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).

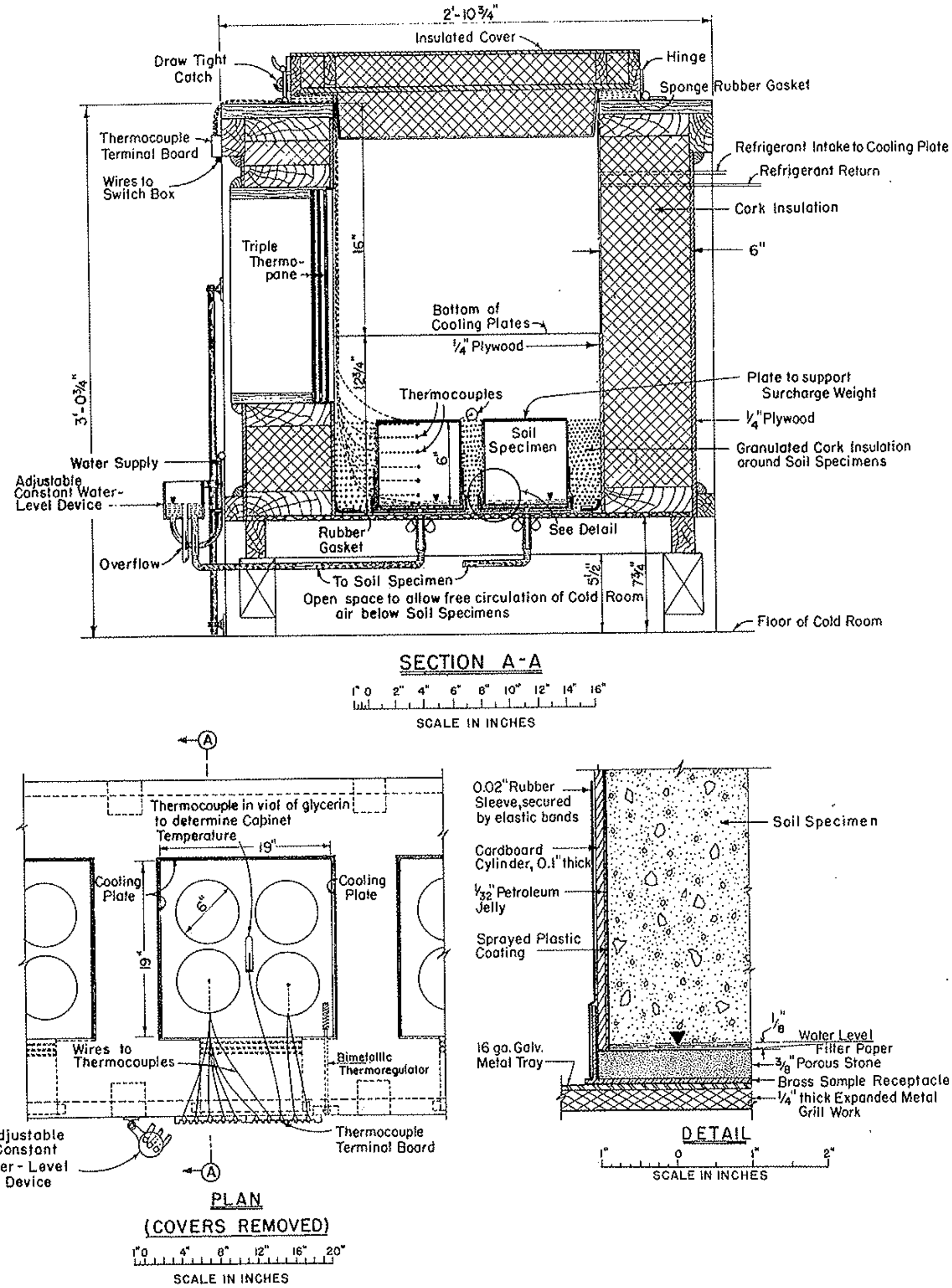


Figure 1. Details of test cabinet and samples, showing specific setup with samples 6 in. high and 6 in. in diameter. The constant-water-level device is adjusted to maintain the water level at 1/8 in. above porous stone.

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.

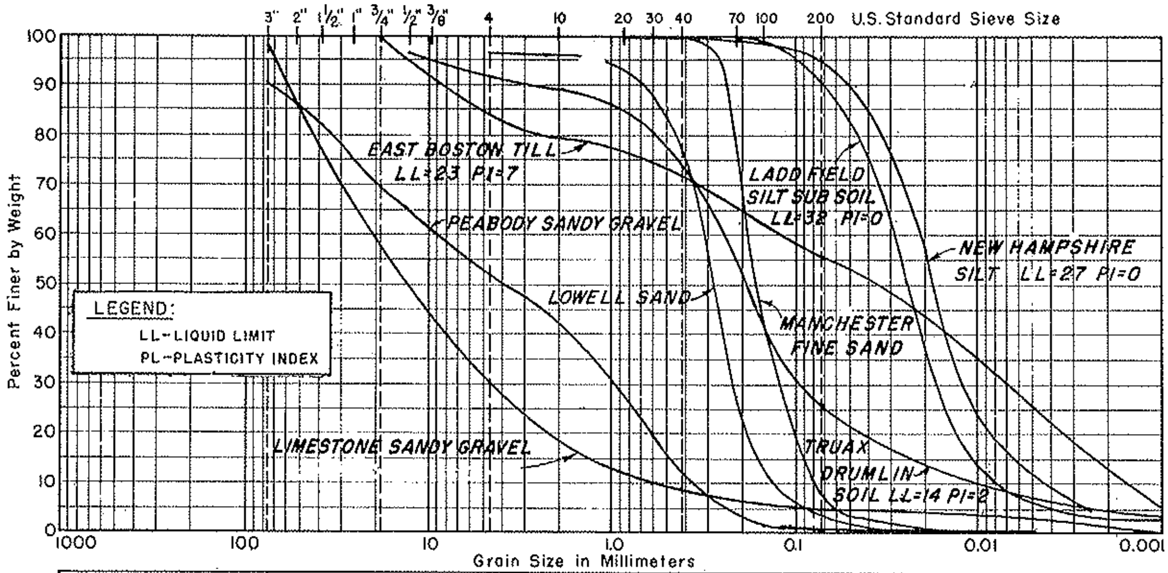
Based exclusively on grain size, it appears that the finer the grains or the higher the percentage of colloidal sizes contained in the fine soil fraction the more effective the finer soil fraction is in producing ice segregation. The Limestone sandy gravel fines that were combined with Limestone sandy 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



COBBLES	GRAVEL		SAND			SILT or CLAY
	Coarse	Fine	Coarse	Medium	Fine	

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.

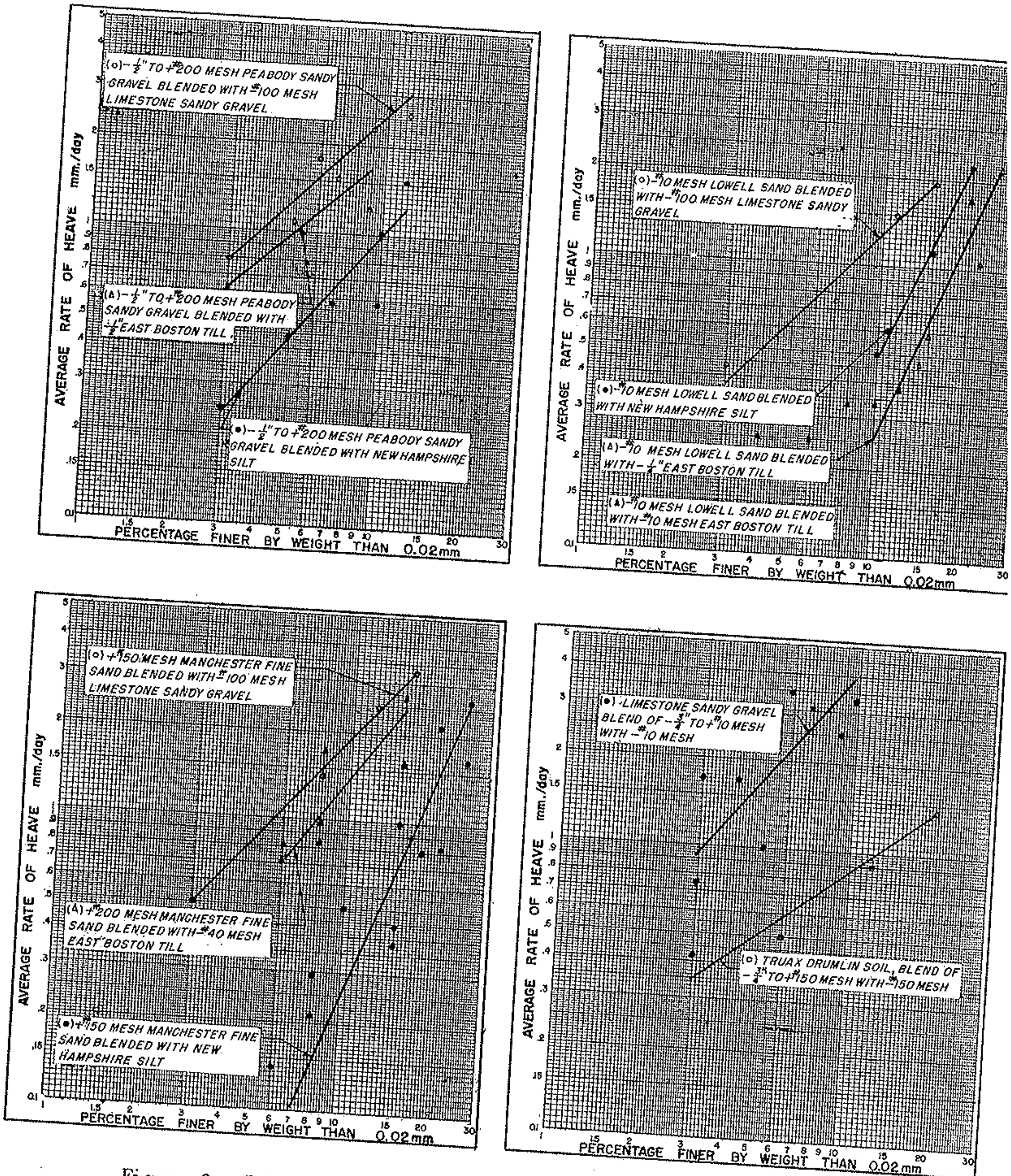


Figure 3. Relationship between rate of heave and percentage finer than 0.02 mm. using soil blends.

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

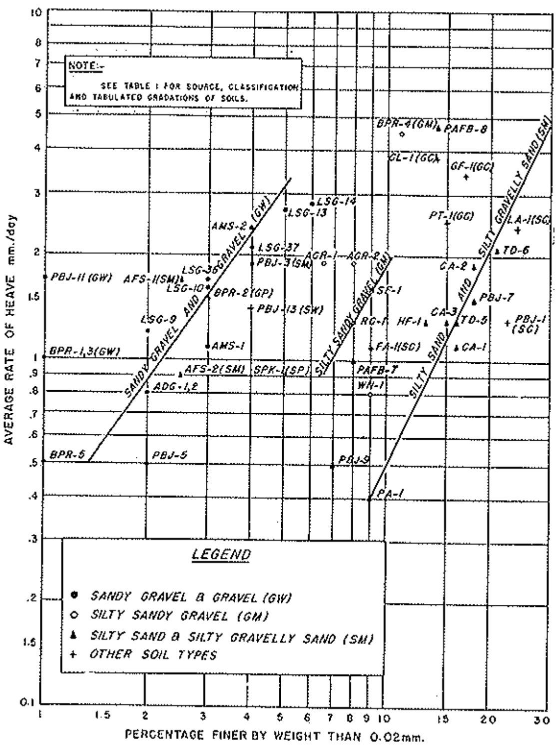


Figure 4. Relationship between rate of heave and percentage finer than 0.02 mm. in natural soils.

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

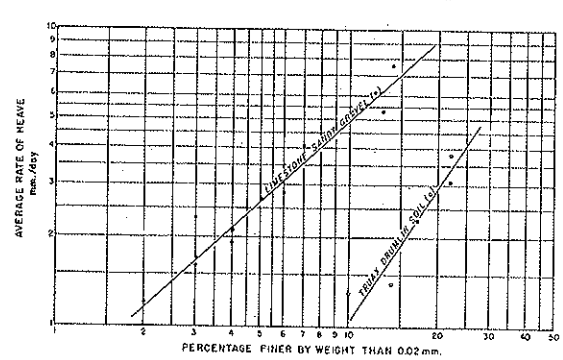


Figure 5. Effect of varying percentage of coarse fraction on rate of heave.

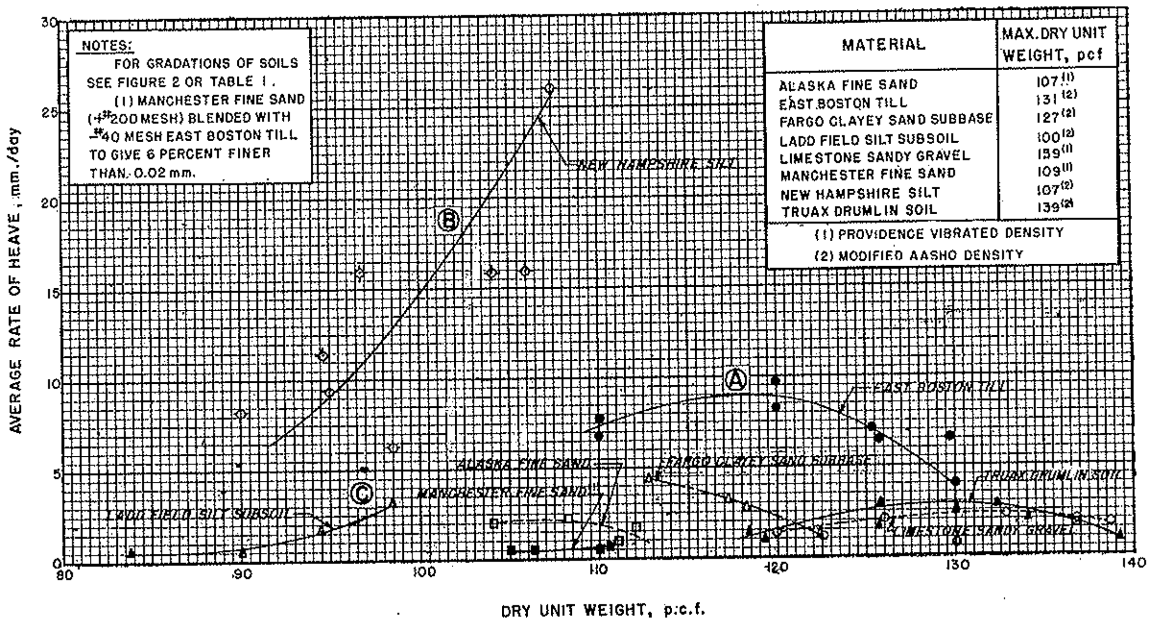


Figure 6. Effect of variation in dry unit weight.

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 $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$ 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, $\frac{1}{4}$ to $1\frac{3}{4}$ 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.

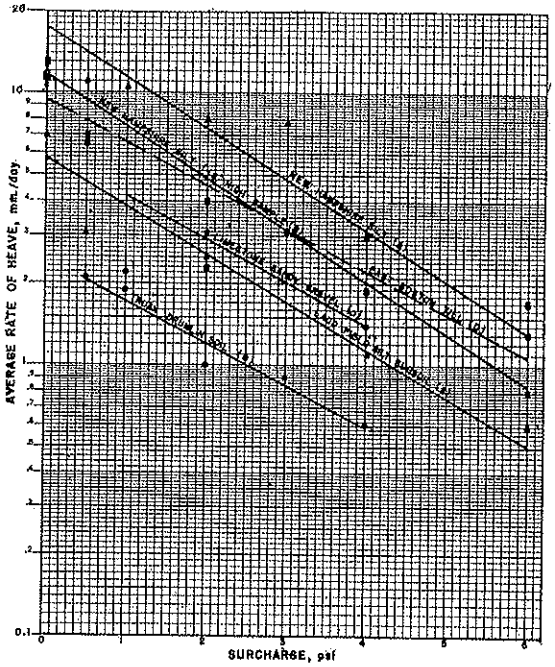


Figure 7. Effect of surcharge.

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

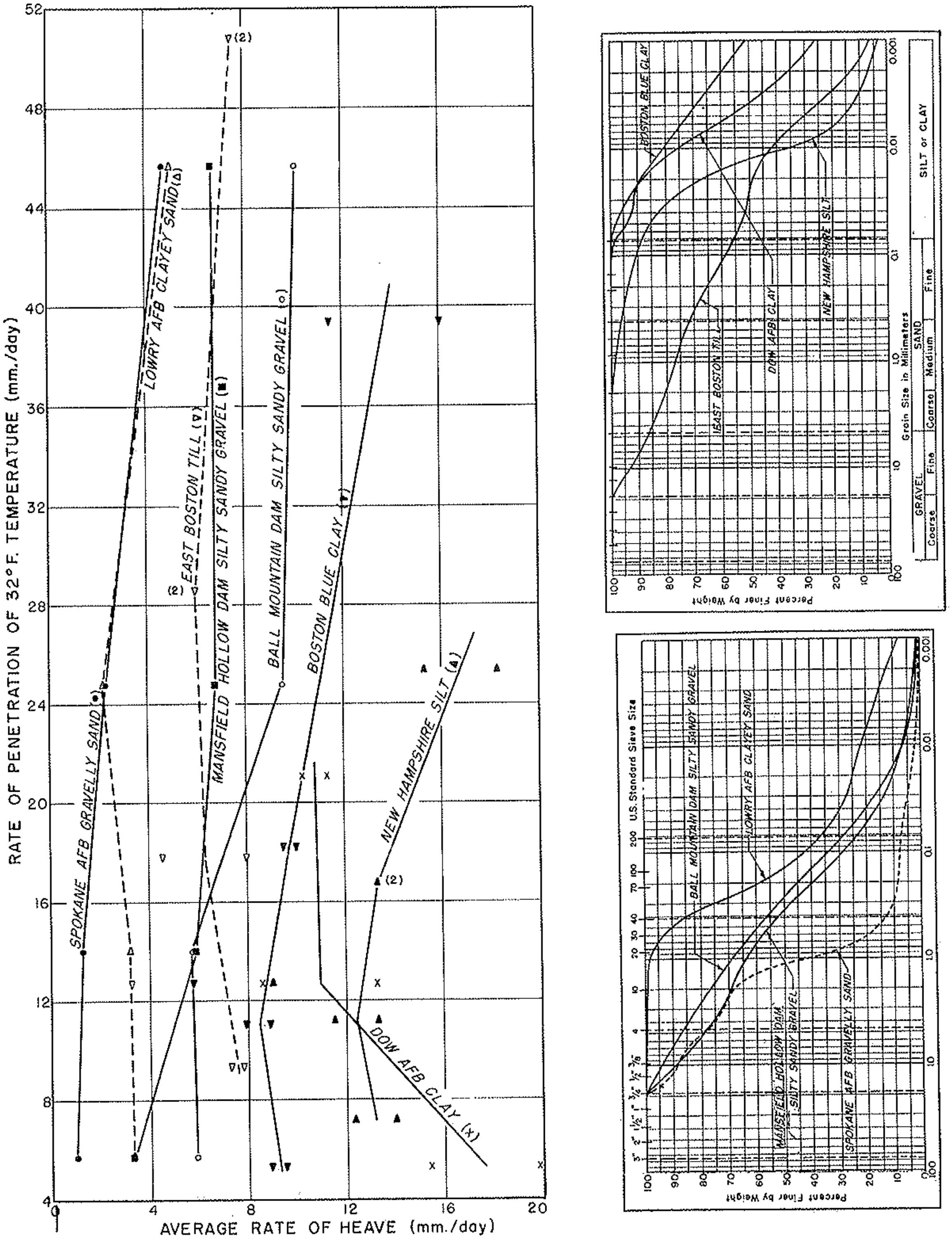


Figure 8. Effect of rate of freezing.

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 andpull away from the container at the lower portions of the specimens.

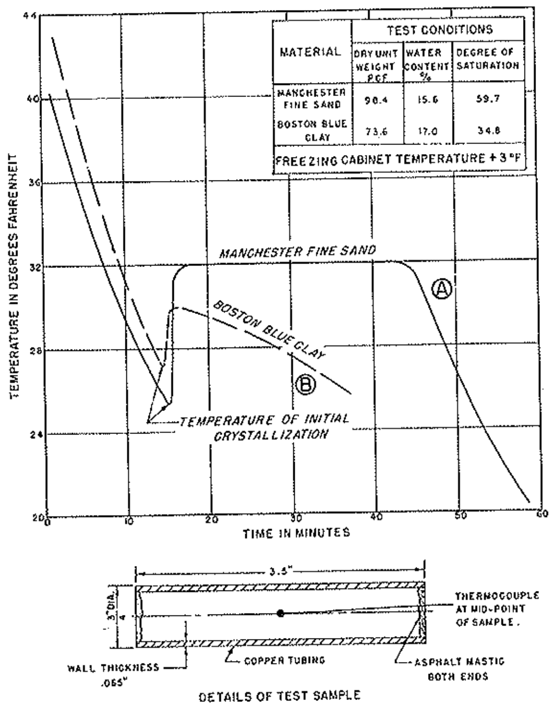


Figure 9. Plot of temperature change during freezing cycle.

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: DESCRIPTION	LETTER SYMBOL	GRAIN SIZE PERCENTAGE FINER THAN: #4 SIEVE	#40 SIEVE	#200 SIEVE	0.02 mm.	0.005 mm.	ATTERBERG LIMITS (1): Lw	Iw	Sw	DRY UNIT WEIGHT pcf.	WATER CONTENT DETERMINATIONS IN PER CENT: TOTAL SAMPLE BEFORE FREEZING: WATER CONTENT	G (2)	AFTER FREEZING: FROZEN ZONE: TOP INCH	SOIL BETWEEN ICE LENSES	UNFROZEN ZONE	PER-CENTAGE HEAVE
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.

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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.

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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