer strings was installed in a series of holes along the edge of the runway. After about a year of observations, the thermometer strings were replaced with thermocouple installations in eight holes. Temperatures were read at approximately weekly intervals until early in 1949.

The soils beneath the runway are principally fine, medium, and coarse-grained sands with some layers of silt or sandy silt near the surface. Unfortunately the soil logs kept during the boring are not as complete, particularly concerning water contents, as would be desired for frost calculations. It has been necessary to make certain assumptions on soil conditions for purposes of this study.

Eielson Air Force Base

Five temperature observation holes were drilled in the runway at Eielson Air Force Base, 26 mi. southeast of Fairbanks, in April 1948. Ground temperatures were measured by thermocouples at weekly intervals from October 1948 through January 1951.

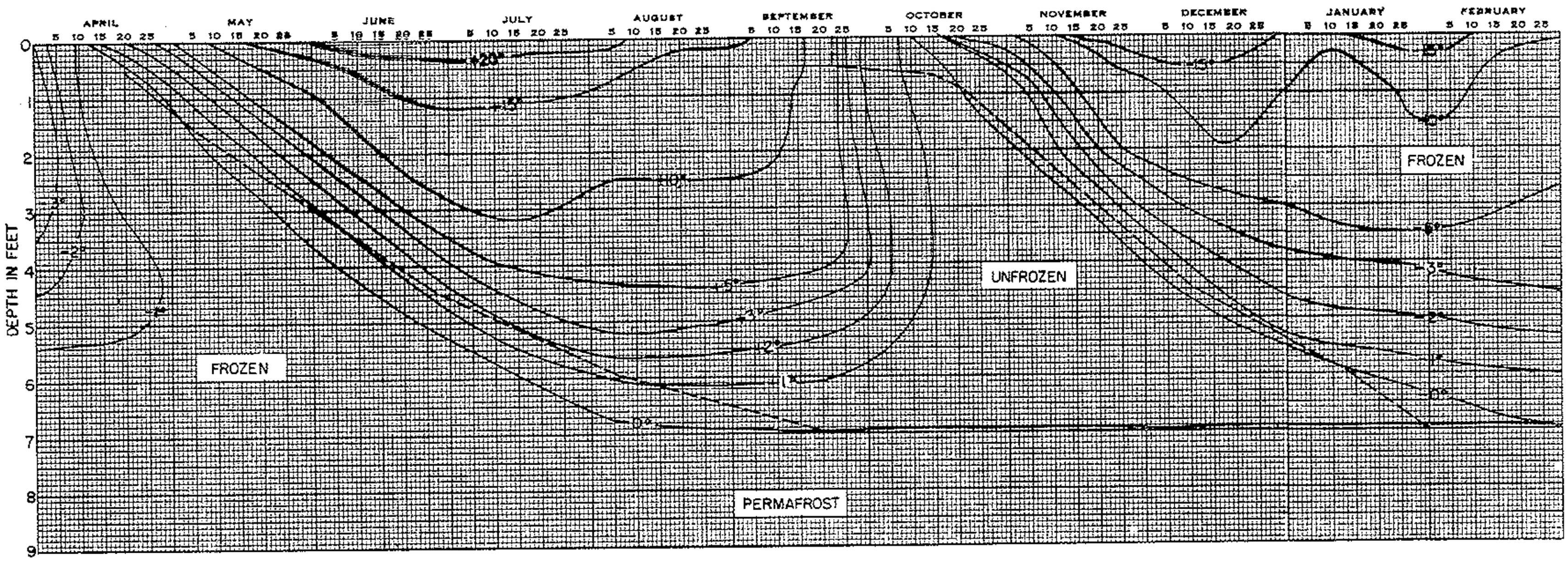
The soil beneath this runway is a gravel with an occasional layer of fine sand. No permafrost was encountered to a depth of 30 ft. The runway has a bituminous-concrete pavement and a crushed-rock-and-gravel base.

Fairbanks Research Area

The Fairbanks Research Area is located 2½ mi. northeast of Fairbanks and was constructed for observing various types of structures erected on permafrost under conditions known and recorded from the time of construction. Included in the extensive research installations at this site are a series of 26 runway test sections, each 50 ft. square consisting of various types and thicknesses of base and pavement. In some instances different types of insulation are included in the base course. The subgrade soil is silt. Thermocouple strings were installed in the center of each of these test sections and readings were taken at approximately weekly intervals from October 1947 to April 1951. In this report data from nine of the test sections are utilized.

Interpretation of Temperature Data

In utilizing plots of ground-temperature data to locate the position of the so-called frost line, or 0-deg.-centigrade isotherm, the results are dependent on the accuracy of the temperature measuring apparatus. The need for accurate measurements is great, because in many instances the thawed ground exists at a temperature



LEGEND

——— GROUND ISOTHERMS DETERMINED FROM THERMOCOUPLE READINGS.

– – – – FROST LINE (0° C. ISOTHERM) DETERMINED BY THEORETICAL CALCULATIONS.

NOTE

TEMPERATURES ARE DEGREES CENTIGRADE.

Figure 1. Ground isotherms and theoretical frost line - Northway Airfield, Alaska. Hole No.2

of only a fraction of a degree above freezing and the frozen ground is likewise only a fraction of a degree below the freezing point. The thermocouple installations in the three test locations presented above consisted of $1\frac{1}{4}$-in. steel pipe filled with SAE 10 motor oil. The thermocouple circuits led from the pipe to a selector switch and measurements were made with a potentiometer. Because of the conductivity of the steel pipe and oil, the thermocouples did not necessarily measure the exact temperature that would exist in the soil at the same depth. In many instances it is known that this resulted in a change from just below to just above the freezing point of the soil, or vice versa. However, by judicious interpretation of the temperature values and comparisons with known conditions, it is considered that location of the frost line can be obtained from the readings by noting the temperature gradients which exist rather than the exact result obtained from a single thermocouple. Determination of the frost line by this method is explained and illustrated in succeeding paragraphs. Wherever possible, the steel pipe is being removed from ground-temperature wells and the thermocouples are being placed in direct contact with the soil or in a pipe which is a poor heat conductor.

CORRELATION OF FIELD OBSERVATIONS AND THEORETICAL CALCULATIONS

To check on the degree of accuracy with which theoretical calculations can be used to predict frost or thaw depths in pavement sections, calculated curves for the three test locations are compared with the results obtained from the thermocouple readings. These comparisons are affected by the accuracy with which the temperature readings in the steel pipes portray the ground temperatures, as has already been discussed. They are also affected by the completeness of the soil information available for use in the theoretical calculations. In this respect, the logs of some of the holes at Northway Airfield are incomplete; those at Eielson Air Force Base are fairly good, although the locations of soil strata changes are not complete; and those at the Fairbanks Research Area are entirely adequate. The basic soil information desired is texture, water content, and dry density; good water content values are of first importance. The dry density can usually be estimated within reasonable limits for the calculations if it has not been measured.

Northway Airfield

To illustrate the interpretation of the temperature data at Northway Airfield, Figure 1 portrays the period of April 1946 to February 1947 for Hole 2. By means of observations of thermocouples of 0 to 6 in. and 1, 2, 4, 7, 11, 15, 20, 25, and 30 ft. at approximately weekly intervals, the 1-, 2-, 3-, 5-, 10-, 15-, and 20-degree isotherms are sketched in as shown. Numerous observations have indicated that the temperature gradient above the frost line during freezing or above the thaw line during thawing approximates a straight line, i. e., there is a uniform increase or decrease in temperature with an increase in depth to the frost or thaw line. Thus the -3, -2, -1 and zero or +3, +2, +1 and zero isotherms are at equal spacings. Utilizing this fact the zero isotherm, or freeze or thaw line, is sketched in below the +1 or -1 C. line. There are certain periods, namely at the start of the freeze or thaw, when the zero isotherm can be quite easily drawn between positive and negative readings. During the latter part of both the freezing and thawing seasons, however, the use of the above scheme is often needed.

The zero-isotherm lines determined by these methods for the period from 1945 to 1949 for all nine test holes are shown in the full lines in Figure 2. In certain instances the full line curves are not complete. This is usually where the temperature information is incomplete, or of such a nature that the zero isotherm cannot be reasonably estimated. Also plotted on Figure 2 are the theoretical curves of the freeze and thaw lines. The calculation of the latter are explained by the example in the following paragraphs.

The log of Hole 1, as drilled in March 1945, is given in Table 1. Nearly all of the soils were in a highly saturated condition. For purposes of calculation where densities were not given, densities which would be saturated by the given water contents in a frozen condition were assumed.

TABLE 1

LOG OF HOLE 1, NORTHWAY AIRFIELD, ALASKA

Depth ft.	Material	Water content %
0 - 0.5	Bituminous pavement	
0.5 - 3.0	Well-graded sand, black (SW)	21[a]
3.0 - 4.0	Gray silt (ML)	28
4.0 - 7.0	Gray silt (ML)	47
7.0 - 8.0	Gray silt (ML)	64 & 77
8.0 - 13.5	Gray silt (ML)	56
13.5 - 17.0	Gray silt (ML)	58

[a] Assumed value, based on data from other holes.

TABLE 2

VALUES FOR USE IN FROST CALCULATIONS HOLE 1, NORTHWAY AIRFIELD

Depth ft.	Material	Water Content %	Dry Density lb. per cu. ft.	Frozen k, per ft.	Thawed k, per ft.	L Btu. per cu. ft.
0.0-0.5	Bit.	0.0		0.83	0.83	0
0.5-3.0	SW	21.0	104	2.00	1.21	3130
3.0-4.0	ML	28.0	92	1.17	0.77	3690
4.0-7.0	ML	47.0	74	1.25	0.60	4990
7.0-8.0	ML	70.0	58	1.25	0.41	5810

Values of the thermal conductivity of the soil, both in a frozen and thawed condition were selected from the diagrams previously mentioned. The latent heat of fusion per cubic foot could be calculated utilizing the density and water contents. The pertinent values for the upper layers of the above section are given in Table 2.

The solution of the degree-days required to thaw the various layers by the equation

$$I = \frac{L_n b_n}{24} \left(\Sigma R + \frac{R_n}{2}\right)$$

can be best carried out in Table 3. The last column in this table is the conversion from the summation of the surface thawing indexes to the corresponding air index, utilizing the correction factor of 1.4. To find the particular dates of a given year on which the thaw penetrates to any given depth, a cumulative tabulation of the degree-days of thaw is made, starting with the advent of the thawing season. From such a tabulation the day on which the thawing index first reaches the totals in the last column of Table 3 can be determined. In the spring of 1946, for example, the thawing season started on April 20, reached 383 on May 25, 747 on June 8, and reached a maximum of 3,280 on September 22. Thus the thaw would not reach the 7-ft. depth, but some value between 4 and 7 ft. To calculate the maximum depth of thaw, the following procedure is used:

Let h = depth of thaw below the 4.0-ft. depth

Degree days available to thaw below 4.0-ft. depth, based on air temperatures = 3280-747 - 2533

Changing to surface thawing index = 2533 x 1.4 - 3546

$$\text{Then } I_n = \frac{Lh}{24}\left(\Sigma R + \frac{R}{2}\right) = \frac{Lh}{24}\left(\Sigma R + \frac{h}{2k}\right)$$

$$3546 = \frac{4990h}{24}\left(3.97 + \frac{h}{2 \times 0.60}\right)$$

Solving for h,

h = 2.8 ft.

Or the total depth of thaw on September 22 is 4.0 + 2.8 = 6.8 feet.

The dates and depths of thaw thus determined are used to construct a "theoretical" curve as shown by the dashed line of Figure 1. This curve may be compared with the zero isotherm to check the theoretical procedure against actual observetions.

Theoretical calculation of the freeze of this thawed depth of 6.8 ft. is given in Table 4. Other intermediate points can be computed to define more closely the theoretical curve. The freeze curve is also shown by a dashed line in Figure 1.

TABLE 3

THAW CALCULATIONS, HOLE 1, HORTHWAY AIRFIELD

Depth ft.	Thickness h, ft.	k, thawed per ft.	L Btu. per cu. ft.	Therm. Resist R = h/k	ΣR	ΣR+ R/2	I, deg.-days	ΣI	$\Sigma I_{air} = \Sigma I/1.4$
						0.30	0	0	0
0 - 0.5	0.5	0.83	0	0.60	0	1.64	536	536	383
0.5 - 3.0	2.5	1.21	3130	2.07	0.60	3.32	511	1047	747
3.0 - 4.0	1.0	0.77	3690	1.30	2.67	6.47	4030	5077	3630
4.0 - 7.0	3.0	0.60	4990	5.00	3.97	10.19	2465	7542	5390
7.0 - 8.0	1.0	0.41	5810	2.44	8.97				

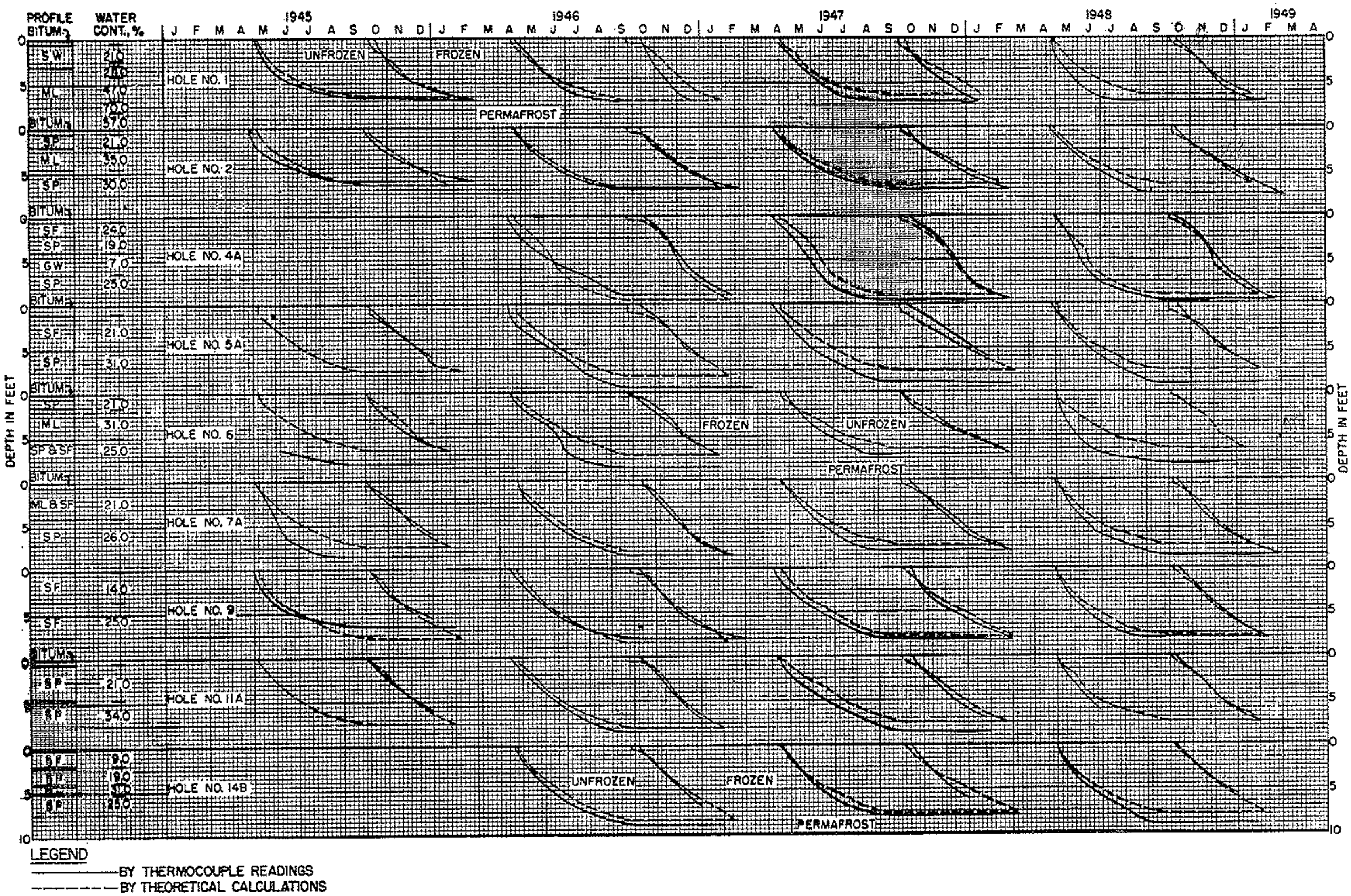


Figure 2. Freeze and thaw lines as determined by thermocouple readings and theoretical calculations, Northway Airfield, Alaska.

TABLE 4

FREEZE CALCULATIONS, HOLE 1, NORTHWAY AIRFIELD

Depth ft.	Thickness h, ft.	k, Frozen per ft.	L Btu. per cu. ft.	Therm. Resist. $R = h/k$	ΣR	$\Sigma R + \frac{R}{2}$	F Degree days	ΣF	$\Sigma F_{air} = \Sigma F/0.6$	Date
0 - 0.5	0.5	0.83	0	0.6	0	0.3	0	0	0	Sept. 23
0.5 - 3.0	2.5	2.00	3130	1.25	0.6	1.23	401	401	668	Nov. 16
3.0 - 4.0	1.0	1.17	3690	0.86	1.85	2.28	351	752	1253	Nov. 28
4.0 - 6.8	2.8	1.25	4990	2.24	2.71	3.83	2230	2982	4970	Feb. 1

Inspection of the calculated theoretical curves together with the curves determined from the thermocouple readings for all nine holes for the entire period of observations in Figure 2 indicates the degree of agreement of the two. The basic shape of the curves, or the rate of freeze and thaw, is substantially the same. The depth of the freeze or thaw at a particular time as calculated theoretically is, on the average, not more than 1 ft. different than the observed depth, and rarely differs by as much as 2 ft. from the observed value. In nearly all instances, the depth of the frost line determined by the thermocouple readings is greater than the calculated depths. This might be accounted for in some part by the error which is introduced into the thermocouple readings by the conductivity of the oil-filled pipe. For example, during the period of thaw, the top part of the pipe and the oil are at temperatures which may be several degrees above freezing. This column may tend to warm the pipe at greater depths in the vicinity of the frost line. Thus at the depth below which the soil is frozen, the temperature in the pipe may be a fraction of a degree above freezing and the change to below freezing in the pipe would be at a depth slightly greater than the frost line in the soil itself. The same possible error occurs during penetration of frost. The upper portion of the pipe located in the frozen depth of soil may be at temperatures several degrees below freezing. This cold column tends to draw some heat from the pipe and oil below and the changes from above-freezing to below-freezing temperatures in the pipe will be at a somewhat greater depth than the actual frost line in the soil.

The soil at depth in the test holes shown in Figure 2 is permafrost. Toward the end of the freezing season, i.e., in March or early April, the entire depth covered by the thermocouples is frozen. During the summer thaw occurs to depths of 6 to 9 ft. This depth is usually refrozen by sometime in January or February of the following freezing season. The depth of 6 to 9 ft. which thaws and freezes annually is called the annual frost zone. In this instance it also represents the suprapermafrost.

Eielson Air Force Base

The test installation at Eielson Air Force Base consisted of five holes spaced on a transverse section across the runway. The holes were 30 ft. deep and had thermocouples at 0 and 6 in., every 2 ft. from a 4- to 12-ft. depth, and every 3 ft. from 15 to 30 ft. The section at all holes consisted of a bituminous pavement about 6 in. thick, a crushed rock base to a depth of 1.8 ft., and a compacted gravel fill to a depth of from 5 to 8 ft. The subgrade was essentially a well-graded sand and gravel. The water table was at about 11 ft. at the time of the borings.

Thermocouple readings were taken at approximately weekly intervals between October 1948 and January 1951 in three of the test holes. In the other two, readings were discontinued in April 1950, due to damage to the installations. The zero isotherm can be distinguished as the dividing line between positive and negative centigrade temperatures during most of the test periods. The exact depth of frost penetration is not always distinctly defined within 3 ft., plus or minus, because of the 3-ft. thermocouple spacing used below 15 ft.

In the logs of the holes as bored water contents were reported at 5-ft. intervals. Closer tests would have been desirable. However, utilizing the information at hand and selecting what were deemed as reasonable density and base course water

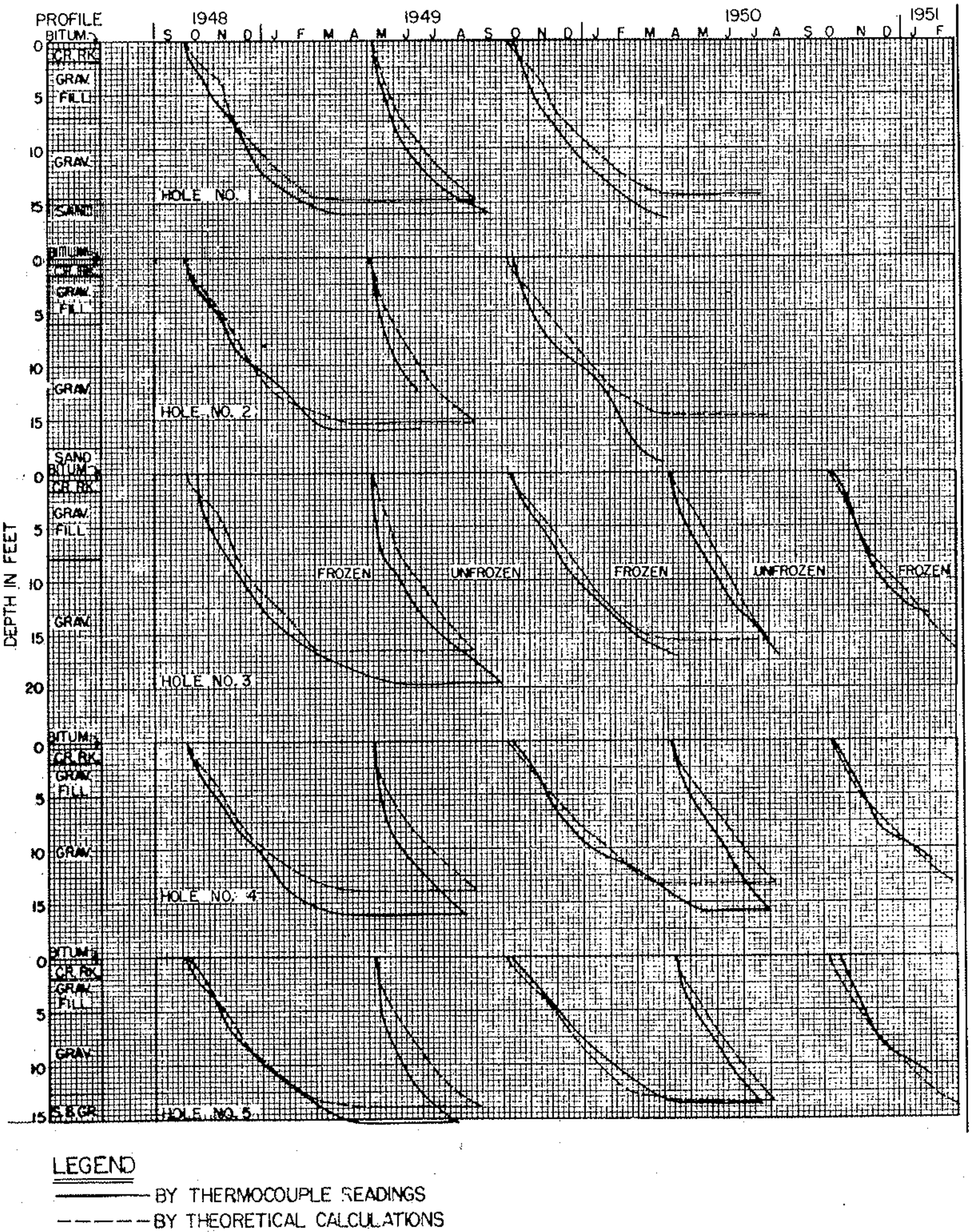


Figure 3. Freeze and thaw lines as determined by thermocouple readings and theoretical calculations, Eielson Air Force Base, Alaska.

content values, theoretical calculations of freeze and thaw were made. Air temperatures at Fairbanks were utilized and the surface correction factors previously mentioned (0.6 for freezing, 1.4 for thawing) were applied to the air indexes. Plots of the frost line as determined by thermocouple readings and by calculation are shown together in Figure 3.

Depths of freeze and subsequent thaw, as shown in Figure 3, were to a depth of 15 ft., plus or minus. This is much greater than the freeze in any of the holes at Northway Airfield. The reason for the difference is essentially in the differences in water contents. The sandy-gravel subgrade at Eielson had a water content of only about 8 to 10 percent in most strata. Frost penetration through such materials is rapid because of the relatively low volumetric heat of fusion.

The comparison of the theoretical and thermocouple-determined curves in Figure 3 is considered to be good. The differences for the most part do not exceed 2 or 3 ft. Again it may be noted that the frost depths determined by the thermocouple readings are in general deeper than the theoretical calculated values. This may be due in part to the conductivity of the oil-filled pipe, as explained previously for the Northway tests.

It will be noted that, although the general appearance of the frost-line loops, or continuous zero isotherms, in Figure 3 is similar to those of Figure 2, the areas inclosed by the zero isotherm are reversed. In Figure 3 the area within the loop represents a frozen condition, in Figure 2 a thawed soil. This is due to the fact that whereas permafrost existed at Northway Airfield, there is none in the test holes at Eielson. The depth of seasonal frost increases during the entire freezing season at Eielson, reaching a maximum in late April or early May. The thaw then starts and continues from the surface down until the entire layer is thawed, which usually occurs during August.

Present plans call for making some borings in the runway during the winter of 1952-53 to obtain a visual check on the frost penetrations indicated by the theoretical calculations and by the thermocouple readings.

Fairbanks Research Area

Two types of analysis of the pavement test sections of the Fairbanks Research Area are presented. In the first, comparisons are obtained between the frost line determined by thermocouple readings and by theoretical calculations, as was done with the Northway and Eielson sections. This has been done for seven different pavement sections, all with a bituminous-concrete pavement and a sand-and-gravel base course. The thicknesses of the base course vary from 2.8 to 12.0 ft. The second study presented is for four sections, two with bituminous-concrete pavements and two with portland-cement concrete, in which borings were made five times between October 1951 and July 1952 to locate the seasonal freeze and thaw lines and surface of the permafrost. These actual observations are compared with theoretical calculations.

The subgrade soils beneath the pavement test sections to a depth of 35 ft. are principally silts. The boring notes indicate frequent inclusions of peat. The water content in the upper 12 ft. of the soil is about 30 to 40 percent, except for some samples which contain considerable ice lenses or peat, in which instance higher water contents are obtained. For purposes of the theoretical calculations, a uniform moisture content of 35 percent, based on an averaging of numerous tests, has been used. A density representing a saturated condition for this water content has been assumed. Tests on the gravel base course material give an average water content of 3.0 percent and an average dry density of 140 lb. per cu. ft. These values have been used for all sections.

Utilizing the soil and base course information above and the degree-day data from Fairbanks, theoretical calculations of the freeze and thaw for the several years covered by the observations were made. These curves are shown as the dashed lines of Figure 4. The frost lines determined from the thermocouple readings are plotted as the full lines. The curves are similar to those of Eielson Air Force Base, Figure 3, in that permafrost is sufficiently deep so that it does not restrict the depth of annual freeze. The permafrost levels are not shown in Figure 4, but in most instances there is a residual thaw layer from about 2 to 4 ft. thick between the maximum depth of annual freeze and the surface of the permafrost. Thus frost penetration continues to increase during the entire freezing season, and this depth thaws during the first part of the thawing season. Inspection of Figure 4 indicates that the annual frost zone is usually thawed by sometime in July or August. During the remainder of the thawing season there would be a degradation of the permafrost. Calculations for such degradation can be made in the same manner as the computation of thaw of a layer of annual frost. The depth to the permafrost surface must be known; the water content of the permafrost is an important item in the calculations.

Inspection of Figure 4 indicates a good agreement between the theoretical annual depths of freeze and that determined by thermocouple readings. In 23 of the 28 comparisons shown (four-year record for each of seven sections), the difference is 1 ft. or less. The depths of annual frost vary from about 8 to 14 ft. The greatest divergence of the theoretical curves from those plotted from the thermocouple readings is in the rate of thaw of the subgrade soil. The theoretical curves in nearly all instances indicate that the thaw of the subgrade would not be completed until several weeks after the time indicated by the thermocouples. The depth of soil which thaws during this additional time in the theoretical calculation is about 1 ft., plus or minus. It may be that the thermocouples, because of their being in the oil-filled pipe, are incapable of showing the presence of a 1-ft. layer of frost. It is also possible that the simplified theory, based on flow of heat from the thawing layer to the atmosphere, is inadequate for the thaw of this last increment.

An additional check is available on the theoretical frost calculations. As a part of an accelerated traffic test of the runway test sections in 1951, test pits were dug in four of the sections in April or June. The depth of annual frost was measured in these pits. The points are shown in Figure 4, and Table 5 lists the theoretical annual frost depths, those determined by the thermocouple readings, and the depths measured in the pits.

TABLE 5

COMPARISON OF FROST DEPTHS
FAIRBANKS RESEARCH AREA, 1950-51

Section	Depth of Annual Frost		
	Theoretical ft.	Thermocouples ft.	Test Pit ft.
RN-12	7.9	9.0	8.5
RN-4	8.4	9.0	8.3
RN-25	8.4	9.8	9.5
RN-15	9.9	10.0	9.3

The maximum difference between the theoretical and test pit values is 1.1 ft. and the average difference is 0.6 ft. The depths interpreted from the thermocouple readings are all greater than those observed in the test pits; the average difference is 0.6 ft.

Since there was some question as to the accuracy to which the frost line could be determined by means of the thermocouple readings installed in the pipes, a program of periodic borings to determine the frost line was initiated in four of the runway test sections in the fall of 1951. In making borings with a hand auger, exact determinations of the level of seasonal frost or thaw and the position of the top of the permafrost could be made. Also, moisture contents of the base course and subgrade were obtained for use in theoretical calculations.

The theoretical calculated curves for the four sections included in this program for the 1951-52 period are shown in Figure 5, together with frost line positions determined by the borings. Different symbols are used for the depth of seasonal thaw, the depth of seasonal freeze, and the top of the permafrost. The latter is of no particular concern in the present discussion. The check between the theoretical calculation and the boring data may be studied by inspection of Figure 5. The plotted boring points in all four sections fall quite close to the theoretical curves, both for penetration of frost and for thaw. The greatest deviation is about 1 ft. This is considered to be a good check. There are some seemingly inconsistent changes in frost levels as indicated by the hand borings. It would be expected, for example, that the surface of the permafrost would be stable during the time period shown. In two of the sections variations of 1 ft. or more in this level are indicated in different borings. Such differ-

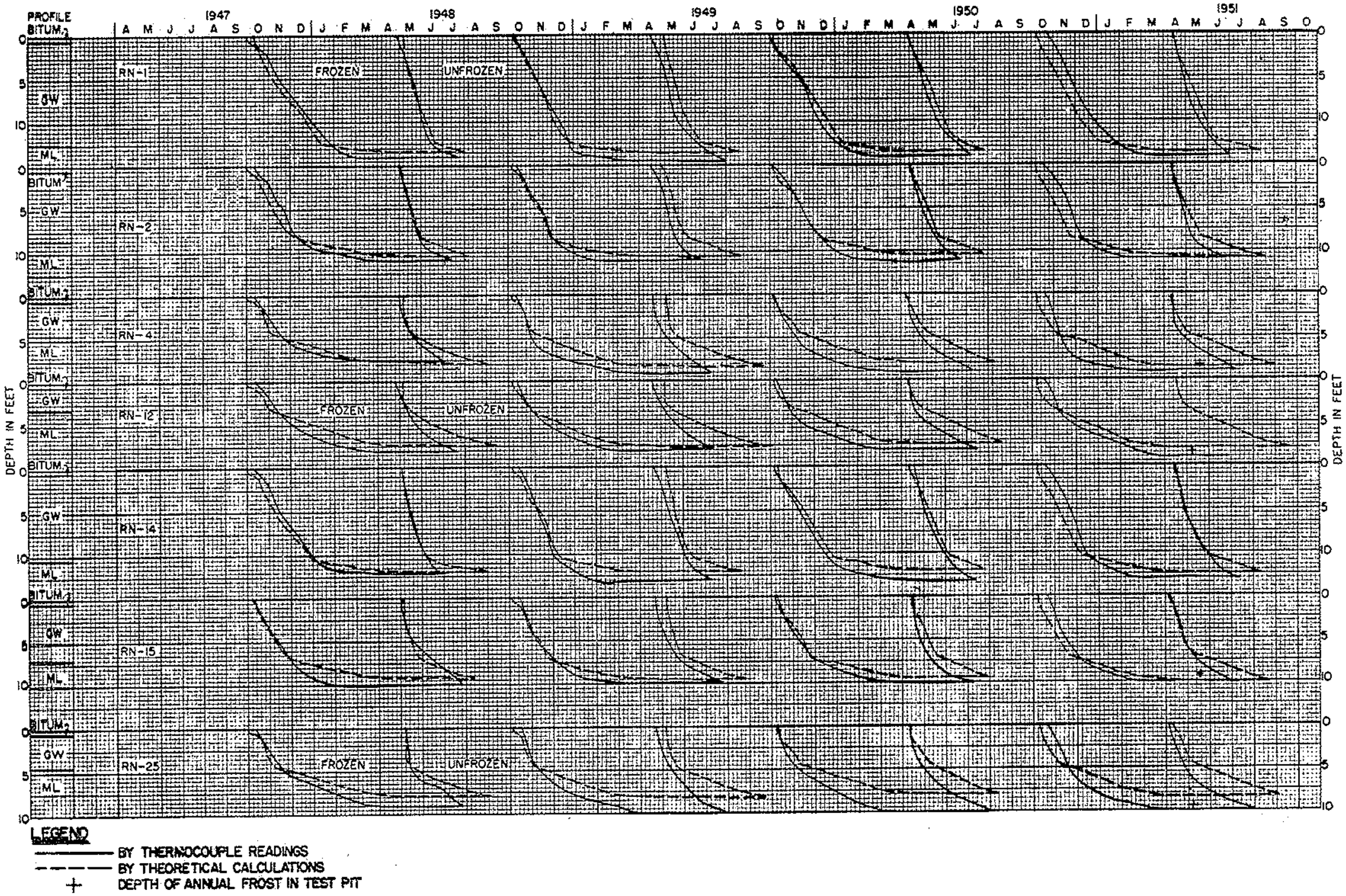


Figure 4. Freeze and thaw lines as determined by thermocouple readings and theoretical calculations, Fairbanks Research Area, Alaska.

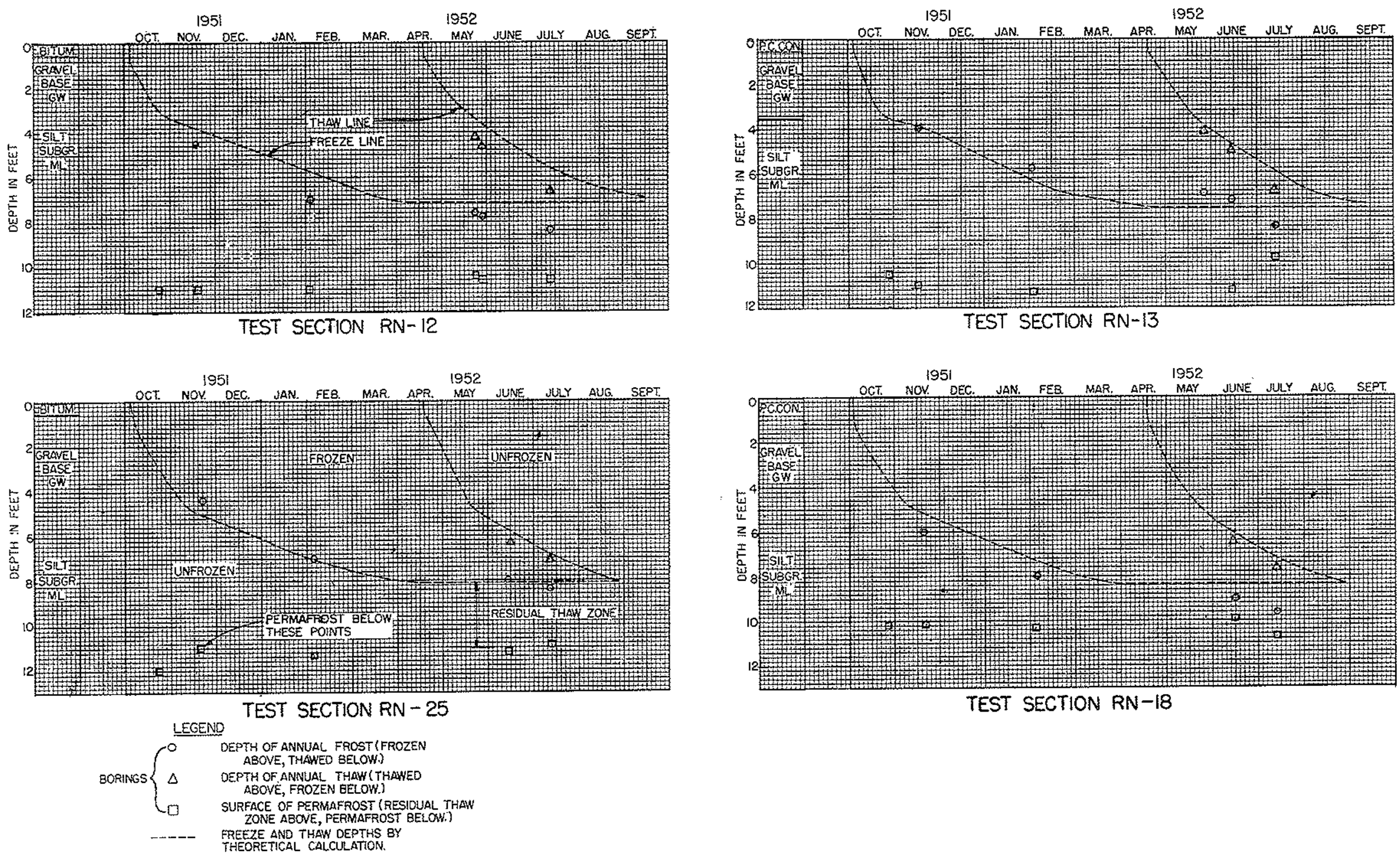


Figure 5. Frost conditions as determined by borings and theoritical calculations - Fairbanks Research Area, Alaska.

ences are due to the fact that the borings were made at various locations in each test section, and local variations in base course thickness, water contents, and other items caused differences.

EFFECT OF BASE THICKNESS ON FROST PENETRATION

The data presented in Figure 4 may be utilized to study the effect of base course thickness on frost penetration. All seven sections shown on this figure had a bituminous concrete pavement about 5 to 6 in. thick. The thickness of the gravel base courses varied from 2.8 ft. for Section RN-12 to 12 ft. for Section RN-1. Table 6 lists the sections with the average values of frost penetration as obtained from the thermocouple observations for the 4-year period. Although there are some discrepancies in order of the sections, it is readily apparent that an increase in the thickness of the base course results in an increase in the total depth of frost penetration, measured from the surface, but a decrease of frost penetration into the subgrade. Even with a base course 12 ft. thick there is about 1.6 ft. of the subgrade which is frozen annually.

TABLE 6

EFFECT OF THICKNESS OF PAVEMENT AND BASE COURSE ON FROST PENETRATION, FAIRBANKS RESEARCH AREA

Section	Pavement Plus Base Course Thickness	Average Frost Penetration	
		From Surface	Into Subgrade
	ft.	ft.	ft.
RN-12	3.3	8.3	5.0
RN-4	4.5	8.6	4.1
RN-25	4.5	9.3	4.8
RN-15	7.0	10.0	3.0
RN-2	8.5	11.0	2.5
RN-14	10.5	12.3	1.8
RN-1	12.5	14.1	1.6

SUMMARY AND CONCLUSIONS

Measurement of temperatures over a period of several years in runway-pavement sections indicate the depth and rate of frost penetration and thawing. There are some shortcomings in the thermocouple assemblies as installed, but judicious use of the readings yields a reasonably accurate picture of the thermal regime of the runway sections. Theoretical calculations by the modified Stefan method utilizing soils information from the specific runway locations, air temperature data from the site, and selected thermal conductivity values and surface correction factors have been made and are compared with the results of the thermocouple observations. Borings and test pits to determine depths of frost were available in some sections for comparison with the theoretical calculations. These comparisons lead to the following statements and conclusions:

1. At Northway Airfield, with essentially sandy soils but some silt layers, annual frost depths of 6 to 9 ft. were obtained with the thermocouples in nine test holes and for four winters' observations. The theoretical calculations checked these depths within 1 ft. in most instances. In the majority of cases, the theoretical depth was less than that determined by the thermocouples. The shape of the time-depth curves by observation and by theoretical calculation were very similar.

2. At Eielson Air Force Base, with essentially clean, gravelly soils, annual frost depths of about 13 to 16 ft. were obtained by both thermocouple measurements and theoretical calculations. Differences between the two methods averaged about 2 ft. Rates of freeze and thaw were similar as judged by the shape of the time-depth curves.

3. At the Fairbanks Research Area, thermocouple measurements and theoretical calculations of frost penetration and thawing both yield similar shapes of time-depth curves, and give depths of annual freeze which usually check within 1 ft. The depths of annual freeze in these sections vary from about 8 or 9 ft. for those with 4 ft., plus or minus, of base course and pavement over a silt subgrade, to about 14 ft. for a section with 12.5 ft. of pavement and base course over the silt subgrade.

4. Both field temperature measurements and theoretical calculations show that increasing the thickness of a high-density, gravel base course over a silt subgrade increases the total depth of frost penetration, as measured from the pavement surface, but lessens the depth of frost penetration into the subgrade.

5. Borings in four pavement test sections in the Fairbanks Research Area with

frost penetrations of as much as 9 ft. checked theoretical calculations for frost and thaw depths within 1 ft. in nearly all instances.

6. On the basis of the reasonable agreement between the frost lines as determined by thermocouple readings and by borings with depths determined by theoretical calculation with the modified Stefan method, it is concluded that this method of calculation will give results reasonably close to actuality. Where frost penetrations are in the range of from about 6 to 15 ft., the error to be expected is about 1 to 3 ft.

7. The agreement between observed and theoretical frost depths is also considered as a verification of the surface correction factors used to change air freezing-and-thawing indexes to surface indexes. It is also a verification of the charts used for thermal conductivity ·lues.

REFERENCES

1. Harry Carlson, "Calculation of Depth of Thaw in Frozen Ground," Frost Action in Soils, A Symposium. Highway Research Board Special Report 2 (1952).

2. Miles S. Kersten, "Laboratory Research for the Determination of the Thermal Properties of Soils - Final Report," Department of the Army, Corps of Engineers, St. Paul District, (September 1948).

3. Miles S. Kersten, "Thermal Properties of Soils," Frost Action in Soils, A Symposium. Highway Research Board Special Report 2 (1952).

Discussion

HARL P. ALDRICH, JR., and HENRY M. PAYNTER, Massachusetts Institute of Technology--The authors are to be commended for obtaining and reporting such excellent field data on the depth of freezing and thawing under pavements in Alaska. There can be no doubt that an important phase of soil mechanics and foundation engineering in the future will be the correlation of theoretical concepts with full-scale field measurements.

The authors have pointed out a significant practical consideration in their Conclusion 4. That is, increasing the thickness of a gravel base course can increase appreciably the total depth of frost penetration. In other words, if the depth of frost in a given locality is three feet, having 3 ft. of gravel below a pavement is no assurance that frost will not penetrate into the subgrade. The gravel base will ordinarily have a smaller water content than the subgrade. Hence, frost will penetrate faster and deeper into the base since the latent heat evolved as the soil freezes is smaller.

The agreement which the authors found between the calculated depth of freezing and thawing using the so-called Stefan formula and the actual depth as determined from thermocouple measurements and test pits, is remarkably good. The writers wish to point out, however, for the benefit of highway and soil engineers working in the United States, that the use of the Stefan equation in the more temperate regions of the United States will generally yield frost penetrations which are too deep. Although this is not mentioned in the paper, other publications by the authors indicate that they are well aware of this probability.

In general, the reason for the discrepancy is that the Stefan equation, while considering the latent heat of fusion of the soil moisture, neglects the effect of the volumetric heat of the frozen and unfrozen soils. This effect is relatively small when the mean annual temperature is near the freezing point as in Alaska. In the United States, however, the mean annual temperature varies from perhaps 40 to 60 F in localities where frost occurs in the winter months. In this instance the volumetric heat of the soil is an important factor. This can be demonstrated mathematically as follows.

Figure A shows the conditions which must hold for the general solution of a rational formula for the determination of the depth of frost penetration. Nearly all formulas are based on the assumption that the soil is a semi-infinite mass of uniform properties and having initially a uniform temperature. Let it be further assumed that the surface temperature is suddenly changed from its initial value v_o above freezing to a temperature v_s below freezing. This temperature value is then maintained constant and uniform over the entire surface to yield a one-dimensional problem.

X is equal to the heat evolved in bringing the unfrozen soil from an initial temperature v_o down to the freezing point plus the volumetric heat of the frozen soil plus the total latent heat of fusion given off as the soil moisture freezes to the depth X. The Stefan equation considers the latter only, while other equations bring in the

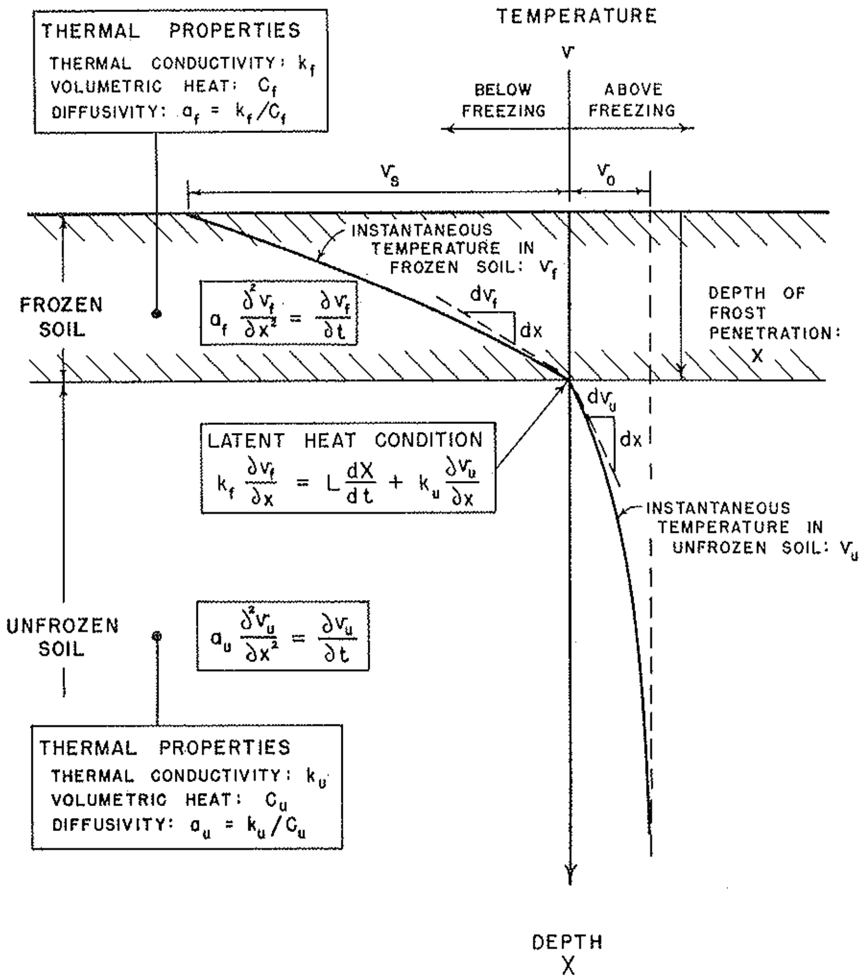


Figure A.

The equations which must hold for this problem are the diffusion equations in both the frozen and unfrozen soil as indicated in the figure. The latent heat property becomes a continuity condition which states that the rate of flow of heat in the frozen soil at the frost interface must be equal to the sum of the rate of heat flow in the unfrozen soil at the interface and the heat given off at the interface when the soil moisture freezes.

The total heat evolved up to the time the frost has reached a penetration depth

effects of the volumetric heat with varying assumptions.

Among others, the following four formulas for the depth of frost penetration X can be written:

$$X = \sqrt{\frac{48knF}{L}} \qquad \text{(Stefan)} \qquad (1)$$

$$X = \sqrt{\frac{48knF}{L + C\left(v_o + \frac{nF}{2t}\right)}} \qquad (2)$$

$$X = \sqrt{\frac{24knF}{L + C\left(v_o + \frac{nF}{2t}\right)}} \qquad (3)$$

$$X = \lambda_4 \sqrt{\frac{48knF}{L}} \qquad (4)$$

where

X = depth of frost penetration in feet

k = thermal conductivity in Btu. per foot per degree Fahrenheit per hour

F = air freezing index in degree days

n = coefficient used to correct air freezing index to pavement freezing index

L = latent heat of fusion in Btu. per cubic foot

C = volumetric heat in Btu. per cubic foot per degree Fahrenheit

v_o = degrees Fahrenheit by which the mean annual temperature exceeds the freezing point

t = duration of freezing period in days

λ_4 = correction coefficient for Equation 4

$\lambda_4 = f_4(\mu, \alpha)$ given by curves in Figure B

fusion parameter, $\mu = \frac{CnF}{Lt}$

thermal ratio, $\alpha = \frac{v_o t}{nF} = \frac{v_o}{nv_s}$

The first expression is simply the Stefan equation which considers the latent heat of fusion of the soil moisture only. Equations

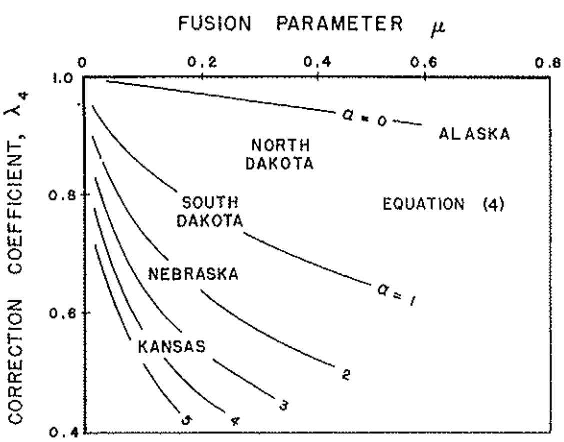


Figure B.

2 and 3 are formulas which have been studied by the Frost Effects Laboratory of the New England Division of the Corps of Engineers. These equations take into consideration the latent heat of fusion and the volumetric heat under various assumptions. Equation 4 was set up in the form shown by the writers. It is similar to a solution obtained by W. P. Berggren[1] in 1943. This formula, a solution of the equations in Figure A, takes into con-

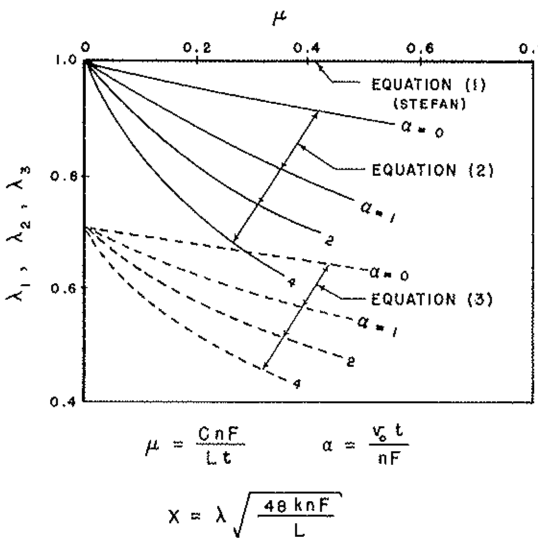


Figure C.

sideration nearly all of the factors of primary significance to the determination of the depth of frost penetration.

It can be shown that the first three equations can also be written in terms of a correction coefficient λ:

$$X = \lambda\sqrt{\frac{48knF}{L}}; \; \lambda = f(\mu, \alpha)$$

where λ is given by the following expression for Formulas 1, 2, and 3:

$$\lambda_1 = 1.0 \qquad (1a)$$

$$\lambda_2 = \frac{1}{\sqrt{1 + \mu(\alpha + 0.5)}} \qquad (2a)$$

$$\lambda_3 = \frac{0.707}{\sqrt{1 + \mu(\alpha + 0.5)}} \qquad (3a)$$

Curves for λ_1, λ_2, and λ_3 are given in Figure C.

The dimensionless parameters μ and α, which are not considered in the Stefan equation, are significant variables af-

[1] Berggren, W. P., "Prediction of Temperature Distribution in Frozen Soils," Transactions, American Geophysical Union, Part III, 1943.

fecting the depth of frost penetration. This can be seen from Figure B. The fusion parameter μ is a measure of the heat removed in the frozen soil below the freezing point as compared to the latent heat of the soil moisture. The thermal ratio α, is a measure of the ratio of the initial ground temperature, or mean annual temperature above the freezing point, to the time-average surface temperature below freezing during the freezing period.

The five localities shown in Figure B demonstrate the effect of varying climatic conditions on values of μ, α and λ. If the mean annual temperature is equal to zero as it is in many parts of Alaska, then α is equal to zero and a correction coefficient of perhaps 0.9 would apply. It can be seen then that the Stefan equation which assumes a correction coefficient of 1.0 for all values of μ would give depth of frost only 10 percent greater than the actual.

On the other hand, in temperate Kansas, for example, the correction coefficient is perhaps 0.55 which means that the actual depth of frost penetration would be about 55 percent of the value determined from the Stefan equation. It is also of interest to note from Figures B and C: in Alaska, Equation 2 gives good results while Equation 3 predicts far too shallow. In Kansas, however, Equation 3 is good while Equation 2 predicts far too deep. The writers' statistical studies of actual frost penetration data[2] have generally confirmed the above statements.

It would seem from the above discussion that the use of the Stefan equation in Alaska would yield depths of frost penetration about 10 percent greater than the actual. The authors found, however, that the equation gave depths about 10 percent too small when a surface correction factor $n = \overline{0.6}$ was used. The following question arises. How reliable are values of n? The authors apparently have data to show that n = 0.6 for bituminous and portland-cement concrete pavements in Alaska. However, if they had used a value of 0.8, their computed results with the Stefan equation would have checked the actual depths very closely on the average.[3] For example, at the Eielson Air Force Base, the actual penetration averaged 16.5 feet while the predicted averaged 14.5 ft. when n = 0.6 was used. In the Stefan equation

$$X \sim \sqrt{n}$$

If n = 0.8 was used in place of 0.6 then

$$\text{computed } X = \sqrt{\frac{0.8}{0.6}} \times 14.5 = 16.7 \text{ feet}$$

which checks the actual reasonably well.

In effect, using n = 0.8 in the Stefan equation is the same as combining n = 1.0 and $\lambda = \sqrt{0.8} = 0.89$ in Equation 4. From Figure B it can be seen that in Alaska $\lambda_4 \approx 0.9$! In other words, it would appear that if the authors had used the air freezing index with the modified Berggren formula (4), which considers all of the significant variables, their computed depths at the Eielson Air Force Base would have checked the actual depths very closely.

The writers are tempted to conclude that while the pavement surface correction factor, n, may not be equal to 1.0 in Alaska, it may be considerably closer to unity than is now believed. Furthermore, it is their general belief that n varies with latitude and may very well be smaller in the more temperate climates.

[2]Corps of Engineers, U. S. Army, New England Division, "Addendum No. 1, 1945-1947, to Report on Frost Investigation, 1944-1945," Frost Effects Laboratory, October, 1949.

[3]In any given locality one could, in fact, find a value of n for use in the Stefan equation which would yield average predicted values equal to the actual. In general, however, the writers would expect more scattering of the results than if a rational value of n was used with equation (4).

Frost-Action Research Needs

A. W. JOHNSON, Engineer of Soils and Foundations, Highway Research Board, and C. W. LOVELL, JR., Research Engineer, Purdue University

● SINCE the earliest of pavements, it has been known that ground freezing has produced rough-riding surfaces and often cracked pavements as a result of heaving. In some instances of intense heaving, subsequent thawing has produced such marked softening of the subgrade material that traffic has forced the soil to the surface in the form of mud, resulting in frost boils. Associated with the increase in the numbers and weights of vehicles, there occurred a more widespread and general structural failure of pavements during the spring thawing season, which became known as spring breakup. Only in recent years have many engineers become aware of a general reduction in the load-carrying capacity of roads during and following the thawing of roadbeds. The overall effect of ground freezing and thawing, as it is now understood, is referred to as the effect of frost action. Soils are spoken of as having a high or low frost susceptibility depending on the degree in which heaving, reduction in load-carrying capacity, and other physical properties are influenced by the freezing and thawing processes. Figure 1 indicates the possible effects of freezing and thawing processes on highway and airfield paving.

Many factors influence the intensity of frost action. Climate, location, degree of exposure, and the nature of the ground cover (including the pavement) influence the depth and rate of both freezing and thawing. The nature of the soil its chemical and physical composition and the state of the soil its moisture content and distribution, its porosity and structure govern its thermal properties and influence the nature of freezing and thawing. Further, the composition and state of the soil govern the physical properties of the soil and thus influence the degree in which frost action affects the load-carrying capacity of the soil. Any further improvement of our knowledge of frost action requires detailed investigation of the effect of a number of influencing factors and their relation to each other.

If the fundamentals of frost action were well understood, and means for applying that basic knowledge to design of pavements for given loads were better developed, it should be possible to construct pavements whose behavior with respect to frost action could be closely predicted. There would remain the economic phase of determining which pavements should be built to insure adequate strength for all seasons, and which pavements should be built to a given design with legal provision to restrict loadings during periods of low strength. The problem of frost action in roads and airfields is not one which presents a simple solution.

The majority of problems faced are of such magnitude as to preclude their complete solution within a short period of time. Extensive research efforts both large and small, are required of many engineering organizations. The total of this experimentation is capable of gradually reducing the complexity of frost-action problems.

The purpose of this paper is to present, in generalized statement, some of the research needs relative to the frost-action problem. Formulation of these needs was achieved through extended review and analysis effort. The writers have read several-hundred references, studied the current research programs of a number of important organizations, and discussed frost-action problems with many qualified individuals. Some portions of this review procedure dealt primarily with seasonally frozen ground, others with permafrost. These efforts, added to personal experience, have constituted the background for and shaped the perspective of this presentation.

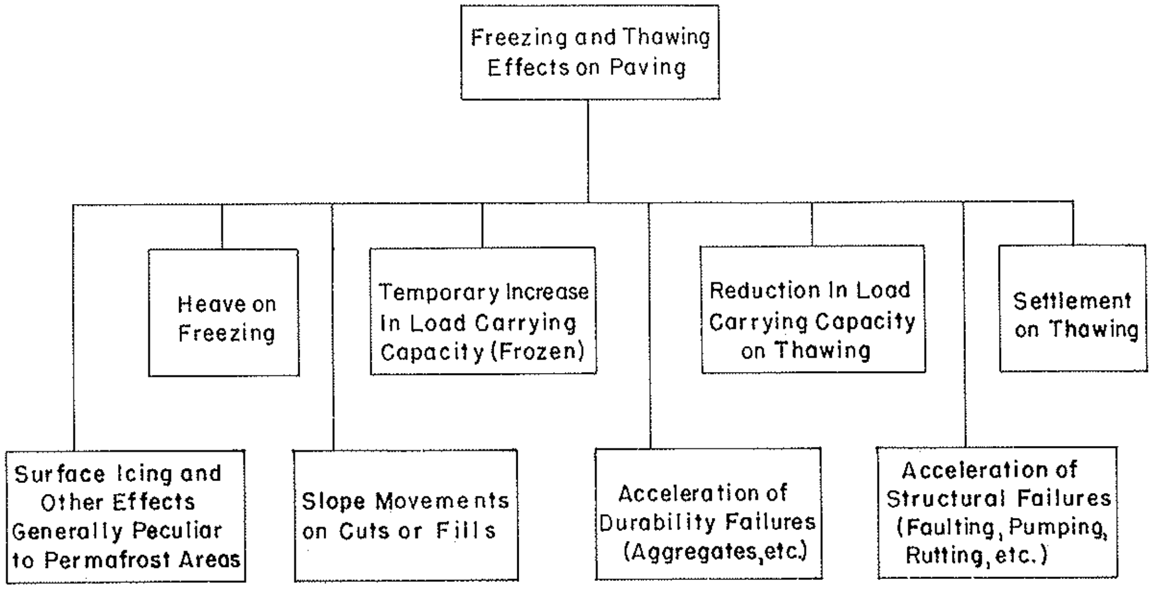


Figure 1.

FACTORS WHICH INFLUENCE FROST ACTION

Because the nature of frost action is complex and involves many variables, no systematic approach to increasing knowledge of the subject can be made without first separating the major variables and then determining the relative influence of them. The factors which influence frost action can be divided into extrinsic and intrinsic, that is, those which are outside but which act directly on the soil and those which belong to or are properties of the soil.

Extrinsic factors are those which determine the nature of the climate and those which modify the effect of climate insofar as climate may influence the depth and rate of frost penetration and the rate and depth of thawing. The intensity of frost action in a base course or subgrade soil is dependent in some degree on the weight of the overlying pavement. Some engineers believe that moving loads also influence frost action, although the writers have found no factual data to support such belief. The extrinsic factors which influence the nature of frost action are summarized in the block diagram of Figure 2.

Intrinsic factors are those inherent to the soil mass which have an influence on frost action. They include the composition of the soil, both chemical and physical, and the state of the soil mass with regard to soil moisture content, density, and structure. They determine not only the thermal properties but also the physical properties. More specifically they determine (1) latent heat of soil moisture, (2) volumetric heat capacity of water and soil, (3) thermal conductivity, (4) specific heat, and (5) thermal diffusivity. They also determine the load-carrying capacity, the ability of the soil to move water to the freezing zone, and thus influence the amount of heave or shrink. The major intrinsic factors are indicated in outline form in the block diagram in Figure 3.

AVAILABILITY AND USEFULNESS OF INFORMATION ON FROST ACTION

Most differences of opinion on engineering matters stem from differences in experiences and in knowledge gained from the experiences of others. First need for any engineering endeavor is for all engineers to have available to them, in usable form, a summary of knowledge gained to date. Some of the knowledge is not readily passed from the more to the less experienced. However, much of the knowledge gained is recorded in published literature. There are now two publications (1, 2) which present in summary form much of the available knowledge on soil freezing and related subject matter. However more work needs to be done with the information which is available and with new information as it becomes available.

Some of the needs briefly stated are:

1. Develop and standardize terminology relative to ground freezing and thawing processes and effects. The Corps of Engineers has recently (3) worked toward this end for their own particular purposes.

2. Make a critical study of presently available information, state fundamental principles where data are adequate to insure their validity, and give such limiting values as can be set from current experience. This has been done within the limits of different engineering organizations, but has not been adequately attempted by a group of highway and airfield engineers whose experiences cross all important limiting boundaries of organizational perspective and geography.

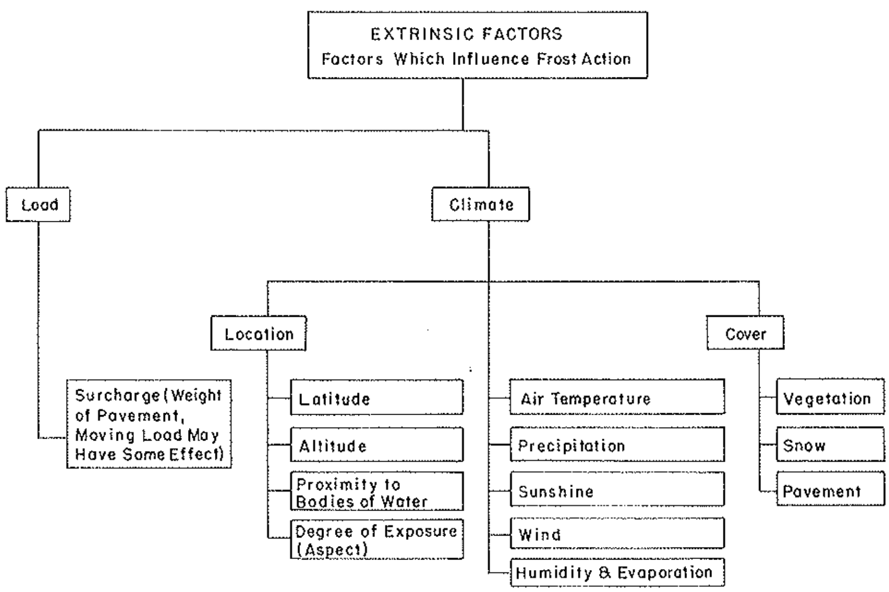


Figure 2.

3. Expand present means for collecting, systematizing, and disseminating information as it becomes available. The delay between time of experimental findings and application of these findings to practice is all too familiar. Certainly this difficulty can be reduced by organizations and committess dedicated to the functions of making new knowledge quickly available in usable form. The efforts of the Snow, Ice and Permafrost Research Establishment, Corps of Engineers (4, 5), the Highway Research Board Committee on Frost Heave and Frost Action in Soil (6, 2), and others are recognized. Much valuable reviewing, abstracting, translating, surveying of research facilities and personnel, and sponsoring of meetings and conferences has been accomplished; but many areas of activity remain undeveloped.

STATE OF THE SOIL MASS

The state of the soil mass, that is, its moisture content and uniformity of distribution, porosity and volume weight, temperature, and structure (including not only the arrangement of soil particles in the soil aggregate but also the profile of the ground as determined by mode of deposition and intensity of weathering) all strongly influence the nature of frost action. Of these factors, soil moisture is of dominating influence in determining the magnitude of freezing and thawing effects.

Effect of Moisture Content and Distribution

The moisture content of soil at the beginning of freezing largely determines the amount of segregated ice and the heaving of the soil on freezing. The increase in amount of soil moisture and change in its distribution through the soil plus the changes in soil density and soil structure which result from ice segregation determine the magnitude of the reduction in load-carrying capacity on thawing. Substantial heaving and very marked reduction in load-carrying capacity can result from freezing of water contained within the soil. That is true for most frost susceptible soils. Thus, an outside source of free ground water is not a requisite for frost action in soils. However, the availability of free ground water near the zone of freezing greatly intensifies all phases of frost action.

The increase in moisture content in the material during freezing is dependent among other things on the initial moisture content. The higher the initial degree of saturation the greater the heave and the greater the reduction in load-carrying capacity on thawing. When free ground water is not available, the moisture content of the soil beneath the frozen layer decreases to a relatively constant value, independent of the initial degree of saturation but dependent on the nature of the soil. Thus, soil water has a double effect. Freezing may increase the available water, so a second freeze may be more detrimental than the first if the water content was low during the first freeze.

The magnitude of the initial degree of saturation necessary to cause ice segregation and subsequent reduction in load-carrying capacity differs for different types of soil, conditions of water availability, and climatic influences. Meager data show no detrimental frost action if the initial moisture content is less than 65 percent of saturation (7, 8). Normal moisture contents of soils in service in subgrades and base courses may range from less than 50 percent for coarsely grained sandy and gravelly soils to almost 100 percent of saturation for the finer-grained silty and clayey soils (9, 59).

The problem here is one of determining: (1) the limits of moisture content at which detrimental frost action begins, (2) the in-service moisture contents of different common base and subgrade gradations, and (3) whether practicable means can be devised to control frost action in various materials by controlling the moisture content of these materials. The following studies are suggested:

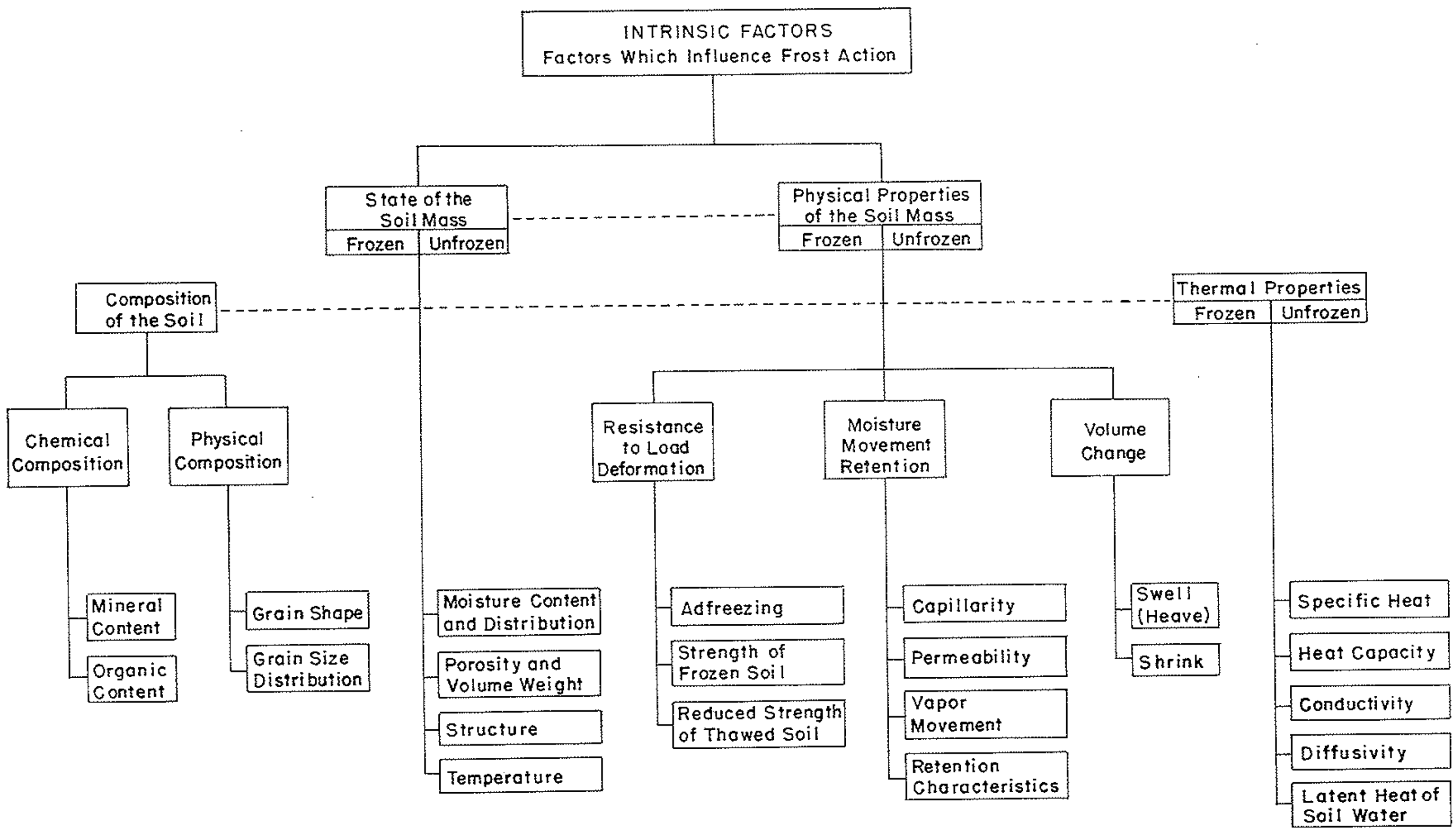
1. Expand determinations of the degree of susceptibility of more soils to detrimental frost action. Include soils of different textures and study the effect of different degrees of saturation at the beginning of freezing. This should provide data on the minimum degree of saturation at which ice segregation is possible in various types of soils, without the availability of an adjacent supply of ground water. Such studies should also indicate the relative intensity of ice segregation (and reduction in strength) which occurs in soils of various textural groups at different initial degrees of saturation.

2. Carry on field studies to check field behavior under maximum, minimum, and normal conditions indicated for the above laboratory investigation.

3. Corollary Studies: (a) Develop for practical field use, automatic devices to record changes of in-place moisture contents of subgrades and granular bases. There are at present no entirely adequate instruments for achieving this purpose (6, 10, 11). (b) determine seasonal and long time period ranges of moisture contents of subgrades and bases of different textures. The practical capacity to achieve this is largely dependent upon success in Corollary a. (c) Determine practical techniques of more effectively draining pavement-subgrade combinations or of stabilizing the subgrade materials so that their water-holding capacity and thus their susceptibility to frost action is reduced, or develop some admixture which will prevent the soil from attracting and retaining water in detrimental amounts.

Effect of Porosity and Volume Weight

The intensity of all phases of frost action depends on the amount of water available, and the rate at which it can be drawn to the freezing zone. Both the amount of water contained by the soil and the rate of water movement to the freezing zone are controlled by the nature (size and total volume) of the soil pores. Thus, frost action in a given soil depends on the degree of densification. Some laboratory tests have been made to evaluate the influence of initial soil porosity on the magnitude of heaving and water gain (12, 8). These tests were made with the soil in



INTRINSIC FACTORS
Factors Which Influence Frost Action
State of the Soil Mass
Frozen
Unfrozen
Physical Properties of the Soil Mass
Frozen
Unfrozen
Composition of the Soil
Thermal Properties
Frozen
Unfrozen
Chemical Composition
Physical Composition
Resistance to Load Deformation
Moisture Movement Retention
Volume Change
Mineral Content
Organic Content
Grain Shape
Grain Size Distribution
Moisture Content and Distribution
Porosity and Volume Weight
Structure
Temperature
Adfreezing
Strength of Frozen Soil
Reduced Strength of Thawed Soil
Capillarity
Permeability
Vapor Movement
Retention Characteristics
Swell (Heave)
Shrink
Specific Heat
Heat Capacity
Conductivity
Diffusivity
Latent Heat of Soil Water

Figure 3.

contact with a water supply. The results indicate that well-graded gravelly soils having sufficient fines to permit detrimental frost action show an intensification of ice segregation with increase in degree of compaction up to a critical density about equal to 95 percent of modified AASHO maximum density. Above that critical density, further densification reduces ice segregation. Intensity of ice segregation increases in inorganic silt soils right up to 100 percent of AASHO modified maximum density. Uniformly-graded frost susceptible sands are little affected by variation in degree of compaction (see Fig. 4).

As in the case of soil moisture, density may have a double effect. Although a soil may be compacted to a density in excess of the critical density (maximum ice segregation), a single freezing may cause sufficient ice segregation to reduce the density and increase the porosity so that subsequent frost action effects become more intense.

The external load (surcharge) carried by the soil also may influence the magnitude of heaving (13, 8); thus, the density of the soil above the freezing zone may have some small influence on heaving.

The problem is one of determining the critical porosity (or density) at which different soils show maximum intensity of frost action under different degrees of saturation. Possessing such information, compaction specifications for subgrades and granular bases can be written to require a degree of compaction consistent with the best performance. That best performance should result in the least permanent change from the as-built to the in-service condition and from season to season after adjustment to the new environment. The following studies are suggested:

1. Continuation of laboratory studies on a wide range of soil types to determine the influence of degree of densification on not only ice segregation and heaving but also on magnitude and rate of reduction in load-carrying capacity following the beginning of the thawing period.

2. Supplementary field studies to permit correlation of and make possible better interpretation of the data from laboratory tests.

3. Determination of influence of degree of densification on soils treated with various admixtures which have possibilities for the reduction of frost effects or the improvement of strength properties.

4. Corollary study: There is currently in development a method using radioactive materials in the determination of soil density (10). There is need for continuation of development of in-place test methods and apparatus to determine soil density and periodic and seasonal changes in this density.

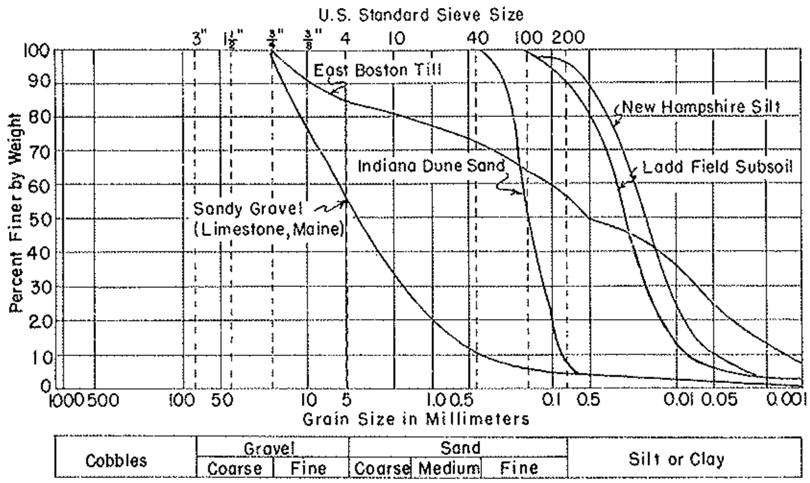
EFFECT OF STRUCTURE

Unfrozen State

Normally the term structure is used to denote the arrangement of soil particles into soil aggregates forming granular, prismatic, blocky, platy, or other types of aggregation. Structure is used here as a comprehensive term which also includes arrangement of soil into (1) large irregular masses of different textures; (2) strata of different texture; and (3) into soil horizons which are developed in the natural processes of soil formation.

Structural arrangement and rearrangement of soil into aggregates occurs only in the upper few feet which also constitutes the frost zone. Aggregation occurs only in clayey soils. Aggregation has many effects, one of which is the formation of fissures along the boundaries of the aggregates (13). These fissures give clayey soils the capacity to contain free ground water in much the same state as water in sands, except in lesser quantities. That ground water may aid appreciably in producing intense frost action.

The existance of textural differences in soil may create nonuniform soil-moisture conditions, that is, local zones of saturation or bodies of ground water (see Fig. 5). The occurrence of very thin layers of silt or clay in sand (Fig. 6) vary in lake deposited materials, textural differences from one soil horizon to another, pockets or "lenses" of sand, silt, or clay, any contact boundary of deposits which differ in texture, aggregation or porosity (and thus differ in ability to retain or transport water and to conduct heat) are examples of conditions where soil struc-



Material	Maximum Dry Density-pcf.
East Boston Till	131(2)
Indiana Dune Sand	107(1)
Ladd Field Subsoil	100(3)
Sandy Gravel (Limestone, Maine)	139(1)
New Hampshire Silt	107(2)

(1) Providence Vibrated Density
(2) Modified AASHO Method
(3) Standard Proctor Method

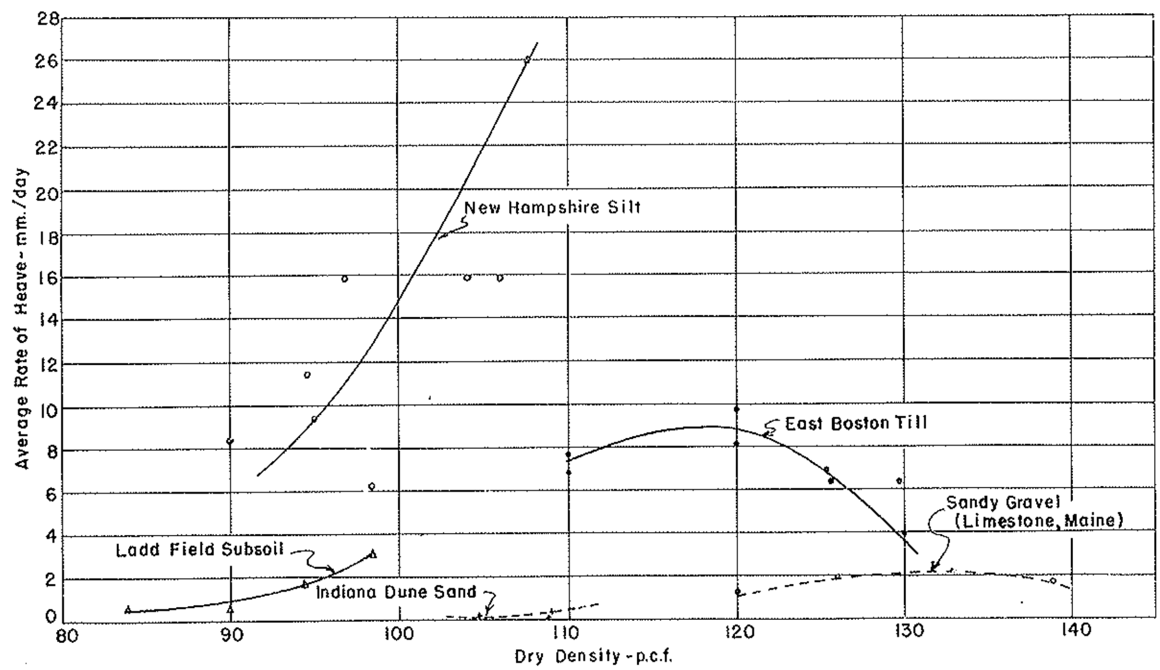


Figure 4.

ture may foster differential frost action (14, 15, 13, 16).

Some investigators have found it practical to correlate frost-action intensity with pedological soil series and type (17). Others (14, 18) have correlated geologic origin and degree of frost susceptibility. The occurrence of ledge rock, boulders, or stumps within or near the zone of freezing has been recognized to be productive of local and often intense frost action.

The effects of stratification, as in varved soils, on flow of moisture to or from a freezing zone have received only limited attention (13, 19).

Not only does soil structure influence frost action, but frost action may modify soil structure. Freezing and thawing may, due to pressures and fissuring produced by ice formation, foster development of soil aggregates and permanent fissures. Intense frost action of the type found in permafrost regions may produce a stirring or mixing of soil materials

(20). Fossil remains (such as involutions in soil horizons) indicative of intense frost action have been observed in areas on the perimeter of the most recent glaciation in the United States.

Frozen State

Frozen ground assumes a structure which reflects the intensity of the processes of freezing and thawing on the inherent nature of the soil and its associated water conditions. The influence of environmental factors of slope and cover are sometimes strongly reflected in such structure.

Seasonally frozen ground is usually classified according to the nature and distribution of the ice it contains. Massive or homogeneous structure denotes soil water frozen in the soil pores and normally occurs in coarse-grained soils, and in fine-grained soils of low moisture content, or those frozen at a rapid rate. Stratified or discontinuous-type structure contains visible ice segregation in lenses, wedges, veins, or needles and is usually associated with wet, fine-grained soils. However, appreciable ice segregation is observed in coarse-grained soils under conditions of great water availability and favorable rates of freezing, particularly cyclic freezing and thawing.

The Corps of Engineers (21) has developed a preliminary nongenetic classification and description system for frozen soils, which is intended to contain adequate detail for engineering purposes. This classification subdivides homogeneous structure into: (1) well-bonded frozen soils in which the ice firmly cements the material together and (2) poorly-bonded to friable materials. Under the stratified or heterogeneous-type structure this system notes several different types of ice concentrations: (1) stratified ice lenses or layers, (2) irregularly oriented lenses, veins, etc., (3) coatings of ice on individual particles, and (4) individual ice crystals within the soil mass. The occurrance of these various subtypes of frozen structure has been correlated in a general way with soil gradation and freezing conditions.

Perennially frozen ground (Permafrost) structures are normally classified on the basis of continuity of the frozen mass below the active layer. One type is continuous, meaning that the ground mass is frozen to full depth without unfrozen inclusions. The other is discontinuous, and contains alternate layers of frozen and unfrozen materials, or islands of frozen ground within an unfrozen matrix. Permafrost has been mapped on an areal scale as continuous, discontinuous, and sporadic (22, 23). The structure of the permafrost proper may be homogeneous or stratified, just as the structure of seasonally frozen ground. If the heterogeneous structure is such that large ice masses are present, description and classification must deal not only with the distribution and shape of the ice accumulations but also with the characteristics of the ice proper.

Frozen-ground structure may often be identified through surficial polygonal delineations, which are usually underlain by wedge-like ice masses. Theories differ as to the formation and growth of these and other types of "patterned" ground attributed to freezing and thawing influences. The various types of patterned ground and their possible origins have been summarized (24). Recent studies (25) have devoted attention to the airphoto identification and classification of various of these patterns as indicators of soil texture, moisture conditions, and the presence of permafrost. One very recent but unreported study by the U. S. Geological Survey examined the genesis and morphology of ice wedges in arctic Alaska.

The problems associated with structure as a factor in frost action are twofold. There is need for (1) better recognition of different soil structure conditions and their potentials for producing frost action and (2) determining the most effective methods for preventing detrimental frost action in the various types of soil structure. The following studies are suggested:

1. The efforts to formulate a practical engineering classification of soil structure in terms of its influence on the intensity of frost action should be continued and expanded. The classification should envelop both frozen and unfrozen ground so a correlation could be made of structure and water availability to permit better prediction of the relative amounts and distributions of ice. Further study of patterned

ground common to permafrost regions is justified, as such study will reveal additional details of the association of such patterns with soil texture, drainage conditions, and depth to permafrost. Surficial evidences of ground-ice formation and modification, such as polygonal ground, are particularly adaptable to further analysis and classification as indicators of ground condition.

2. Practical, in-place field studies to determine, for an extended time period, the relationship between various soil structure types and intensity of frost action are also needed. Such studies would yield useful data, pertinent not only to natural soil structure but also to artificial soil structures consisting of bases of various texture on subgrade soils of various textures.

3. Experimental studies to determine the feasibility and effectiveness of various methods (for example subgrade drainage) to reduce or eliminate frost action for various soil structure conditions are required.

4. Future emphasis should also be placed upon the effects of stratification on water movement, particularly capillary movement. Variations in moisture content with height above the water table and rate of capillary flow are especially needed for such soils as silts with organic streaks or laminations as are common to permafrost regions.

Effect of Temperature

If there is to be improvement in accuracy of prediction of ground freezing and thawing from climatic data, there must be available more adequate data on depth of ground freezing and thawing to use as bases for correlation with climate. Data on depth of the line of freezing and thawing taken at frequent time intervals over a long period of time for a variety of soil types and a wide range of soil states under various thicknesses of different types of pavement and surface vegetation and snow cover would be necessary to complete correlation. Some recent data (26, 7, 27, 28) have covered these variables over a brief time period.

It is obvious that because of difficulties of observing depth of freezing with present methods, data on depth of freezing and thawing are costly to obtain. Therefore, until better methods are available, correlation must be through the use of soil-temperature data.

Published data relative to soil temperature is voluminous. However, reviews (1, 2, 29) have shown a meager amount of soil temperature data useful in the study of frost action in bases and subgrades for highway and airfield pavements. Generalized charted data are available showing average annual and maximum annual depths of frost penetration. However data on type and state of soil, type of cover, and conditions of exposure all needed to make the data really useful, are lacking.

This brings out the obvious need for reliable methods for obtaining soil temperature data, and installations for collecting temperature data. Both recording-type thermometers and thermocouple installations can yield data of sufficient accuracy for the primary needs of knowing where and when soil freezing and thawing occur. Resistors are available which can distinguish frozen from unfrozen ground. The problem concerning data on ground freezing and thawing is therefore, one of determining depth of freezing and thawing and accurate appraisal of conditions of exposure, ground cover, and subsurface soil type and state which, together with climatic conditions, have been responsible for the conditions of freezing and thawing.

The following suggestions are offered as means of extending the field of useful knowledge in this regard: (1) Install temperature-measuring apparatus in locations of common or typical conditions. (2) Determine depths of freezing and thawing by means of excavation or by electrical resistance means. (3) Evaluate pavement type, soil type, and soil state for places of temperature or ground-freezing observations. (4) Corollary Studies: (a) Continue development of automatic temperature-recording devices for installations for frost studies and (b) develop automatic devices for determining time of soil freezing and soil thawing. Possibly present resistance type devices can be further developed so they can record automatically when freezing and thawing occur.

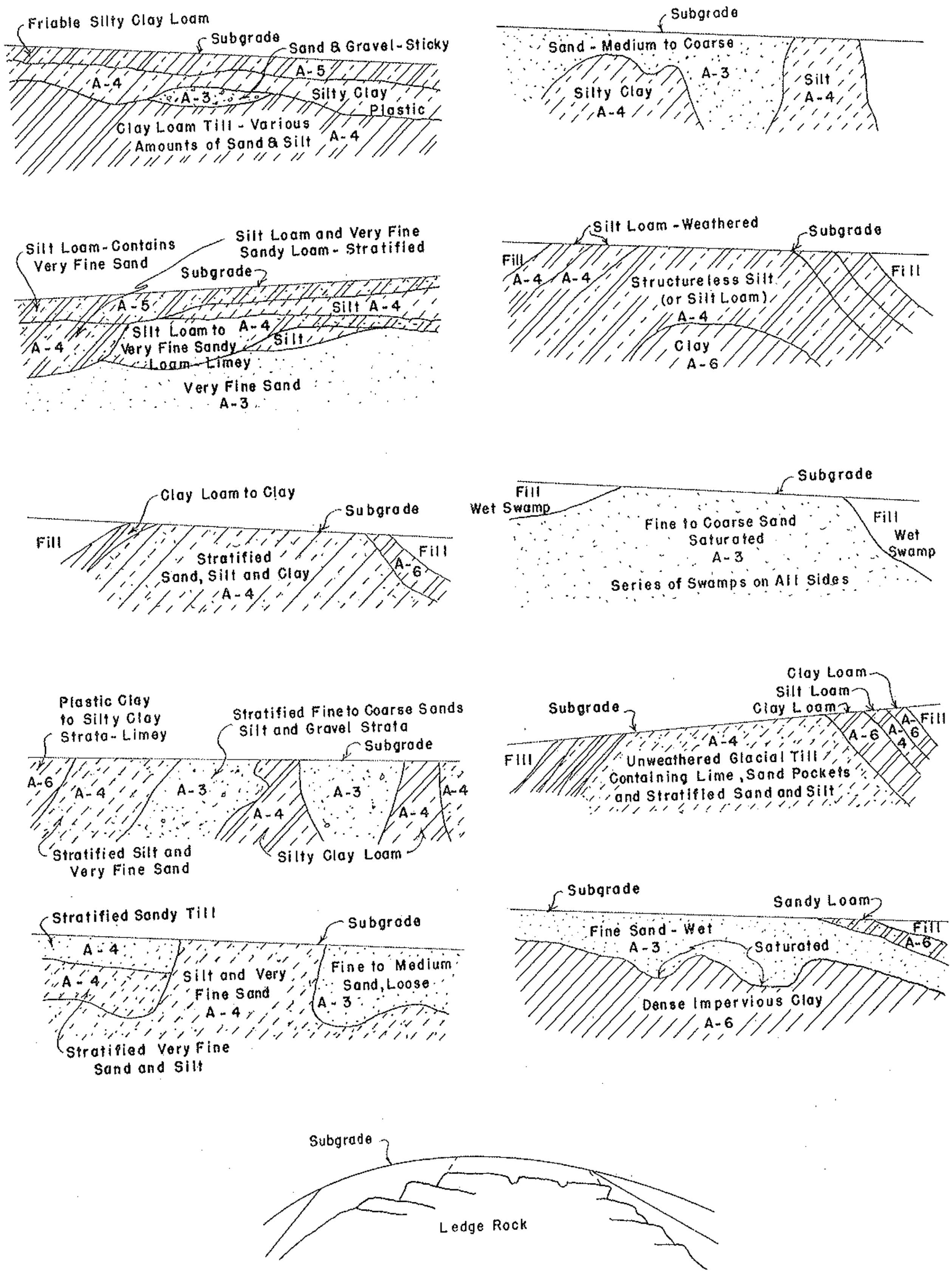
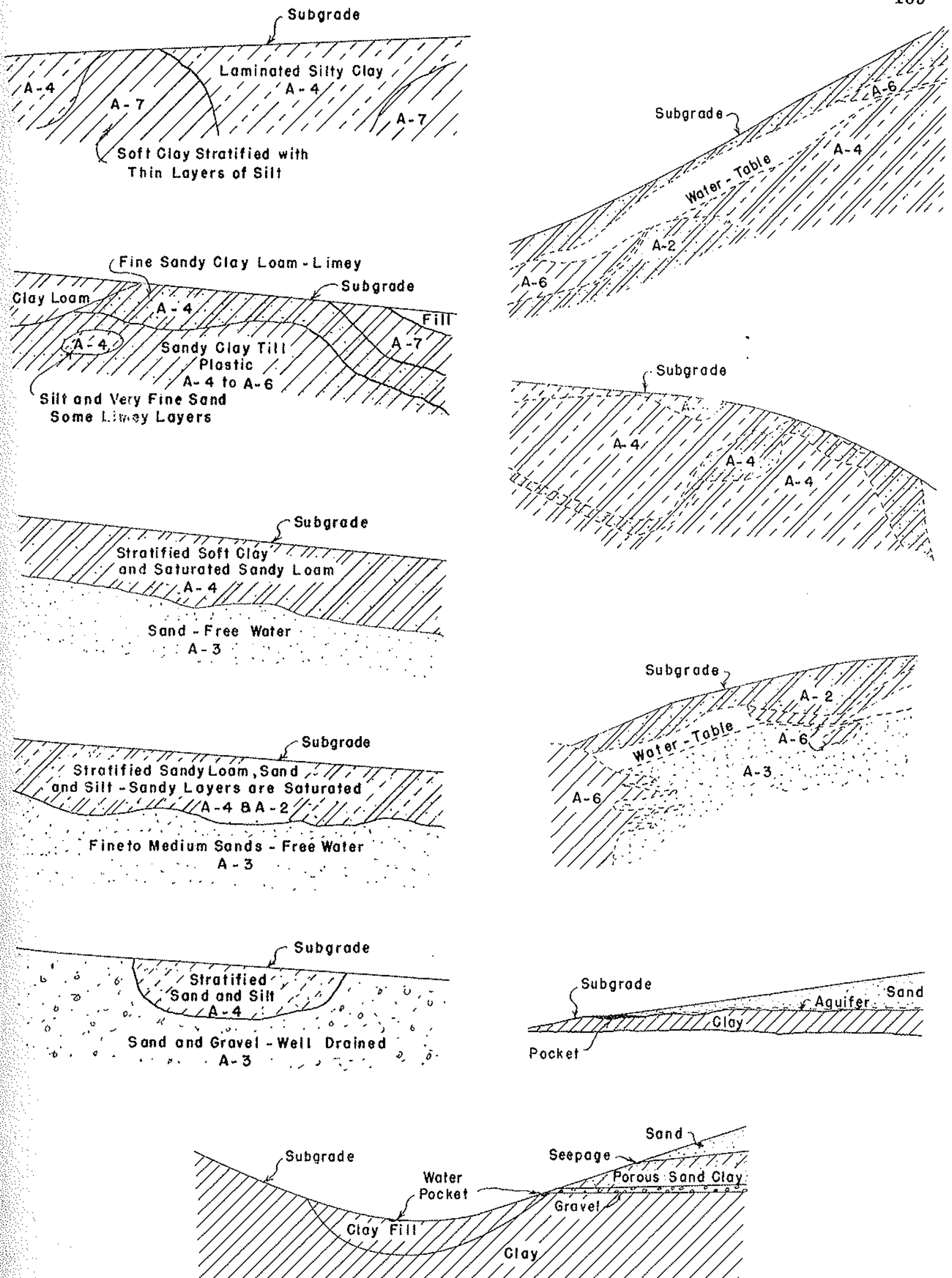


Figure 5. Soil Profiles in Which Detri-



mental Frost Heave has been Observed.

COMPOSITION OF THE SOIL

Water and temperature are the dynamic elements in frost action. The soil solids may either facilitate or restrain movements of water and freezing temperatures, both of which are necessary for frost action. The problem as it concerns the soil solids portion of the soil mass is to determine which qualities or characteristics of their makeup have the greatest influence in producing or in preventing frost action. In attempting to find those qualities, it is necessary to relate frost susceptibility to the inner or chemical composition, as well as to the outer or physical composition, for collectively they determine both the thermal and physical properties of soil.

Chemical Composition

Chemical composition is usually expressed in terms of content of different minerals which make up the soil fines and organic matter. Clay minerals differ greatly in the degree in which the particles adsorb water to their surfaces. The clay mineral montmorillonite, for example, has high surface area and great capacity to adsorb and hold water in a state not considered fluid or mobile enough to feed growing ice crystals. The mobility of the water is governed in a large measure by the nature of the adsorbed ion. Kaolinite, on the other hand, has relatively low adsorption capacity and thus can contain a more mobile supply of water. Thus, for soils made up entirely of fine particles, one being composed largely of kaolinite-type mineral would be more susceptible to segregation of water and detrimental freezing. However, although several investigators have agreed on this, they also agree that, regardless of the types of minerals present, if the soils are dominantly fine grained they are sufficiently susceptible to frost action to be considered dangerous.

The problem becomes one of determining the influence of mineral (and organic) content on frost action in sandy and gravelly soils which contain borderline proportions of fines. Investigations made to date have failed to show clearly the effect of mineral and organic contents, singly or in combination.

It appears that chemical composition may need to be analyzed not only in terms of mineral and organic makeup but also in terms of the nature of the ion carried. Also, the chemical composition needs to be interpreted in terms of the proportions of fines of different types and their joint influences on the mobility of soil water with respect to forces operating in the freezing and thawing processes.

The increasing use of differential thermal analysis, X-ray diffraction and colorimetric methods to identify type and proportions of clay minerals; various methods including the electron microscope, to determine relative grain shape and size distribution; and methods for determining the affinity of soil particles for water, indicate these tools have potential use as aids in determining why soils differ in degree of frost susceptibility.

Physical Composition

The most-common means for distinguishing frost susceptibility of soils is to relate intensity of heaving with size distribution in the fine-grain fraction. This has been done on a more or less general basis through some soil classification systems, (and for a specific soil in terms of the percentage passing the No. 200 sieve or the percent finer than 0.02 mm. in diameter).

Some use has been made of the pedological system as a means of defining soils of low frost susceptibility (17, 30). The results of testing and experience with sands of some natural soil series have shown them to be suitable for subbases and bases where low frost susceptible materials were desired.

Percent of Fines. The percent passing the No. 200 sieve has been used most widely by highway departments to relate to frost susceptibility. Maximum values specified for low-frost-susceptibility materials normally range from about 5 to 10 percent. This is in substantial agreement with military-airfield practice, which specifies maximum values of 3 and 10 percent finer than 0.02 mm. in diameter for well-graded and uniformly graded gravels, sands, and sand-gravels, respectively. The Corps of Engineers (31) has further classified frost-susceptible soils according to texture into four F groups of increasing susceptibility, the group F4 having greatest susceptibility.

Swedish practice is somewhat similar to that of airfield practice in that it permits a higher proportion of fines in the more-uniformly graded sediments than in well-graded morainic materials. Generally, the finer the grains (in the fine-grain fraction), or the greater the propórtion of colloidal sizes, the more effective the fine soil fraction is in producing ice segregation (8). The presence of plasticity is an indication of the possibility of greater ice segregation.

The standard specifications of several state highway departments and federal agencies recognize frost susceptibility, although indirectly, in the grading requirements for granular bases and subbases, as they reflect experience in areas where frost action has been a serious problem.

Size and Proportion of Coarse Materials. The focus of attention on proportions and types of the smaller frost-susceptible sizes has tended to obscure the influence of the coarser particles, both as to their influence on ice segregation and on stability following thawing. The latter is brought out under "Resistance to Load Deformation."

The proportion of stone or coarse aggregate bears a definite relation to the nature of frost action. Laboratory tests (8) have shown that for a given soil, increasing the coarse aggregate content decreases the rate of ice segregation in proportion to the corresponding reduction in fines. The same tests showed formation of ice lenses on the under side of the coarser aggregates, similar to those found in nature under stones.

The influence of the overall grading of the coarse fraction (retained on No. 200 sieve) on the decrease in strength following thawing has been largely neglected. That is true particularly with respect to their use in granular bases covered with thin bituminous surfacing.

Although durability and wear tests are in common use for aggregates for concrete and bituminous surfaces, it has been a common concept that any gravels which met grading and plasticity requirements are suitable for use in granular base courses. Some engineers are now questioning the suitability of aggregates which appear to degrade under construction traffic or to disintegrate under freezing and thawing under service conditions and thus foster more intense frost action than that which is expected from preconstruction tests.

To summarize, much has been done to refine and improve simple grain-size distribution criteria for use in definition of frost susceptibility. The present criteria are certainly much more accurately descriptive than in the past. However these criteria are still not able to evaluate the effect of the character of the finer fraction and thus lend themselves to further refinement and study.

The problem associated with the effect of composition on frost action is essentially one of means of identification of materials according to their susceptibility to frost action. Knowledge of the basic chemical composition may aid in identification. However, it is evident that evaluation of chemical composition must go hand in hand with evaluation of the effect of the grain-size distribution within the fine fraction.

The following field and laboratory studies are suggested:

Chemical Composition. 1. Determine the relative effect of organic matter, particularly in natural sands which are being used more frequently as bases and subbases under rigid and flexible types of pavement, respectively.

2. Continue study of chemical composition of the soil grains as a means of identifying frost-susceptible soils. This may involve differential thermal analysis, X-ray diffraction, colorimetric and electron-microscopy methods. The study should go beyond mere identification of type of mineral; it should include the effect of various ions. The influence of a mineral may differ markedly with the proportions present; hence, evaluation of the effect of chemical composition should be in terms of the grain-size distribution within the fine fraction and the proportions of fines in the total material. Along with fundamental research, a practical type of research studies on materials based on their parent rock may have value. For example: Of soil fines derived from quartz,

feldspar, limestone, schist, which are associated with the least frost action? Which clays are the most effective in small amounts sodium, hydrogen, calcium, potassium? Are there different critical grain sizes for different chemical compositions? To what extent are fines having plasticity a measure of their frost susceptibility in granular mixtures?

which are productive of frost action and (2) relate wear and soundness with degradation under construction and in service traffic with frost susceptibility.

THERMAL PROPERTIES

Soil freezing occurs when sufficient heat is withdrawn to reduce the temp-

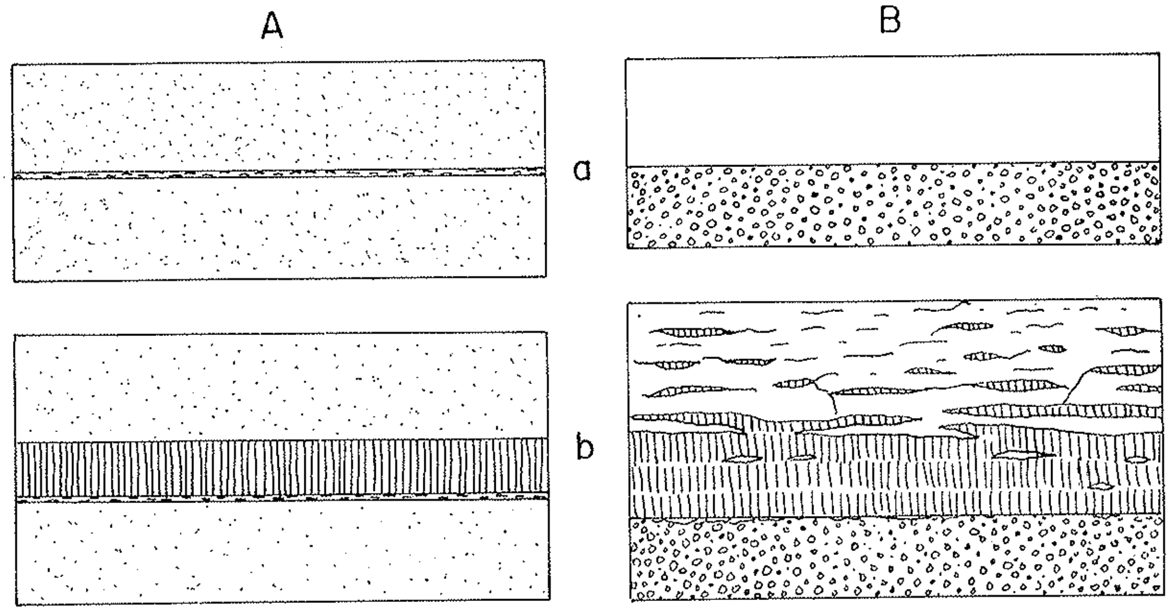


Figure 6.

Physical Composition. Continue studies to evaluate the influence of grain size distribution, primarily on materials which may be suitable for subbases and bases.

1. Are the maximum permissible proportions of frost susceptible fines identical for well-graded materials having different maximum size? For example, maximum proportions of fines for a given degree of frost susceptibility for a fine aggregate sand-gravel (all passing No. 4 sieve) compared to maximum proportions for similar frost susceptibility in a 3-in. maximum size material.

2. Relative frost susceptibility of different gradings from contained water at various degrees of saturation (without a source of free ground water).

3. Relate grain-size distribution in both coarse and fine fractions more closely to load-carrying capacity in before-frozen and after-thawed conditions.

Corollary Studies. (1) Develop quick field aids to identification of soil fines

erature of the mass to a point where at least a part of the soil water solidifies. Finely grained soil first solidifies at some temperature below 32 F. The soil continues to gain strength as its temperature is further reduced and more soil water freezes (32, 31). The rate at which the freezing temperature moves into the soil (diffusivity) is dependent on: (1) the specific heat of the soil water and of the soil solids; (2) the amount of heat which must be removed from a given volume to reduce the temperature to freezing (volumetric heat capacity; temperature difference); (3) the latent heat of the soil water (which depends upon the percentage of the soil water frozen at a given temperature); and (4) the rate at which the heat can be conducted through the soil (conductivity).

Knowledge of these thermal properties of soils and pavements plus climatic conditions makes possible calculation of depth and rate of freezing in unfrozen soils and depth and rate of thawing in frozen soils. Much work has been done in recent years (33, 34, 35, 36) in the study of thermal properties of soils and factors which influence those properties. These studies have evaluated more adequately than in the past the relationships between thermal properties and variations in temperature (above and below freezing), moisture content, porosity, texture, composition, and natural structure.

Difficulties have long been encountered in laboratory determinations of soil thermal properties. Principal among these difficulties is the migration of moisture under maintenance of an applied thermal gradient. The increase in temperature at the hot face produces an increase in vapor pressure of the soil water, a decrease in surface tension and viscosity, and a flow or a vapor movement of moisture to location of cooler temperature, lower vapor pressure, and higher surface tension (37, 38). The establishment of this undesirable moisture gradient may be minimized, but not eliminated, through use of small, short-time-applied thermal gradients, the effects of which are measured over an increment of thickness located as far as is feasible from the hot and cold faces.

A number of field or in-place techniques of determining soil thermal properties are being developed (39, 40, 29). These techniques employ a heater, usually electric, at whose surface temperature change is measured under controlled energy output. If experimental time is short, moisture migration is slight. The theoretical heat-flow equations for a source of no dimension within a homogeneous, infinite medium are at variance with actual conditions; but these equations may be applied and errors kept very small by proper attention to such variables as time interval and effective radius of measurement. The thermal probe and the cylindrical heater have been studied as line heat sources and small spherical shapes as approximations of a point source.

The problem associated with thermal properties is to develop reliable thermal data on various types of soil existing under a wide range of conditions of moisture content and density in both frozen and unfrozen state and also to develop thermal data on various types of cover, including pavements and bases. The data need to be sufficiently inclusive that practical calculations can be made for almost any condition encountered.

The following suggestions are made for future studies:

1. The correct value for latent heat of water depends on the proportion of the soil moisture frozen at different temperatures below 32 F. Knowledge of the freezing point, or rather the range of freezing temperature of soil moisture, is inadequate. Studies of a highly practical nature need to be undertaken with typically fine-grained materials of common occurrence to ascertain the proportions of moisture frozen within these materials at various sub-32-F. temperatures. Not only should moisture, density, and rate of temperature change be incorporated as variables in these studies, but also the character of the clay minerals present and of the adsorbed ions should likewise be incorporated. These determinations of percentage of water frozen could be translated into further engineering meaning by conducting strength tests on the soil specimens at various sub-32 F. temperatures (the percent moisture frozen at these temperatures being known).

2. Values of the thermal properties at conditions of low density and for high degree of saturation are relatively unknown. This is of course largely due to inadequacies of laboratory thermal instrumentation. Since many of our more serious thermal problems deal with wet, low-density materials (particularly in the permafrost regions), efforts should be made to improve instrumentation and to study these ranges.

3. The increase in thermal conductivity expected from the presence of ice strata in soil may be further increased where consolidation of soil occurs between ice strata or counteracted where freezing is associated with a general loosening of the soil. The effect of various ice-stratified frozen structures on thermal values can well receive more study.

4. Laboratory determination of thermal properties is further complicated by moisture migration, which is activated by

application of a thermal gradient. Techniques of minimizing or compensating for moisture migration can well receive additional attention.

5. Continued development of the thermal probe and other in-situ thermal instruments to permit field measurement of thermal values representative of in-place moisture content and density values in existing soil profiles is justified.

6. Corollary Studies: Study further the forces operating in depressing the freezing point of soils. This study could well be integrated with a fundamental study to determine the nature of depressants which can be mixed with and retained by soils to improve their resistance to frost action.

PHYSICAL PROPERTIES OF THE SOIL MASS

The soil properties which more nearly express the dynamic nature of the soil also have a critical bearing on the nature of frost action. Frost action, in turn, alters the measure of those properties. The properties which permit the soil to transport moisture against gravitational forces by capillary "suction," or vapor movement and distillation, or to move soil water laterally or vertically under hydrostatic head or gravitational pressure are of greatest single influence in determining the magnitude of frost-action effects.

The intensity of frost-action effect may be measured in terms of magnitude of volume change on freezing, swell (the surficial manifestation of which is heave), or shrinkage. The ability of a frozen or of a thawed soil to resist deformation under load is another measure of frost effect, whether this ability be expressed as capacity to support loads, to resist frost-activated slope movements, or to grip, through adfreezing, foundation or pavement members (see Fig. 7).

Moisture Movement

During Freezing. The susceptibility of a soil to ice segregation and heaving is governed by its capacity to retain moisture and to move moisture to a freezing zone.

Disagreement exists as to the nature of forces operative in moving moisture to the freezing zone. It is generally believed that the forces effective in the immediate zone of freezing bringing water into the growing ice crystal are those of molecular cohesion in the film water (16, 41). This results in a drying

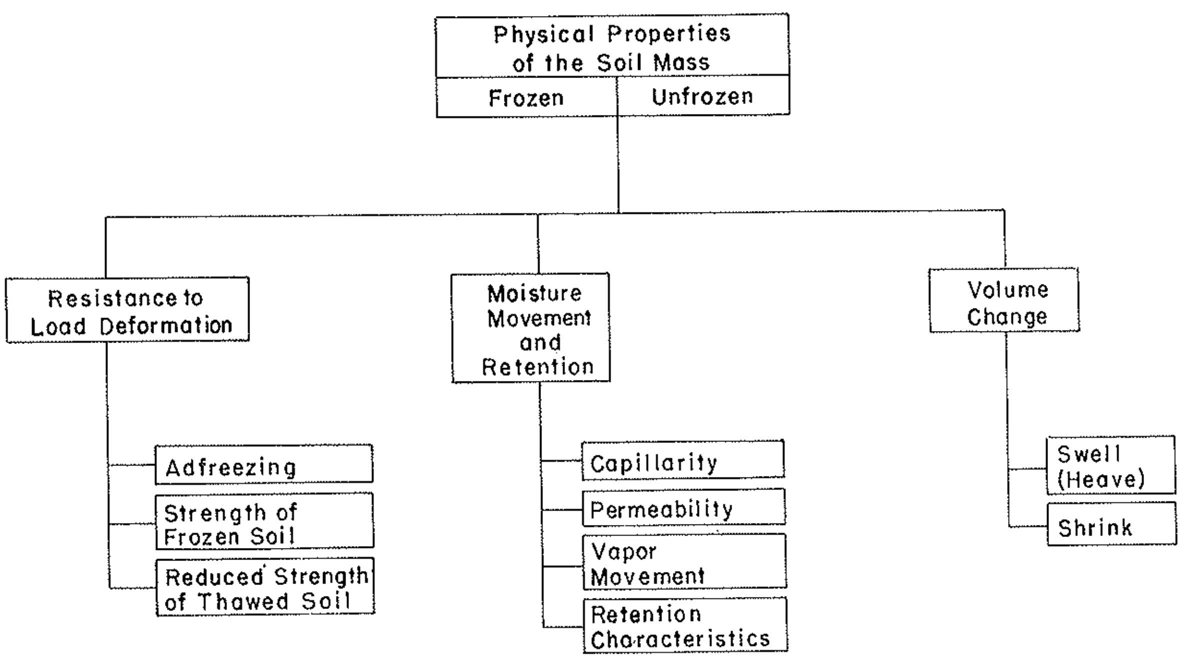


Figure 7.

out (42, 13) near the frost line in the manner that evaporation reduces moisture content near the surface of the ground. Consequently the reduced moisture content causes a water suction and capillary flow. The magnitude of molecular cohesion forces are so great that they will permit ice to grow under restraining forces approaching the crushing strength of ice (43). Regardless of the exact nature of the forces, the water supply to the freezing zone does not move through channels of capillary size, and detrimental amounts of ice segregation depends on adequate water contained in the soil or from a ground-water source near the freezing zone.

Freezing of moist soil in nature for practical purposes is always associated with some ice segregation, either in the form of crystals or lenses. The ice is not always visible, although it is usually detectable in terms of water gain. That gain may be limited to very thin strata, so thin that they are often overlooked in routine sampling of depths of 6 or 12 in. or more.

The effectiveness of vapor flow as a means of moving significant amounts of moisture to the freezing zones is a matter of some controversy. Limited laboratory experimental results available (13, 44, 45, 8) indicate that small amounts of soil water are moved in the form of vapor and that those amounts are of no consequence in frost heaving. It is not clear exactly how important vapor movement is as a continuing process of moving and building up soil moisture in subgrades to a degree which makes frost action (in the form of reduced strength) significant.

Following Thawing. When the soil has thawed the increased water content, whether limited to relatively thin strata or prevalent throughout the frozen depth, seeks to redistribute itself in a manner to satisfy forces which prevail. Regardless of the magnitude of moisture gain, its release on thawing creates a soil state different from that which existed prior to freezing. That water may be restrained from downward movement by the relatively impervious frozen soil beneath or, on completion of thawing, by saturated soil beneath. In the latter case, reduction and redistribution of moisture to prefrozen condition must be accomplished by forces of gravity and evaporation. If no ground-water source was available during freezing and all moisture gain above was at the expense of moisture loss below, the normal forces of soil suction will bring about redistribution.

The rate of that redistribution is dependent upon (1) the length of time during which it was moved upward by thermal forces due to below-freezing thermal gradients, (2) the duration of the freezing period, and (3) the relative effect of all forces operative during freezing. It may be that the time for redistribution following thawing is proportional to (1) and (2) above. However, if the forces operative in moving moisture to the freezing zone are, as one investigator (41) holds, greatly in excess of the forces causing its redistribution, that redistribution may be a much slower process than was the period of active freezing.

The problem here is one of a clearer understanding of the forces which prevail throughout both freezing and thawing processes and how the elements of time and those forces effect soil moisture movements. A clearer understanding of the two-stage process of freezing and thawing should make possible better base and pavement designs and better application of load restrictions for roads which become seasonally inadequate.

The following studies are suggested toward bringing about a better understanding of water movements, as related to freezing and thawing:

1. Establish more clearly the forces operative in moving water during freezing. Also, establish the relative distances through which the forces are effective and the influence of time on their relative effectiveness in soils of differences in texture and chemical composition and for different degrees of saturation. Evaluate the forces operative in causing a redistribution of water following thawing and the influence of time in changing soil moisture condition.

2. Establish more clearly, by both field and laboratory experiments, the real significance of water movement in the form of vapor. It is recognized that it is difficult to conduct small-scale laboratory tests which bring all natural forces into play with the same propor-

tional effect as occurs under pavements under natural conditions. Therefore, laboratory experiments need be supplemented with full-scale field experiments which include all natural variables and not just those of temperature difference.

Volume Change

Swell (Heave). Frost action in soil has two major detrimental effects of prime interest to engineers responsible for building of airfields and roads. One of these is differential volume change. The other is its effect on load-carrying capacity, both in the frozen and in the thawed condition.

The gain in moisture content associated with the freezing of most soils is associated with an increase in volume, which is spoken of as heaving if it occurs in visible amounts. When heaving differs markedly within short distances or in limited area, those differences in magnitude recognized as abrupt heaving are capable of causing severe damage to pavement and culvert structures. Such heaves are usually associated with abrupt changes in soil texture or soil water conditions and are readily recognized by most engineers experienced in construction in regions where deep freezing may occur.

Heaving is intensified in arctic regions where permafrost occurs. Deep freezing in soil whose drainage is retarded by the underlying permafrost is provacative of destructive heaving (46). The condition is most severe in the subarctic, where it is difficult to build without degrading the permafrost, thus tending to increase the depth subject to seasonal freezing and thawing and the intensity of heaving.

Hydrostatic conditions (47, 60) further increase the intensity of ground-surface movements. In the fall season, penetration of frost may trap large quantities of ground water between the seasonally frozen layer and the permafrost. Under such conditions the ground may bulge, ice may form in the core of the upheaval, and the upheaval may crack open and discharge quantities of water. Many conspicuous manifestations of surficial heaving are observed in permafrost regions. Such features as pingoes, frost blisters, icing mounds, peat mounds, and mud boils are indicative of intense ground freezing in areas where ground water is available in large amounts.

Minor heaving, although the actual increase in the elevation of the pavement profile may range from $^3/_4$ to 2 in. or more, is seldom detected by visual means. Consequently, many engineers are unwilling to recognize its presence or to appreciate its significance. It does not crack pavements, but it does cause reduced load-carrying capacity and also produces a more insidious effect in roughening the riding surface of pavements, particularly to the thinner pavements.

The problem, as it concerns major heaving, is principally one of defining different degrees of heaving according to degree of detriment and identifying and classifying ground conditions which are pertinent to different intensities of heaving. This needs to be done in a systematic manner. This problem is only partly satisfied by information in present literature, partly because of differences in terminology and partly because the information can be obtained only from numerous sources not available to many engineers.

Shrinkage on Freezing. Shrinkage, associated with soil freezing may occur in different forms. Shrinkage below the zone of freezing may occur due to soil consolidation on removal of water as it is drawn into the freezing zone. This form of shrinkage is never seen in nature and normally has little significance beyond the appreciation that it reduces total heaving so that heaving is not directly proportional to the thickness of ice lenses obtained and that it contributes to developing fissures in the soil.

A second form of shrinkage has far greater significance. Such shrinkage (48) results from freezing water-saturated, well-compacted, heavy clay soils. The shrinkage manifests itself in the form of marked downward movement of the soil surface (49) and for the development of large and often deep transverse cracks (50) coincident with cracks or joints in the pavement. Such shrinkage cracking may be detrimental in that it permits early spring rains to increase the soil moisture content. This type of shrinkage

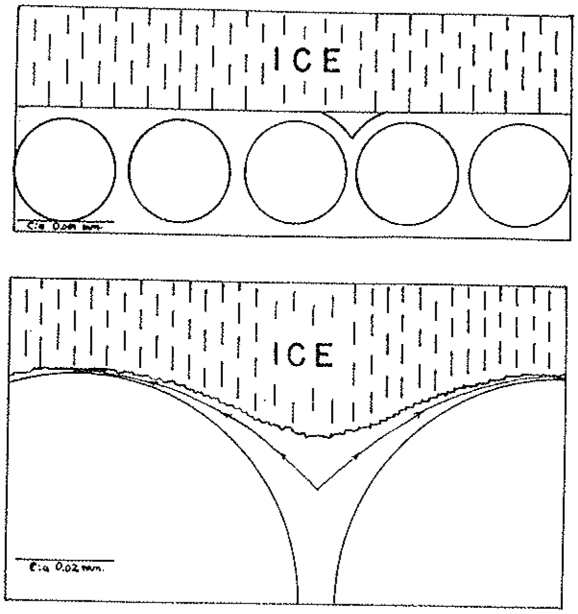


Figure 8.

has been attributed to a change from water to a high pressure form of ice (48) and to the natural contraction (50) of the pavement on cooling which also moves the frozen soil believed to be firmly attached to the pavement.

The greater range in temperatures below freezing in northern to arctic regions makes shrinkage increasingly more significant in the colder climes (24, 58).

The problem concerning soil shrinkage attributable to frost action is essentially that of identifying conditions which causes the shrinkage and establishing the degree in which it is detrimental, so it can be prevented in new construction where economically feasible to do so.

The following studies are suggested to bring about better understanding of soil shrinkage:

1. Conduct laboratory tests to determine the temperature, moisture content, and density conditions necessary to bring about shrinkage of the type associated with cracking of the ground surface.
2. Conduct full-scale field tests to determine the validity of criteria established above and the climatic and soil conditions under which they obtain. This project should have sufficient scope to establish (1) the extent in which they become detrimental and (2) whether or not it is practicable to prevent their occurrence on the types of soil in which they occur.

Resistance to Load Deformation

Frost action has two and opposite effects on the capacity of soils to carry loads. In the frozen state it provides a rigid pavement which may develop tremendous load-carrying capacity. But in the early thawed state the soil may lose up to 70 or 80 percent of the strength it had prior to freezing.

Frozen Soil. There is a great accumulation of information available concerning the elastic and plastic properties and strength of unfrozen soils. However, there is relatively little known of the strength characteristics of soil in the frozen state. These strengths may be of considerable significance where permafrost exists or where seasonally frozen ground layers of appreciable depth are maintained over the cold season. Foundations and bases may derive principal support from permafrost layers. Seasonally frozen layers may make possible increased loads on pavements and cross-country travel over ground which has low carrying capacity when unfrozen. Most effective use of frozen ground in these and other ways requires that its strength properties be more conpletely known.

The compressive, tensile, and shear strengths of frozen ground have been studied to some extent by the Russians (47). These foreign studies have recently been supplemented by American research (21, 32). These latter studies have attempted to evaluate in an orderly manner the effects of temperature, texture, moisture, density, etc., on frozen strengths.

The Corps of Engineers study (21) revealed that: (1) strength of frozen soils increases with decrease in frozen temperature, (2) clean, cohesionless materials have highest frozen strengths and clays have lowest, and (3) clean, uniformly graded sand has greater frozen strengths than more-well-graded sand and gravel soils. (The specimens tested were frozen slowly in one direction under conditions of full saturation with free access to water).

Among other findings of interest (21), the following are noted: (1) At temperatures just below freezing (26 to 30 F) even very small compressive loads produced continuous plastic deformation and (2) crystal structure of ice specimens frozen simultaneously with soil specimens was not indicative of the crystal structure in segregated ice lenses in naturally frozen soil. Strength properties may be expected to vary appreciably with successive thawings and refreezings. Strength properties of frozen ground are definitely and closely related to those of ice. Unfortunately, the available data for the ultimate strengths and for the elasticity, plasticity and viscosity of ice are rather unsatisfactory (51).

The grip or bond of frozen ground to a pile or foundation wall or pavement is termed "adfreezing force." This bond tends to produce a lifting of the foundation member as the ground freezes and heaves and to crack pavements where differential uplift occurs. Tangential adfreezing strength, a measure of the resistance that must be overcome to produce sliding of an object with respect to ground to which it was frozen, varies for any building material with temperature, composition, texture, and moisture content of the surrounding ground. The surface roughness of the foundation member itself is an additional factor. Few values of adfreezing strength are available from other than Russian sources (47). However, at the present time the St. Paul District of the Corps of Engineers is engaged at a subarctic location in rather extensive pile-loading and extraction tests which should yield valuable data.

The following studies are suggested:

1. Additional evaluation of the tensile, compressive, and shear strengths, plus elastic and plastic constants, of frozen soils of various compositions, textures, porosities, and moisture contents and distributions, under ranges of subfreezing temperatures is needed. Effects of rate and direction of freezing must also be considered.

2. Adfreezing strengths inherent to frozen contact between various subgrade, base, and pavement materials should be developed. Particular attention should be devoted to the rates of development of this adfreezing strength under known thermal influences.

Load-Carrying Capacity. One of the most outstanding studies relative to frost action in soils has been the recent investigations of load-carrying capacities of roads and airfields. Investigations have been reported by eight state highway departments (52, 53, 54, 55) and the Corps of Engineers (56). Additional studies are reported under way in permafrost areas. Highway studies were limited to flexible pavements, while the airfield investigation included both flexible and rigid types. The investigations had two purposes. Highway studies were made primarily to determine the degree of reduction in load-carrying capacity on which to base load restrictions during the spring season. The airfield study was pointed toward evaluating pavements on specific airfields for all season use. The findings are significant and in general agreement, and show a marked reduction in load-carrying capacity of the average order of 40 to 50 percent of the fall season value.

Reduction in load-carrying capacity is associated with a soil condition of increased moisture, decreased density, and perhaps, altered soil structure. Soils in which much water is accumulated and segregated into ice lenses during freezing will ordinarily undergo great reduction in load-carrying capacity on thawing. However, observations (57, 53) have revealed that significant reductions may occur with relatively small water gain and little ice segregation on freezing. Most of the data thus reported were from tests after thawing and for rather large depth increments.

Intensity and duration of the reduction are greatly dependent upon the rate and depth of freezing or thawing. Distribution of the ice within the frozen soil is critical. Rates of freezing which produce large segregations of ice near the surface and deep frost penetrations, in combination with early and rapid thawing to shallow depths, produce the most unfavorable condition of supersaturation above a residual frozen layer. It is then to be expected that the impedance to internal drainage effected by underlying frozen soil, plus the presence of large accumulations of ice in the frost zone and also, perhaps, great depths of this zone, produce a condition conducive to large reductions in the soil's bearing capacity. Further, reductions can be expected to have longer durations in permafrost areas than prevail in seasonally frozen ground regions. Settling and caving actions are also in frequent occurrence.

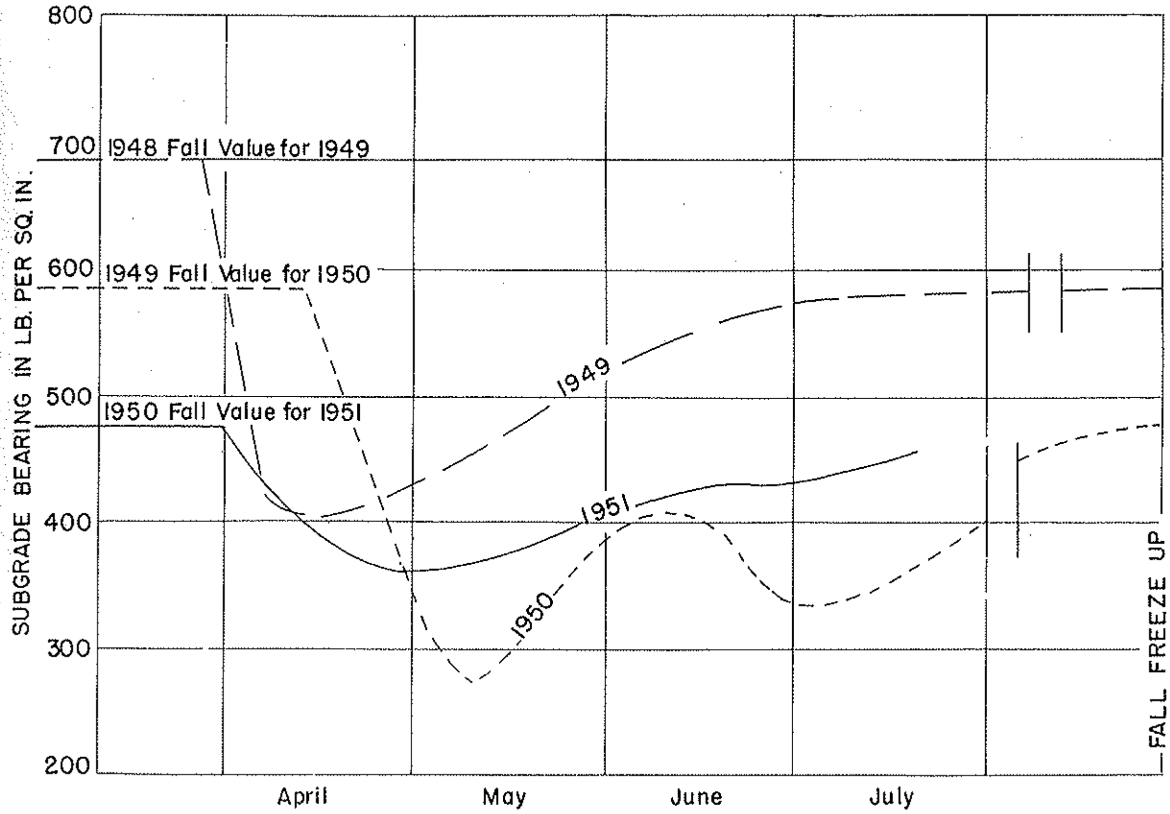


Figure 9.

Efforts to evaluate reductions in load-carrying capacity and the adequacy of various subgrades and base and pavement courses during the frost-melting period have utilized accelerated traffic tests, plate-bearing tests, in-place California Bearing Ratio tests, and other penetration or instrument tests. A great deal of plate-load testing has been accomplished; however, such tests are criticized (56) because the gradually applied load allows escape of water, consolidation, and build-up of resistance in the subgrade. In addition, these tests do not reflect the weakening due to subgrade disturbance under repetitive loadings of the nature imposed by traffic. It is significant to note that the ratios of weakening as determined by static plate tests on rigid pavements (rupture tests on slab corners) are reported (56) to be comparable to ratios determined by actual traffic testing. However, such agreement has not been achieved in the case of plate loading of flexible pavements.

Certain small instrument tests, the North Dakota cone, the Housel penetrometer, and the Iowa subgrade-resistance meter are being studied by several state highway departments under the coordination of a committee of the Highway Research Board (52, 55). Emphasis has been placed upon correlation of these instrument tests with field plate-bearing tests. No extensive or conclusive results have been reported as yet.

A statement of research needs would include:

1. Present comprehensive programs being conducted in determination of reductions in load-carrying capacity on thawing and in validation or formulation of design criteria are producing significant results. Complementary studies in point of soil areas and climatic coverage are needed, particularly in the subarctic. Measured reductions in carrying capacity for various soil textures and moisture conditions under closely observed climatic conditions should be correlated with: (1) Amounts of ice segregation and heave. (2) Degree of saturation before freezing. (3) Changes in soil condition from prefrozen to thawed; (a) increase in moisture content, (b)

increase in soil porosity, (c) modification of soil structure. (4) Position and movement of water table.

In making measurement of reductions, attention should be given to the cycles of climatic variation for the region in question. It is hazardous to evaluate measurements for any particular year, without knowledge of whether that year was very mild, very severe, or about normal, climatically speaking.

2. Although the success achieved to date in correlating the results of traffic, plate, and instrument test evaluations of load-carrying capacity are somewhat limited, it is anticipated that efforts to achieve such correlation will be continued and expanded. There is obvious need for a testing technique that requires little time and light equipment for performance. Modification of test instruments to more closely simulate traffic loading should be given further consideration.

EXTRINSIC FACTORS WHICH INFLUENCE FROST ACTION

Two major external factors have vital influence on the nature of frost action in soil: climate and load. The more important of these is climate, which exercises control over ground temperature. The major elements of climate in normal order of relative importance of influence are: air temperature, precipitation and humidity, sunshine, and wind. Climatic influences may be considered to be modified by location, degree of exposure, and the nature of surface cover.

The effect of location may be evaluated through the elements of latitude, altitude, and proximity to bodies of water. Degree of exposure to sunshine and wind is largely governed by slope and aspect. Surface cover may be composed of vegetation, snow or ice, highway or airfield pavement or other structures. Load (whether in the form of surcharge weight, such as overlying subgrade, base and pavement, or as moving wheel loads) has somewhat less influence than climate but is, nevertheless, an important factor.

Obviously, an attempt to evaluate the relative influences of these factors on frost action would necessitate a lengthy summary. They are merely mentioned here to emphasize that study of the intrinsic factors constitutes only a portion of the overall needs.

PRACTICAL DESIGN AND CONSTRUCTION PROBLEMS

Emphasis in this outline of needed research has been placed upon an understanding of the fundamental technology of freezing and thawing processes. It is felt that improved understanding of these fundamentals is prerequisite to marked improvement in engineering practice relative to frozen ground. However, the development of such basic data does not mean that practical problems of design and construction should be neglected. There is need for field verification of findings by investigations of full-scale construction of embankments, subgrades, bases, pavements, insulation courses, subsurface-drainage installations, etc. This phase of study should be carried on concurrently with the fundamental investigations. There is great need for correlation of traffic testing with normal laboratory testing, in order that the benefits of increased knowledge of laboratory performance may be properly reflected in field design and construction.

REFERENCES

1. Lovell, C. W. and Herrin, Moreland (1953) Review of Certain Properties and Problems of Frozen Ground Including Permafrost. To be published by the Snow, Ice and Permafrost Research Establishment, Corps of Engineers in 1953.

2. Johnson, A. W. (1952) Frost Action in Roads and Airfields, A Review of the Literature, 1765-1951. Highway Research Board Special Report No. 1, Washington, D. C. 287 pp.

3. Minutes of Conference on Permafrost and Frost Definitions. Held in the Office of the Chief of Engineers, Corps of Engineers, Washington, D. C., on July 1, 1952.

4. Cryological Facilities in North America (1951) SIPRE Report No. 6, Engineer Research and Development Laboratories and Snow, Ice and Permafrost Research Establishment (SIPRE), Corps of Engineers, 66 pp.

5. Annotated Bibliography on Snow, Ice and Permafrost (1952) SIPRE Report 12. Vols. 1 & 2. Prepared by the Library of Congress for the Snow, Ice and Permafrost Research Establishment, Corps of Engineers, Wilmette, Illinois. Sept. 1951, 226 pp; July 1952, 356 pp.

6. Highway Research Board (1952) Frost Action in Soils, A Symposium. Highway Research Board Special Report No. 2, Washington, D. C. 385 pp.

7. Corps of Engineers (1947) Report on Frost Investigation 1944-1945. New England Division, Boston. 66 pp. Supp. Plates.

8. Corps of Engineers (1951). Frost Investigations (Fiscal Year 1951) - Cold Room Studies. Frost Effects Laboratory, New England Division for the Office of the Chief of Engineers. Vol. 1. 58 pp. Supp. tables and plates.

9. Kersten, M. S. (1945) "Subgrade Moisture Conditions Beneath Airport Pavements." Proceedings, Highway Research Board. Vol. 25. pp. 450-463.

10. Belcher, D. J., Cuykendall, T. R. and Sack, H. S. (1952) Nuclear Metus for Measuring Soil Density and Moisture in Thin Surface Layers. CAA Technical Development Report No. 161. Technical Development and Evaluation Center, Indianapolis. 8 pp.

11. Aldous, W. M., Lawton, W. L. and Mainfort, R. C. (1952) The Measurement of Soil Moisture by Heat Diffusion. CAA Technical Development Report No. 165. Technical Development and Evaluation Center, Indianapolis, 17 pp.

12. Winn, H. F. and Rutledge, P. C. (1940) Frost Action in Highway Bases and Subgrades. Research Series No. 73, EES, Purdue University, Lafayette, Indiana. Vol. 2, pp. 14-15, 70-72.

13. Beskow, Gunnar (1935) Soil Freezing and Frost Heaving with Special Application to Roads and Railroads. The Swedish Geological Society, Series C, No. 375, 26th Year Book, No. 3. (With a special supplement for the English translation of progress from 1935 to 1946. Translated by J. O. Osterberg. Published by the Technological Institute, Northwestern University, Evanston. Nov. 1947. 145 pp.)

14. Burton, V. R. and Benkelman, A. C. (1931) "The Relation of Certain Frost Phenomena to the Subgrade." Proceedings, Highway Research Board. Vol. 10, pp. 259-279. Discussion: Willis.

15. Aaron, Henry (1934) "Frost Heave in Highways and Its Prevention." Public Roads, Vol. 15, No. 1, pp. 10-16, 25.

16. Taber, Stephen (1930) "The Mechanics of Frost Heaving." Journal of Geology. Vol. 38, pp. 303-317.

17. Michigan State Highway Department (1946) Field Manual of Soil Engineering (Revised). Lansing. 304 pp.

18. Shelburne, T. E. and Maner, A. W. (1949) "Analysis of Spring Break-Up Data in Virginia." Pavement Performance. Bull. No. 20, Highway Research Board, Washington. pp. 1-20.

19. Spangler, M. G. and Pien, W. T. (1952) "Distribution of Capillary Moisture at Equilibrium in Stratified Soil." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2, Washington, D. C. pp. 120-125.

20. Hopkins, D. M. and Sigafoos, R. S. (1951) Frost Action and Vegetation Patterns on Seward Peninsula, Alaska. U. S. Geological Survey Bulletin 974-C. Washington, pp. 51-100.

21. Corps of Engineers (1951) Investigation of Description, Classification and Strength Properties of Frozen Soils. Report of Investigation for Fiscal Year 1951, with Appendix A. SIPRE Report 8. New England Division, Boston, Mass. 88 p. Supp. tables and plates.

22. Black, R. F. (1950) "Permafrost." Applied Sedimentation, A Symposium. (Edited by P. D. Trask). Wiley & Sons, New York. pp. 247-275.

23. Muller, S. W. (1947) Permafrost or Permanently Frozen Ground and Related Engineering Problems. J. W. Edwards, Inc., Ann Arbor, Michigan. 231 pp.

24. Washburn, A. L. (1950) "Patterned Ground." Revue Canadienne de Geographic. Vol. 4, No. 3-4. Montreal. p. 5-59.

25. Frost, R. E. (1952) "Interpretation of Permafrost Features from Airphotos." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2. Washington, D. C. pp. 223-246.

26. Yoder, E. J. and Lowrie, C. R. (1952) "Some Field Measurements of Soil Temperatures in Indiana." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2, Washington, D. C. pp. 41-50.

27. Arndt, W. J. (1943) "Temperature Changes and Duration of High and Low Temperatures in a Concrete Pavement." Proceedings, Highway Research Board, Vol. 23, pp. 273-279.

28. Swanberg, J. H. (1945) "Temperature Variations in a Concrete Pavement and the Underlying Subgrade." Proceedings, Highway Research Board, Vol. 25, pp. 169-180.

29. Crawford, C. B. (1952) "Soil Temperatures, A Review of Published Records." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2, Washington, D. C. pp. 17-41.

30. Missouri State Highway Commission (1948) Soils Manual. Bureau of Materials, Jefferson City. 194 pp.

31. Corps of Engineers (1951) "Airfield Pavement Design - Frost Conditions." Engineering Manual for Military Construction. Part 12, Chapt. 4, p. 3-4.

32. Kersten, M. S. and Cox, A. E. (1951) "The Effect of Temperature on the Bearing Value of Frozen Soils." Load Carrying Capacity of Roads as Affected by Frost Action, Bulletin No. 40, Highway Research Board. Washington, D. C. pp. 32-38.

33. Kersten, M. S. (1949) Thermal Properties of Soils. Bull. No. 28. EES, University of Minnesota, Minneapolis. 225 pp.

34. Shannon, W. L. and Wells, W. A. (1947) "Tests for Thermal Diffusivity of Granular Materials." Proceedings, American Society for Testing Materials. Vol. 47. pp. 1044-1055.

35. Penrod, E. B. et al (1949) Earth Heat Pump Research, Part 1. Bull. No. 14, Bull. Series Vol. 4, No. 2, EES, University of Kentucky, Lexington, 64 pp.

36. Toulonkian, Y. S., Bottorf, J. D. and Harsem, Thor (1952) "Heat Transfer and Temperature Distribution in Soils for Transient Heat Flow Due to Cylindrical Sources and Sinks." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2. Washington, D. C. pp. 147-160.

37. Keen, B. A. (1931) The Physical Properties of the Soil. Longmans, Green and Co., London. pp. 297-333.

38. Baver, L. D. (1948) "Soil Temperature," Soil Physics. 2nd Ed. Wiley & Sons, New York. pp. 288-310.

39. Misener, A. D. (1952) "An Absolute Method of Determining Thermal Conductivity and Diffusivity of Soils." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2, Washington, D. C. pp. 51-57.

40. Hooper, F. C. (1952) "The Thermal Conductivity Probe." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2. Washington, D. C. pp. 57-59.

41. Taber, Stephen (1930) "Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements." Public Roads. Vol. 11, No. 6, pp. 113-132.

42. Bouyoucos, G. J. and McCool, M. M. (1928) "The Correct Explanation for the Heaving of Soils, Plants, and Pavements." Journal, American Society of Agronomy. Vol. 20, No. 5, pp. 480-491.

43. Taber, Stephen (1929) "Frost Heaving." Journal of Geology, Vol. 37, No. 5, pp. 428-461.

44. Bouyoucos, G. J. (1915) "Effects of Temperature on Movement of Water Vapor and Capillary Moisture in Soils." Journal of Agricultural Research. Vol. 5, No. 4. pp. 141-172.

45. Smith, W. O. (1943) "Thermal Transfer of Moisture in Soils." Transactions, American Geophysical Union. Part 2, pp. 511-524. Discussion: Baver.

46. Taber, Stephen (1943) Perennially Frozen Ground in Alaska: Its Origin and History. Bulletin of the Geological Society of America. Vol. 54, pp. 1433-1548. Supp. plates.

47. Muller, S. W. (1947) Permafrost or Permanently Frozen Ground and Related Engineering Problems. J. W. Edwards, Inc., Ann Arbor, Michigan. 231 pp.

48. Winterkorn, H. F. (1943) "The Condition of Water in Porous Systems." Soil Science, Vol. 56, No. 4.

49. Allen, Harold (1945) "Report of Committee on Warping of Concrete Pavements." Proceedings, Highway Research Board, Vol. 25, pp. 199-250.

50. Bleck, A. T. (1949) Pavements and Their Influences Affecting or Determining Their Performance. Highway Research Board Bull. No. 20, Highway Research Board, Washington, D. C.

51. University of Minnesota (1951) Review of the Properties of Snow and Ice, SIPRE Report 4. Institute of Technology, EES, for the Snow, Ice and Permafrost Research Establishment, Corps of Engineers. Minneapolis, Minnesota. 156 pp.

52. Motl, C. L. (1948) "Report of Committee on Load Carrying Capacity of Roads as Affected by Frost Action." Proceedings, Highway Research Board. Vol. 28, pp. 273-281.

53. Motl, C. L. (1950) Committee Report and Manual of Recommended Testing Procedures on Load Carrying Capacity of Roads as Affected by Frost Action. Highway Research Board Research Report No. 10-D.

54. Motl, C. L. (1951) Load Carrying Capacity of Roads as Affected by Frost Action. Committee Report. Highway Research Board Bull. No. 40.

55. Motl, C. L (1952) Load Carrying Capacity of Roads as Affected by Frost. Report of Committee, Highway Research Board Bull. No. 54.

56. Haley, J. F. and Kaplar, C. W. (1952) "Cold-Room Studies of Frost Action in Soils." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2, Washington, D. C. pp. 246-267.

57. Lund, O. L. (1952) "Remedies and Treatments for the Frost Problem in Nebraska." Frost Action in Soils, A Symposium, Highway Research Board Special Report No. 2, Washington, D. C., pp. 334-341.

58. Leffingwell, E. deK. (1919) The Canning River Region, Northern Alaska. Professional Paper 109. U. S. Geological Survey, Washington. 251 pp. Supp. plates.

59. Kersten, M. S. (1944) "Survey of Subgrade Moisture Conditions." Proceedings, Highway Research Board. Vol. 24, pp. 297-513.

60. Dept. of the Army (1950) Construction of Runways, Roads, and Buildings on Permanently Frozen Ground. TB5-255-3. Washington. p. 88.

The Highway Research Board is organized under the auspices of the Division of Engineering and Industrial Research of the National Research Council to provide a clearinghouse for highway research activities and information. The National Research Council is the operating agency of the National Academy of Sciences, a private organization of eminent American scientists chartered in 1863 (under a special act of Congress) to "investigate, examine, experiment, and report on any subject of science or art."