62. Sharp, R. P., "Soil Structure in the St. Elias Range, Yukon Territory," Journal of Geomorphology, Vol. 5, No. 4, 1942.

63. Hobbs, W. H., "Soil Flow," Bulletin, American Geographical Society, Vol. 45, No. 4, 1913.

64. Dalquest, Walter W. and Scheffer, Victor B., "The Origin of the Mima Mounds of Western Washington," Journal of Geology, Vol. 50, No. 1, January-February, 1942, p. 68-84.

65. Krinitzsky, E. L., "Origin of Pimple Mounds," American Journal of Science, Oct. 1947. Vol. 247, p. 706-714.

66. Campbell, M. R., "Natural Mounds," Journal of Geology, Vol.14, November, December, 1906, pp. 708-717.

67. Koons, Frederick C., "The Sand Mounds of Louisiana and Texas," Scientific Monthly, Vol. 66, April 1948, pp. 297-300.

68. Price, W. A., "Pocket Gophers as Architects of Mima Mounds of the Western United States," Texas Journal of Science, Vol. 1, 1949, pp. 1-17.

69. Scheffer, V. B., "The Mystery of the Mima Mounds," Scientific Monthly, Vol. 65, 1947, pp. 283-294.

70. Pewe, Troy L., "Origin of the Mima Mounds," Scientific Monthly, Vol. 66, April 1948, p. 293.

COLD-ROOM STUDIES OF FROST ACTION IN SOILS

James F. Haley, Assistant Chief, and Chester W. Kaplar, Engineer
Frost Effects Laboratory, New England Division, Corps of Engineers, U. S. Army

Synopsis

Cold-room studies of frost action in soils are being performed by the Frost Effects Laboratory, New England Division, Corps of Engineers, for the Airfields Branch, Office, Chief of Engineers, Department of the Army, as part of a continuing program of frost investigations aimed toward establishing and improving design and evaluation criteria for roads, highways and airfield runways constructed on soils subject to seasonal freezing and thawing. The present laboratory studies are being made chiefly to determine the quantitative effects of individual factors which influence ice segregation in soils, such as gradation, percent finer than 0.02 mm., percent stone, permeability, capillarity, proximity of water supply, compaction, and the initial degree of saturation in a closed system.

The chief purpose of this paper is to present the testing program and methods and equipment used. The cold-room studies were begun in February 1950 and are currently in progress. The data presented herein are incomplete, and final conclusions must await the completion of the various phases of the investigation.

The data available indicate that percentage finer than 0.02 mm. size is not, by itself, an adequate indicator and that other factors must be considered in recognizing with accuracy a frost-susceptible soil or in predicting the intensity of ice segregation possible in a given soil. Tests have shown the character and distribution of the fines have an important bearing on frost susceptibility.

In some soils the degree of compaction at the start of freezing has a marked effect on the amount of heave which occurs. In other soils the effect may be small. In some a critical degree of compaction may occur at which ice segregation is most intense, with less heaving occurring at densities higher or lower than the critical density.

Closed-system tests on a saturated lean clay indicate considerable ice segregation can occur without water being available from an outside source.

The increase in the weights of military and commercial aircraft and increased use of highways by heavily loaded trucks during the last decade has intensified problems encountered in the 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 frost susceptible soils may result in nonuniform heaving of the pavements or loss of supporting capacity during the frost-melting period, and costly maintenance or repair measures may be required. Loss of pavement strength results when rapid thawing occurs from the surface down and the excess water released from ice lenses is prevented from draining downward by the still-frozen underlying soil and ice layers. Frost boils, pumping, and subsequent pavement breakup may occur under traffic as a result of the nearly liquid condition of the subgrade during this period. Interruption of traffic and damage to aircraft as a result of frost action must be avoided.

To develop pavement design and evaluation criteria for such frost conditions the Frost Effects Laboratory was established in the New England Division in 1944 by authority of the Chief of Engineers, Department of the Army. The Laboratory has since conducted field investigations, including traffic tests, at various airfields in the northern part of the United States to observe and study the effects of frost action. As a result of these studies, extensive field data have been compiled from a number of sites, covering many naturally varying conditions of soil, temperature, and moisture. These data have been assembled by the Frost Effects Laboratory in two published reports entitled "Report on Frost Investigation, 1944-1945," dated April 1947, and "Addendum No. 1, 1945-1947, to Report on Frost Investigation, 1944-1945," dated October 1949. A third major report, entitled " Summary Report of Frost Investigations, 1944-1947," has been prepared and will be published in the near future. It unifies and summarizes the principal results of observations and tests made and presents design and evaluation criteria for both airfield and highway pavements.

The field studies have shown a need for comprehensive laboratory investigations, under controlled conditions, to study the effect of each of the several variables on ice segregation in soils. To meet this need, the Chief of Engineers in June 1949 authorized the construction of a cold room at the Frost Effects Laboratory. The room was completed and placed in operation in January 1950. 1/ Studies conducted with its specially-designed facilities give a clearer understanding of frost action in soils, resulting in the development of improved criteria for the design and evaluation of pavements. These criteria are useful in construction not only of airfield runways, taxiways, and aprons but also of roads and highways.

With the available facilities, base-course and subgrade soils whose frost susceptibility is in question may be tested in the cold room prior to construction to determine behavior under freezing conditions. This more precise determination of degree of frost susceptibility permits closer and more economical design. Borderline soils available in the subgrades or in the proximity of construction sites which under present criteria would be rejected or would require expensive treatment may, in many cases, be proven non-frost susceptible and satisfactory for use after being subjected to the laboratory tests.

Overall Program of Tests

The cold room and its equipment have been designed to enable studies to be made under controlled conditions of all frost phenomena occurring in soils which are reasonably adaptable to investigation by laboratory methods. The presently planned program includes tests to determine the following: (1) Effect of particle size distribution on ice segregation in soils; (2) Effect of degree of compaction on ice segregation in frost susceptible soils; (3) Effect of initial degree of saturation on ice segregation in a frost-susceptible soil in a closed system (in which no water is made available to the bottom of the sample);(4) Effect of surcharge or overburden pressure on ice segregation in frost-

---

1/ A supplementary cold room designed for tests on ice, snow, and frozen soil specimens at temperatures down to -40 F., constructed during 1950, is not covered in the present paper.

susceptible soils; (5) Effect of alternate freezing and thawing on permanence of initial compacted density and strength of soils; (6) Effect of soil properties such as void ratio, permeability, and capillarity on ice segregation; (7) Effect of proximity of water table on ice segregation in frost-susceptible soils; (8) Effect of frost melting on strength characteristics of soils, including time required for weakened soils to return to normal strength after thawing; (9) Effect of admixtures in preventing or retarding the formation of ice lenses in frost-susceptible soils; (10) Effect of the chemical nature of the soil minerals and of the dissolved salts in the pore water on ice segregation; (11) Frost-susceptibility or non-frost-susceptibility of base and subgrade soils from various airfields in northern United States; (12) The nature of physical laws governing ice segregation in soils, an understanding of which is needed to aid the development of design criteria.

Laboratory studies in the cold room were begun in February 1950. This report presents only the data and results available up to mid-1950, covering partially completed phases of the first four items of the above-listed general program, on which tests are still in progress.

Definitions

Description of the tests and analysis of results involve specialized use of certain terms and words. Definitions of these words and terms as used in this paper are as follows:

Frost Heave - is the raising of the surface of the test specimen due to the accumulation of ice lenses in the underlying soil. The amount of heave in most soils is approximately equal to the cumulative thickness of ice lenses.

Frost-Susceptible Soils - are those in which significant ice segregation will occur when moisture is available and the requisite 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. Cold-room tests now in progress in the Frost Effects Laboratory are expected to result in improved knowledge concerning limits between frost-susceptible and non-frost-susceptible soils.)

Frost Action - is a general term used in referring to freezing of moisture in materials and the resultant effects of these materials and on structures of which they are a part.

Ice Segregation - in soils is the growth of bodies of ice during the freezing process, most commonly as ice lenses or layers oriented normal to the direction of heat loss, but also as veins and masses having other patterns.

Percent Heave - is the ratio, expressed as a percentage, of the amount of heave to the depth of the frozen soil before freezing.

Degree of Saturation - is the ratio, expressed as a percentage, of the volume of water in a given soil mass to the total volume of intergranular space. Percent saturation is synonymous with degree of saturation in this report.

Ground-Water Table - is the free-water surface nearest to the ground surface.

Dry Density - is defined as the dry unit weight in pounds per cubic foot.

Capillarity - is that property which enables a soil to draw and hold water above the elevation at which atmospheric pressure exists in the water.

Overburden Pressure - is the force exerted at any given point in a soil by the weight of the overlying material.

Closed System - is a test condition where no free water is made available from outside the specimen during the freezing process.

Open System - is a test condition where free water is made available from outside the specimen during the freezing process.

This investigation is being conducted by the Frost Effects Laboratory for the Airfields Branch, Engineering Division, Military Construction, Office of the Chief of Engineers, Department of the Army, of which Gayle MacFadden is chief and Thomas B. Pringle is head of the Runways Section. Colonel H. J. Woodbury is the division engineer, New England Division, Corps of Engineers. John E. Allen is chief of the Engineering Division, to which the Frost Effects Laboratory is attached. The testing program was initiated under the direct supervision of the late Ralph Hansen, former chief of the Frost Effects Laboratory, who was succeeded by Kenneth A. Linell.

Arthur Casagrande of Harvard University, Philip C. Rutledge of Northwestern University and Kenneth B. Woods of Purdue University are consultants on the Frost Investigation program.

The cold-room studies have as their basis the fundamental relationships and tests developed and presented by previous investigators, particularly S. Taber (1 to 8), A. Casagrande (9), G. Beskow (10), H. F. Winn and P. C. Rutledge (11), and A. Ducker (12, 13).

Description of Room and Equipment

The cold room is a walk-in refrigerator, approximately 9 ft. wide, 20 ft. long, and 6. 5 ft. high (in inside dimensions). It is insulated on all sides with 6 in. of mineral wool. It is constructed of 22 separate panels bolted together, enabling reasonably easy dismantling and providing flexibility for enlargement when and if necessary. The panels are faced on both sides with 20-gauge galvanized sheet metal.

A 1-1/2-H. P. water-cooled compressor located outside the cold room wall furnishes the Freon gas refrigerant to two unit coolers mounted at the rear of the cold room. Room temperature is controlled with a Minneapolis-Honeywell bimetallic mercury-bulb thermostat, within limits of plus or minus 2 F. The cold room has been designed to operate between plus 10 and plus 40 Fahrenheit.

Test Cabinets - Nine individual test cabinets insulated on the top and sides with 6 in. of sheet cork are located in the cold room. Refrigerant is provided separately to each by 1/4-H. P. aircooled units. Cooling inside the test cabinets at temperatures ranging from cold-room temperatures to -20 F. is accomplished by passing the refrigerant through single embossed coils inside a 14-in. wide, zinc-coated, copper refrigerating plate fitted to three sides of the cabinet, beginning 13 in. from the bottom and continuing to the top. Temperature in each cabinet is controlled by a De Khotinsky bimetallic helical thermoregulator with an accuracy of plus or minus 1/2-deg. Exterior views of the test cabinets are shown in Figures 1 and 2. A section through the cabinets is shown in Figure 3.

The bottoms of the test cabinets consist of open grill work to allow the cold room temperature to be applied to the bottoms of the soil specimens being tested, while the tops of the samples are being subjected to the cabinet temperatures. During freezing tests, cabinet temperatures are gradually lowered in small daily decrements to produce a rate of frost penetration into the samples simulating natural field conditions. Samples are placed over porous discs in individual receptacles to which water can be

Figure 1. Inside of Cold Room as Seen Through Thermopane Window. Work Bench and Saturating Equipment at Lower Right.

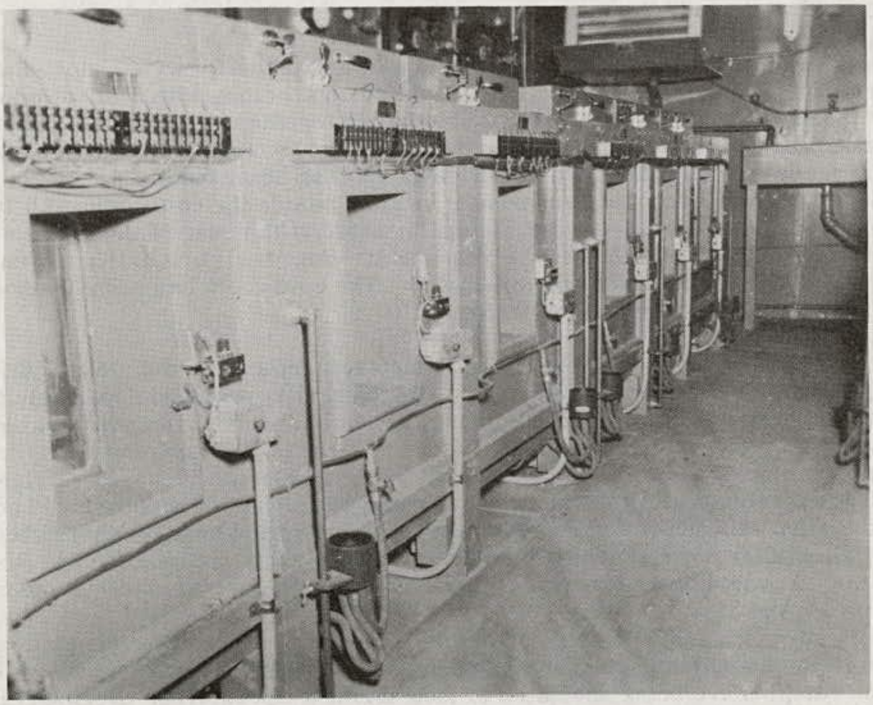
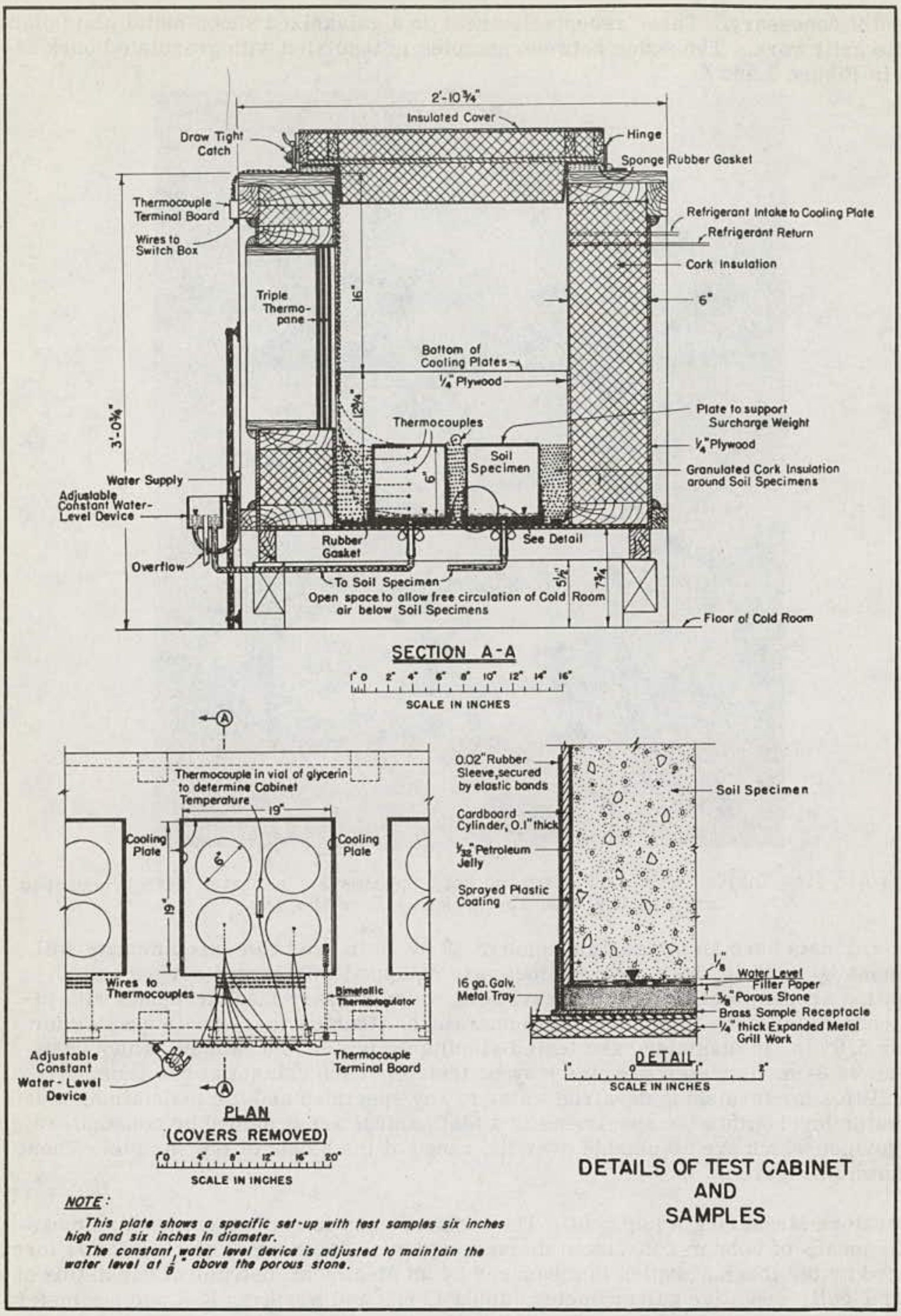


Figure 2. View of Left Side of Cold Room Showing Six Test Cabinets.



NOTE:

This plate shows a specific set-up with test samples six inches high and six inches in diameter.

The constant water level device is adjusted to maintain the water level at $\frac{1}{8}$" above the porous stone.

DETAILS OF TEST CABINET
AND
SAMPLES

Figure 3.

supplied if necessary. These receptacles rest on a galvanized sheet-metal plate placed over the grill work. The space between samples is insulated with granulated cork as shown in Figure 3 and 4.

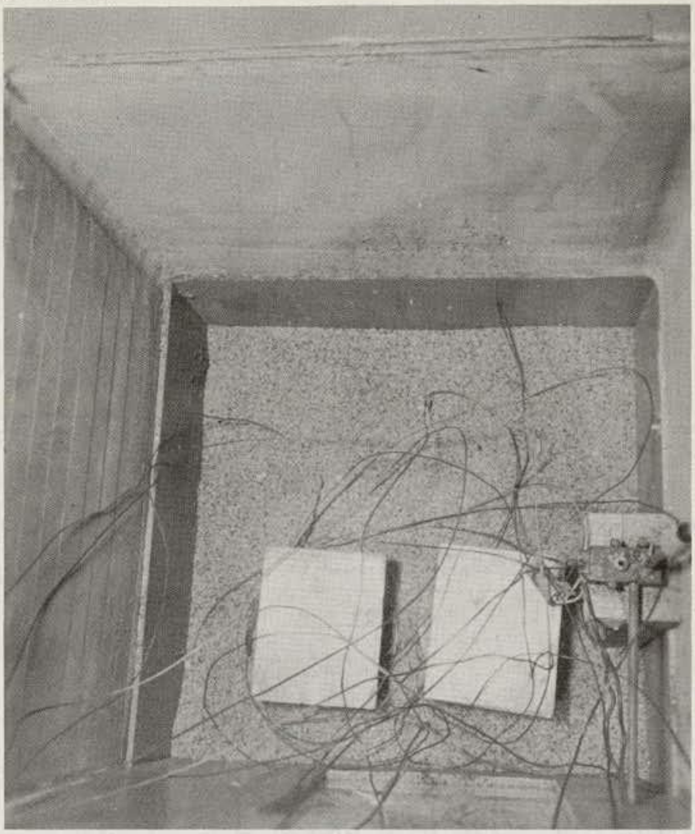


Figure 4. View Inside Cabinet Showing Two Soil Specimens, Insulated with Granulated Cork, in Position for Freezing From the Top.

The cabinets have an inside dimension of 19 by 19 in. and can accommodate soil specimens up to 12 in. high. All cabinets are equipped with hinged covers on top, facilitating access to cabinet for observations and necessary measurements with insignificant disturbance to the cabinet temperature. Usually four specimens, either 4.28 or 5.91 in. in diameter, are tested simultaneously in one cabinet, although as many as 36 3-in. diameter samples may be tested in each cabinet at one time.

Facilities for furnishing de-aired water to any specimen and for maintaining a definite water level within the specimens in a test cabinet are provided by constant-water-level devices which are adjustable over the range of the height of the sample. These are shown in Figure 2.

Temperature Measuring Equipment - The temperatures in soil specimens are measured by means of copper-constantan thermocouples. The thermal electromotive force produced by the thermocouples is measured by an electrical instrument consisting of a standard cell, sensitive galvanometer, and a Leeds and Northrup K-2 potentiometer. Temperatures are read and recorded to 0.1 F. A toggle switchboard enables any one of 100 available thermocouples to be placed rapidly in the measuring circuit. This equipment is conveniently placed in an instrument room outside the cold-room wall.

Each test box is equipped with a glass thermometer which can be read from the outside through the thermopane window. A close check of each cabinet temperature is maintained, however, by means of a thermocouple inserted in a glycerin-filled, rubber-stoppered glass vial, 1 in. in diameter and 3 in. long, suspended near the top of the specimens. The glycerin damps out the temperature fluctuations occurring in the test cabinet during a normal operating cycle of the compressor, thus permitting an average temperature to be read and recorded. The value of the average daily cabinet temperature is determined from the average of several readings with the thermocouple in the vial.

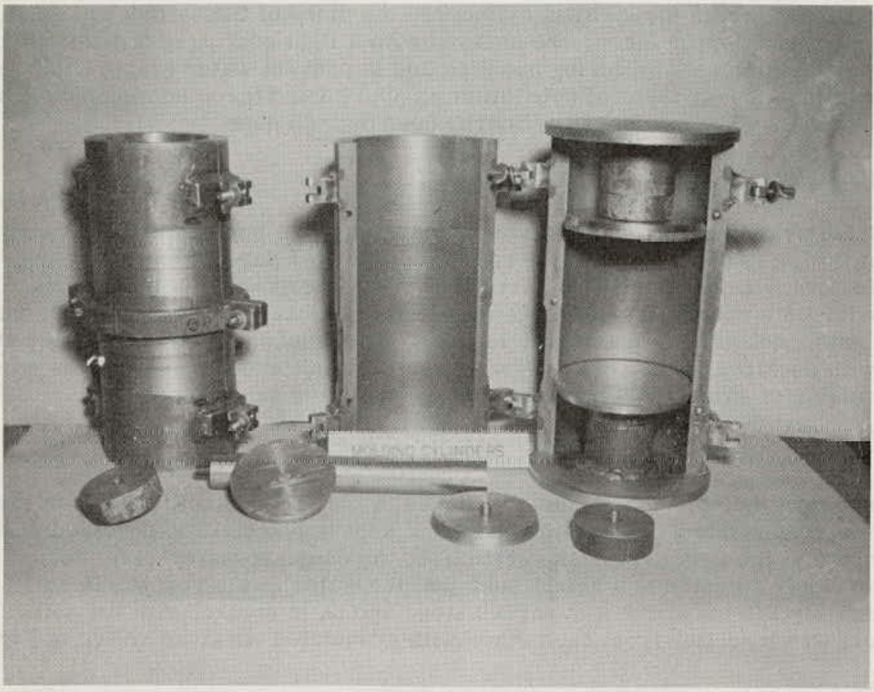


Figure 5. Split Steel Molding Cylinders, 4.28 Inches and 5.91 Inches in Diameter, Respectively. Note Movable Pistons in Cylinder on Right.

Molding of Specimens

The specimens being tested in the cold room for this investigation are prepared in steel cylindrical molds to a 6-in. height. Generally, the fine-grained soils, or those containing grains smaller than 1/4-in., are prepared in a 4. 28-in. diameter mold, and soils with stones up to 2 in. in diameter are prepared in a 5. 91-in. steel mold.

Two methods are used in compacting these specimens to the desired density. Coarse-grained or gravelly soils, such as the sands and gravelly sands, are generally prepared by an adaptation of the Providence Vibrated Density Test method. In the method used, a predetermined dry weight of soil is placed in the steel cylinder and a load of approximately 1,000 lb. applied by a piston at each end and a heavy spring at the top. The soil within the cylinder is compacted by vibrating the cylinder with hammer blows on the sides. Finely grained soils, such as the uniform fine sands, silts, and glacial tills, are prepared in an open-ended steel cylinder by applying pressure to movable pistons at both ends with a Southwark-Emery compression machine, using an average pressure of 1,500 lb. per sq. in. and a maximum 4,000 lb. per sq. in. Some specimens have been prepared by a combination of the two methods described.

Split-molding cylinders were used during the early stages of the testing program but were later replaced by solid-steel cylinders because of the distortion of the cylinder caused by hammer blows. Samples are removed from the latter cylinders by piston pressure at the bottom of the sample; the inside walls of the cylinder are lubricated with a thin coating of petrolatum, followed by paraffin, before molding. The split-molding cylinders, of both diameters, are shown in Figure 5.

Specimens are compacted when moist to densities approximately 95 percent of Modified AASHO density or of Providence Vibrated density, whichever is applicable for the type of soil being tested. Base and subgrade soils obtained from beneath airfield pavements are compacted to approximately natural field densities as shown in Airfield Pavement Evaluation Reports.

After removal from the molding cylinders, the sides of the cylindrical specimen, excluding top and bottom faces, are sprayed with a light coating of a plastic material to hold the sample together during handling and to prevent water evaporation. Over the plastic coating a heavy layer of petrolatum is applied and the specimens are fitted snugly into 6-in. -high cardboard cyliners, open on both ends.

Saturation of Specimens

All specimens thus far tested in the open system have been saturated prior to freezing. Saturation is carried out in the cold room. Filter papers, porous discs 3/8-in. thick, and brass caps (which also serve as sample receptacles in the freezing cabinets) are fitted to both ends of the soil specimen in its cardboard container, using rubber sleeves and bands to seal against air leakage. Specimens are then evacuated and saturated with de-aired water. The degree of saturation for each specimen is computed from weights of sample and container before and after saturating.

Placing Specimens in Test Cabinet

After saturation, the specimens are placed in the test cabinet, the upper cap or receptacle removed and the bottom receptacle kept in place. The de-aired water supply is connected to the bottom of each receptacle, the constant-water-level device having been previously adjusted to a height such that the water in the receptacle will rise to approximately 1/8 in. above the porous stone and be in contact with the soil. The specimens are insulated from each other with granulated cork, as shown in Figures 3 and 4.

Surcharge

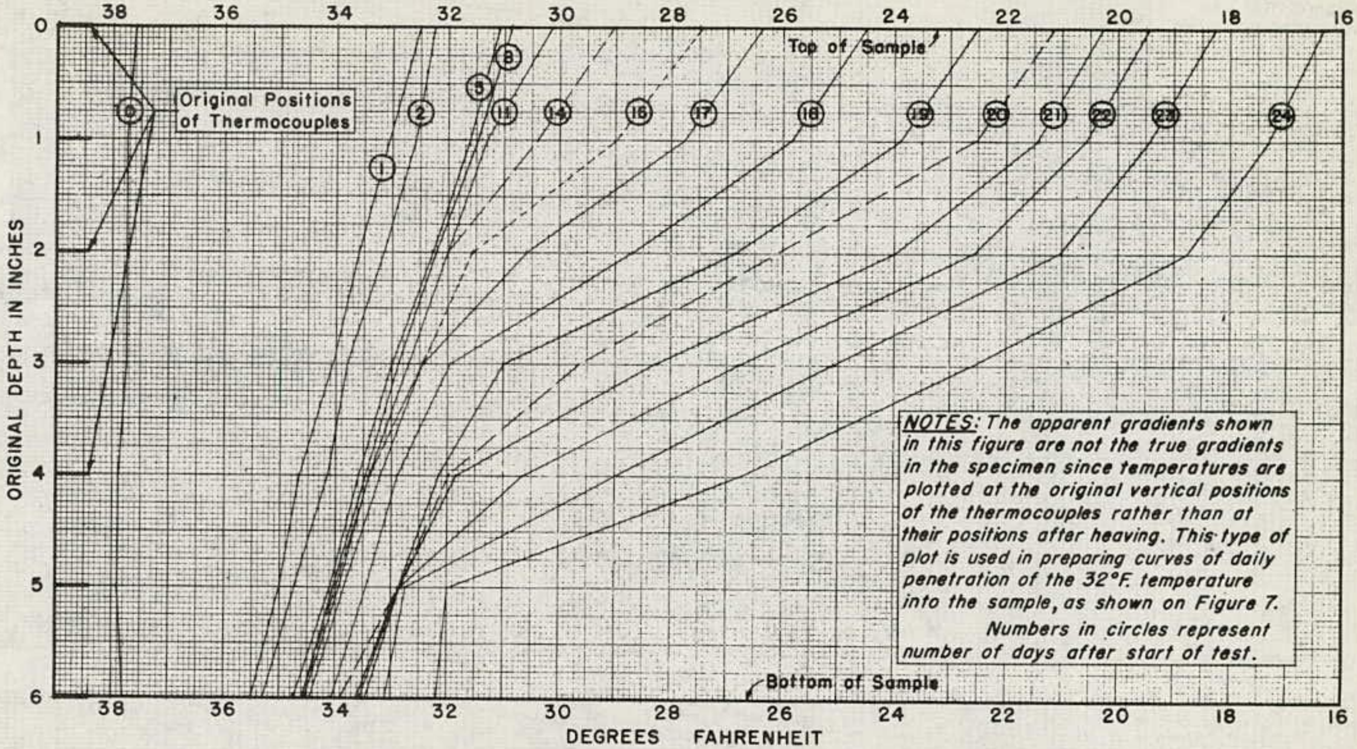
Most specimens are tested under a surcharge load of 0. 5 lb. per sq. in. to simulate field conditions consisting of a 6-in. thickness of pavement and base. A thin layer of bentonite is spread over the top of the sample before the base-plate is set to provide a uniform contact between the steel surcharge-weight baseplate and the soil particles. Four lugs are attached to the base plate to raise the lead weights 1-1/2-in. , so as to permit air circulation over the top of the sample.

Thermocouples in Samples

Thermocouples are placed at 1-in. intervals along the longitudinal axis, including top and bottom, in one of the four specimens in a test cabinet, providing a means of checking the temperatures within the specimen and observing the progress of freezing temperature into the specimen. Two thermocouples are also placed, at the top and bottom, in one additional specimen in each cabinet. The thermocouples are inserted through the side of the specimen in holes punched with a slender pointed instrument. Entrance points are sealed with heavy grease.

Specimen Freezing Procedure

Tests are begun when the specimens in the cabinet have cooled uniformly to cold room temperature of approximately 38 F. , which usually is attained after the specimens have been in place overnight with the cabinet lid open. The freezing test is



NOTES: The apparent gradients shown in this figure are not the true gradients in the specimen since temperatures are plotted at the original vertical positions of the thermocouples rather than at their positions after heaving. This type of plot is used in preparing curves of daily penetration of the 32°F. temperature into the sample, as shown on Figure 7.

Numbers in circles represent number of days after start of test.

PLOTS OF TEMPERATURES IN SAMPLE NH-13 (NEW HAMPSHIRE SILT)

Figure 6.

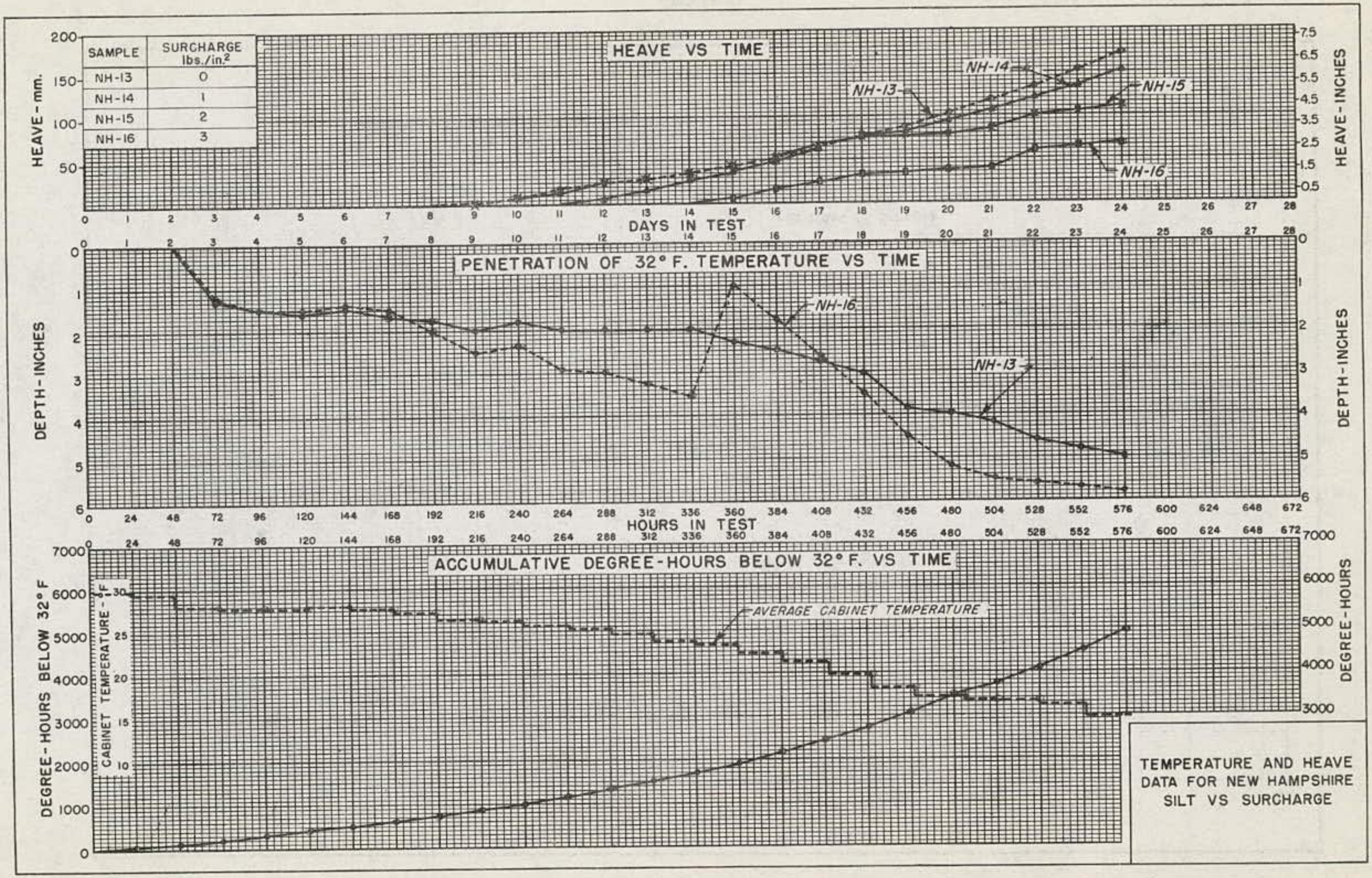

HEAVE VS TIME
HEAVE - mm.
HEAVE - INCHES
SAMPLE
SURCHARGE lbs./in.^{2}
NH-13 0
NH-14 1
NH-15 2
NH-16 3
NH-13
NH-14
NH-15
NH-16
DAYS IN TEST
PENETRATION OF 32° F. TEMPERATURE VS TIME
DEPTH - INCHES
NH-16
NH-13
HOURS IN TEST
ACCUMULATIVE DEGREE-HOURS BELOW 32° F. VS TIME
DEGREE - HOURS BELOW 32° F
DEGREE - HOURS
CABINET TEMPERATURE - °F
AVERAGE CABINET TEMPERATURE
TEMPERATURE AND HEAVE DATA FOR NEW HAMPSHIRE SILT VS SURCHARGE

Figure 7.

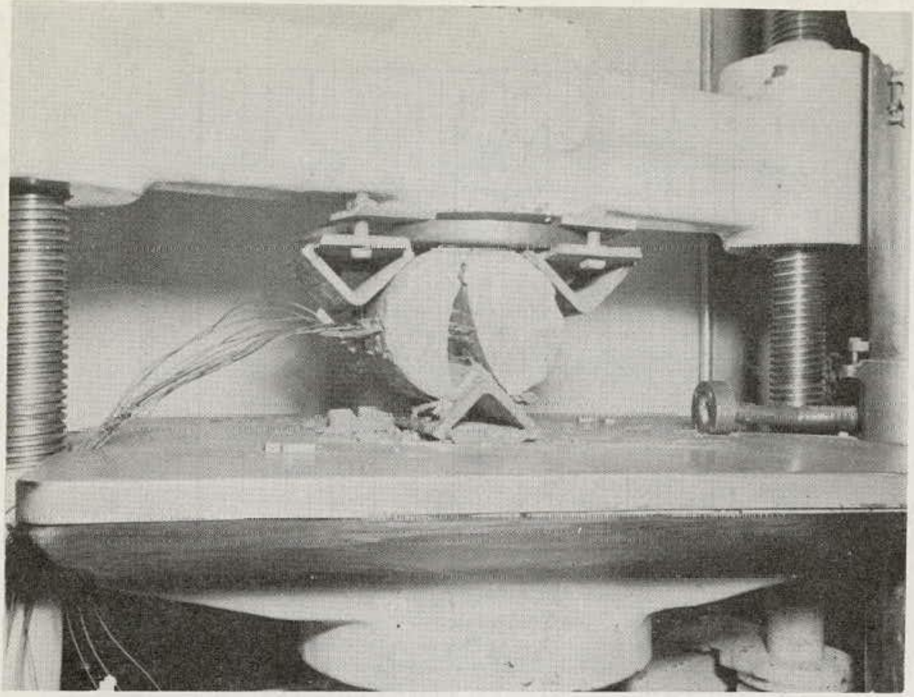


Figure 8. Photograph of Soil Specimen Being Split on the Compression Machine. Note Thermocouple Wires in Place.

started by closing the lid and lowering the temperature in the cabinet to approximately 30 F. for a period of two days and then dropping it to 29 F. for two more days and to 28 F. for two days. After that period, the temperatures within the cabinet are changed only by an amount necessary to maintain the rate of penetration of the 32 F. temperature in the samples at approximately 1/4 in. per day. Temperatures within the soil specimens are read daily and temperatures in the cabinets are adjusted accordingly, depending upon the progress of the 32-F. temperature within the sample. Readings of vial temperatures to determine the average daily cabinet temperature are obtained at intervals of 10 to 15 minutes for a continuous period of 1 to 2 hr. each day. A typical plot showing the daily temperatures in a sample of New Hampshire Silt is shown in Figure 6. The position of the 32-F. temperature in the sample is indicated by the intersection of the apparent temperature gradient and the vertical 32-F. line.

Heave readings are made daily and are read to the nearest half-millimeter. Measurements are obtained with a meter stick placed on a designated point on the surcharge weights over the sample; the reading is taken at the intersection of the stick and a steel bar across the top of the cabinet opening.

A typical plot showing the heave, degree-hours and the penetration of the 32-F. temperature versus time for two New Hampshire Silt specimens is shown in Figure 7.

At completion of test, usually after 24 days, the samples are removed from their containers, weighed to determine the change in water content, and then split longitudinally in a compression machine with the aid of a steel wedge. A photograph of a sample being split is shown in Figure 8. Measurements for amount of heave and observations for the location, distribution, and magnitude of ice-lens formation are made on one-half of the specimen. The remaining half of the sample is photographed and retained for supplemental laboratory tests. A photograph of a typical specimen after splitting is shown in Figure 9. Water contents are obtained for every inch of the depth of the split specimen.

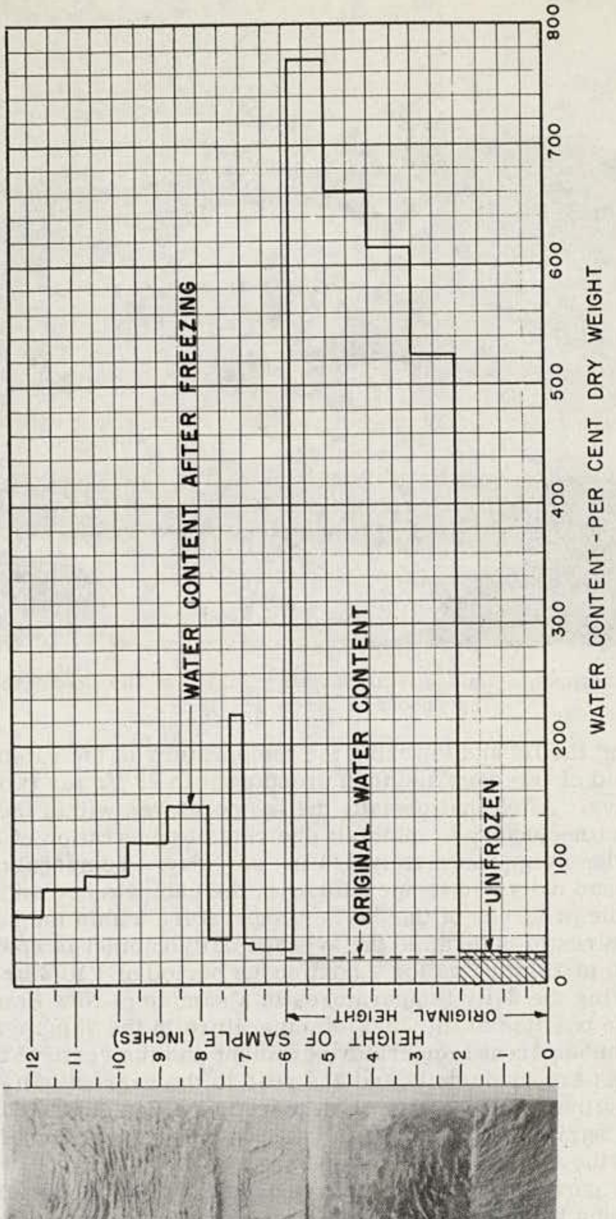
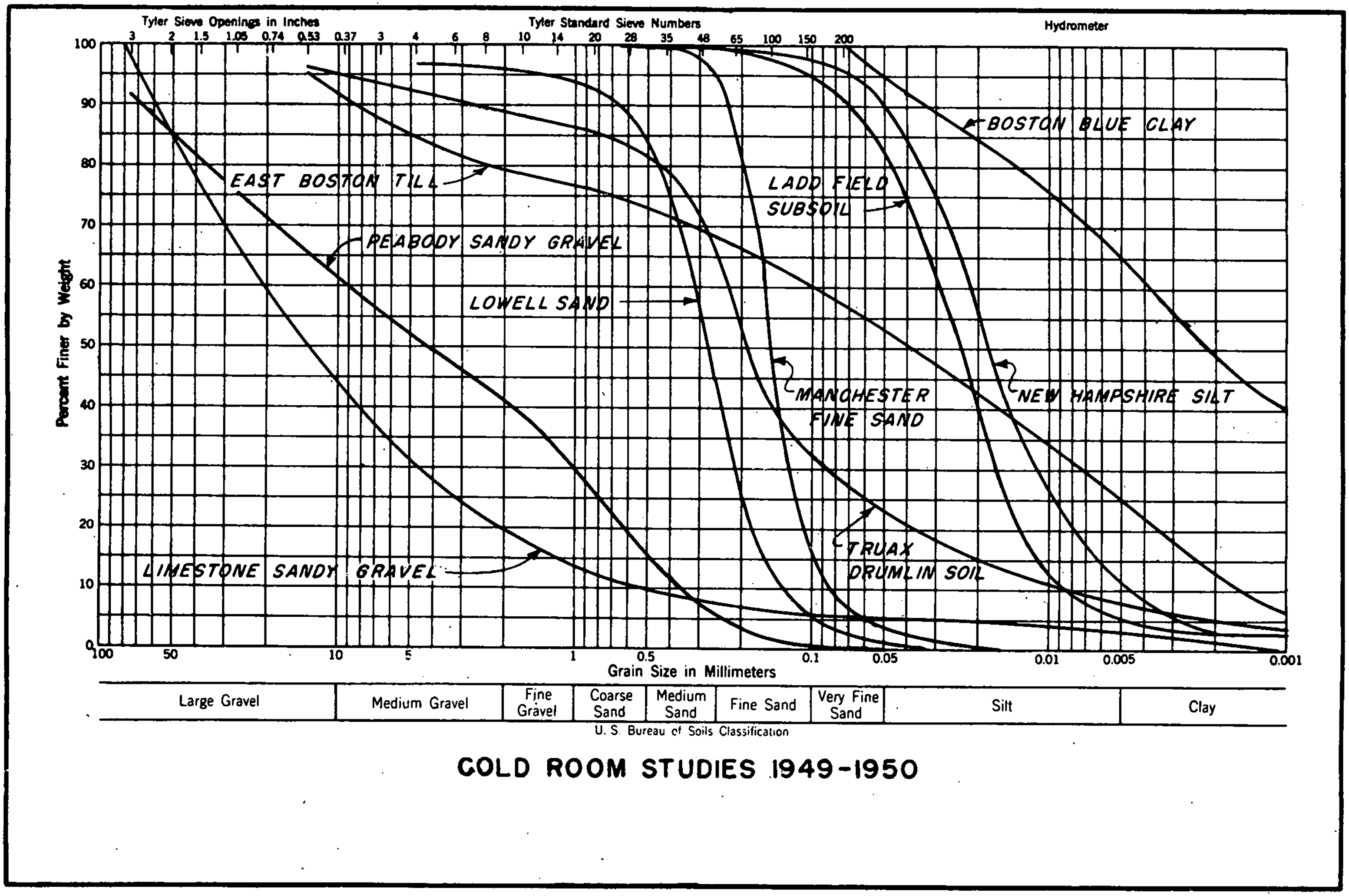


Figure 9. Water Content Versus Depth of Frozen Sample of New Hampshire Silt.



COLD ROOM STUDIES 1949-1950

Figure 10. Gradations of Basic Soils Used for Tests.

Supplementary Tests

The following laboratory tests are performed on all specimens tested, using standard procedures, for correlation, if possible, with heave or rate of ice segregation: (1) gradation, (2) permeability, (3) specific gravity, (4) atterberg limits (if applicable), (5) compaction characteristics (if necessary).

Soils Selected for Tests

The soils selected for testing in this investigation are summarized in Table 1. They consist of two groups: (1) nine basic soils ranging from a well-graded sandy gravel (GW) to a medium plastic clay (CL), chosen for testing both in their natural gradations and in various blends with one another in order to vary the physical characteristics which influence ice segregation, and (2) base and subgrade soils obtained from 11 airfields in the northern United States, to be tested for degree of frost susceptibility for correlation with field data available in the Corps of Engineers Frost Investigation Reports or Pavement Failure Reports. Results of tests on soils in group (2) are not presented in this paper.

The gradations of the nine basic soils in group (1) are given in Figure 10.

Status of Investigations

The studies initiated up to July 1950 are summarized in Table 2, which lists the investigational categories, materials used, and results of basic measurements and tests.

Only elementary analysis of results is attempted at this time. Because of the interrelationships between the numerous factors to be examined, detailed analysis must await completion of the program, so that effects of all factors may be considered together.

It should be noted that the percent heave values obtained in these laboratory tests and reported herein are not necessarily quantitatively the same as would be obtained under natural field conditions. This laboratory-field relationship is presently in process of determination. However, this does not affect the value of the data in showing the relative influence of the variables involved.

Tests on Soil Finer than 0. 02 mm.

These tests are being made to check the validity of the present criteria for frost susceptible soils and to determine, for soils of various gradations, ranging from well-graded gravelly sand to uniform fine sand, the minimum percentages of grains finer than 0. 02 mm. at which ice segregation will occur.

The initial results, summarized at the top of Table 2, are shown in Figure 11 in a plot of percent heave versus percent finer than 0. 02 mm. The data presented indicate considerable variation in heave may result among soils having a given percent finer than 0. 02 mm. Figure 11 shows, for example, that specimens of Peabody, Mass. sandy gravel blended with East Boston Till (sample AGI-5 in Table 2), heaved 10. 9 percent with 3 percent, by weight, finer than 0. 02 mm., whereas some other soils having about the same percent finer than 0. 02 mm. heaved only one or two percent. Even greater differences occur if degrees of compaction are varied.

The effect of the character of the portion of material finer than 0. 02 mm. is clearly brough out in Figure 11, which shows that much greater heave resulted in a specimen of uniform fine sand (Manchester, N. H.) blended with a glacial till (East Boston, Mass.), samples MFS-1 through MFS-4 in Table 2, than in the same sand blended with a silt soil from New Hampshire, samples MFS-5 through MFS-8 in Table 2. Only that portion of the glacial till passing the No. 40 U. S. Standard sieve was used for blending. The great difference in heave, at approximately equal percentages by weight of soil grains finer than 0. 02 mm., is undoubtedly due to the greater

TABLE I
SOILS SELECTED FOR COLD ROOM TEST PROGRAM

TEST IDENTIFICATION SYMBOL	SOURCE	DESCRIPTION	CORPS OF ENGINEERS UNIFORM SOIL CLASSIFICATION	% FINER THAN		MAXIMUM DRY DENSITY
				#200 MESH SIEVE	0.02 mm.	
(a) BASIC SOILS						
LSG	Limestone AFB Limestone, Maine	Sandy gravel base	GW	7	5	139 (2)
AG	Peabody, Massachusetts	Clean sandy gravel (Used to make artificial gradations for blending with other soils. Denoted by symbols AG1 and AG2)	GW	< 1		130 (3)
LS	Lowell, Massachusetts	Well-graded sand (1)	SW	3		110 (3)
MFS	Manchester, New Hampshire	Uniform fine sand (1)	SP	8	1	109 (3)
NH	Goff's Falls, New Hampshire (Referred to as New Hampshire Silt)	Silt	ML	97	58	107 (4)
EBT	Governor's Island, East Boston (Referred to as East Boston Till)	Gravelly, sandy, clayey silt (Glacial Till)	ML-CL	57	44	131 (4)
BC	North Cambridge, Massachusetts (Referred to as Boston Blue Clay)	Clay	CL	99	84	
TD	Truax AFB, Madison, Wisconsin	Drumlin Soil, Silty gravelly sand Base and Subbase (Tested in natural and artificial gradations)	SM	28-30	16-18	139 (4)
LF	Ladd Field, Fairbanks, Alaska	Silt Subsoil	ML	91	37	
(b) TYPICAL BASES AND SUBGRADES FROM VARIOUS AIRFIELDS						
LA	Lowry AFB, Denver, Colorado	Clayey silty sand Subgrade	SM-SC	36-42	24-31	
PA	Pierre Airfield, Pierre, South Dakota	Silty gravelly sand Base	GM-SM	17	9	
CA	Casper AFB, Casper, Wyoming	Silty gravelly sand Base and Silty sand Subgrade	SM SM	23 21-39	15 16-18	
FA	Fargo Municipal Airfield, Fargo, N.D.	Clayey gravelly sand, Base	SC	16	9	
WN	Wendover AFB, Wendover, Utah	Silty sandy gravel Base	GM	14	9	
SF	Sioux Falls Airfield Sioux Falls, S.C.	Silty sandy gravel Base	GM	15	9	
RC	Rapid City AFB (Weaver Base) Rapid City, S.D.	Silty sandy gravel Base	GM	12	8	
HF	Hill AFB, Ogden, Utah	Silty sand Subgrade	SM	27	13	
PT	Patterson Field, Fairfield, Ohio	Clayey, silty, sandy gravel Base	GM-GC	22	15	
CL	Clinton County AFB, Wilmington, Ohio	Clayey, silty, sandy gravel Base	GM-GC	20	14	
SPK	Spokane AFB, Spokane, Washington	Gravelly sand Base	SP-GP	6	4	

NOTES: (1) Blended with New Hampshire Silt and also with East Boston Till to vary the fines.
(2) Providence Vibrated Density on minus 3/4-inch material.
(3) Providence Vibrated Density on minus 1/2-inch material.
(4) Modified AASHO Method.

TABLE II
SUMMARY OF TEST DATA*

Type of Test	Sample Number	Material	Grain Size mm. - % Finer 2.0	0.42 (1)	.074 (2)	0.02	Per Cent Heave (3)	Dry Unit Weight lbs./ft³	Void Ratio (4)	Permeability, k x 10⁻⁴ cm/sec.	Degree of Saturation at Start of Test	Atterberg Limits (5) L.L.	P.I.
Effect of Per Cent Finer Than 0.02 mm. (Open System)	LSG-1	Limestone AFB Sandy Gravel (3/4" max. size)	28	11	4	3	6.6	136.4	0.240	-	100	Non-Plastic	
	LSG-2		31	13	7	5.5	8.2	136.4	0.240	-	100	"	"
	LSG-3		29	14	9	6.5	18.1	136.4	0.240	-	96	22	8
	LSG-4		27	17	11.5	9	14.7	136.4	0.240	-	100	26	7
	AG1-1	Peabody Sandy Gravel Blended with New Hampshire Silt (1/2" max. size)	49	20	5	2	0.2	123.0	0.370	49.0	100	Non-Plastic	
	AG1-2		47	23	9	5	1.3	123.0	0.370	49.0	93	"	"
	AG1-3		45	24	12	7	2.3	123.0	0.371	54.0	87	"	"
	AG1-4		44	27	17	9	2.1	123.0	0.371	350.0	91	"	"
	AG2-5	Peabody Sandy Gravel Blended with New Hampshire Silt (1/4" max. size)	66	31	7	3	2.1	125.0	0.346	7.0	100	Non-Plastic	
	AG2-6		69	32	11	6	7.3	127.0	0.325	2.55	91	"	"
	AG2-7		72	35	13	7	5.8	127.0	0.325	2.05	97	"	"
	AG2-8		70	34	18	10	7.9	127.0	0.325	1.06	86	"	"
	AG1-5	Peabody Sandy Gravel Blended with East Boston Till (1/2" max. size)	51	23	6	3	10.9	133.0	0.268	0.85	100	Non-Plastic	
	AG1-6		47	23	8	5	10.8	133.0	0.270	0.40	94	"	"
	AG1-7		49	25	10	7	12.0	134.2	0.259	0.215	91	"	"
	AG1-8		50	27	13	9	11.0	134.2	0.260	0.138	89	16	3
	LS-1	Lowell Sand Blended with East Boston Till	100	72	6	3	0.9	104.0	0.611	-	96	Non-Plastic	
	LS-2		100	69	8	4	0.5	104.0	0.612	-	87	"	"
	LS-3		100	60	10	6	0.8	104.0	0.615	-	88	"	"
	LS-4		100	78	14.5	11	1.9	104.0	0.618	-	90	"	"
	LS-5	Lowell Sand Blended with East Boston Till	99	69	13	9.5	3.5	108.6	0.548	41.0	99	Non-Plastic	
	LS-6		99	70	19	14.5	6.9	109.5	0.539	10.8	100	"	"
	LS-7		97	75	24	18	21.1	109.5	0.543	4.9	100	"	"
	LS-8		97	77	31	26	25.3	108.5	0.561	2.8	100	"	"
	MFS-1	Manchester Fine Sand Blended with East Boston Till	100	99.5	11	3.5	8.8	107.0	0.564	7.2	100	Non-Plastic	
	MFS-2		100	99.5	17	6	11.9	107.0	0.565	3.05	100	"	"
	MFS-3		100	99.5	17	9.5	10.1	107.0	0.568	4.1	100	"	"
	MFS-4		100	99.5	20.5	11	16.9	107.0	0.570	2.5	100	"	"
	MFS-5	Manchester Fine Sand Blended with New Hampshire Silt	100	99.5	16	7	1.0	107.0	0.560	8.1	99	Non-Plastic	
	MFS-6		100	99.5	18	9	2.1	107.0	0.562	5.7	99	"	"
	MFS-7		100	99.5	22	11	2.7	107.0	0.562	4.25	99	"	"
	MFS-8		100	99.5	27	14	2.5	107.0	0.564	3.00	95	"	"
	MFS-9	Manchester Fine Sand Blended with New Hampshire Silt	100	99.5	29	16	6.6	114.0	0.465	1.47	100	Non-Plastic	
	MFS-10		100	99.5	34	18	9.6	114.0	0.465	0.74	96	"	"
	MFS-11		100	99.5	39	21	5.0	114.0	0.470	0.88	100	"	"
	MFS-12		100	99.5	45	26	16.0	114.0	0.470	0.36	97	"	"
	TD-1	Truax AFB Silty, Gravelly Sand (regraded to vary the fines 3/4" max. size)	81	68	7	2	3.7	125.0	0.348	-	96	Non-Plastic	
	TD-2		83	72	11	6	8.3	127.5	0.321	-	100	"	"
	TD-3		85	76	22	13	10.2	130.0	0.295	-	98	"	"
	TD-4		90	82	36	20	17.1	132.4	0.270	-	100	"	"
	TD-5	Truax AFB Silty Gravelly Sand (TD-5 is a mixture of two subgrade samples. TD-6 is a typical natural subgrade)	88	79	28	16	23.2	129.5	0.300	-	92	Non-Plastic	
	TD-6		88	78	35	21	28.2	128.8	0.315	-	94	14	2
Effect of Degree of Compaction (Open System)	NH-1	New Hampshire Silt	100	99	96	58	60.4	90.0	0.872	0.78	100	27	0
	NH-2		100	99	96	58	68.8	95.0	0.773	0.415	100	"	"
	NH-3		100	99	96	58	72.7	98.4	0.712	0.285	100	"	"
	NH-4		100	99	96	58	126.2	106.0	0.589	0.131	100	"	"
	SBT-1	East Boston Till (3/4" max. size)	80	72	56	44	109.1	110.0	0.565	0.13	100	23	7
	EBT-2		80	72	56	44	145.0	120.0	0.435	0.0046	100	"	"
	EBT-3		80	72	56	44	95.3	125.6	0.371	0.00093	100	"	"
	EBT-4		80	72	56	44	47.7	130.0	0.324	0.00028	100	"	"
	LF-1	Ladd Field, Alaska, Silt Subsoil	100	100	90	37	7.8	83.8	1.040	2.1	98	32	0
	LF-2		100	100	90	37	11.2	90.0	0.899	1.2	96	"	"
	LF-3		100	100	90	37	25.5	94.4	0.811	0.86	100	"	"
	LF-4		100	100	90	37	36.5	98.4	0.737	0.64	100	"	"
	LSG-5	Limestone AFB Sandy Gravel (3/4" max. size, graded to contain approximately 3% finer than 0.02 mm.)	28	9	3	2	13.8	123.0	0.374	-	91	Non-Plastic	
	LSG-6		30	10	4	3	8.3	130.0	0.300	-	98	"	"
	LSG-7		32	11	4	3	18.3	136.7	0.237	-	100	"	"
	LSG-8		33	12	5	4	14.6	136.7	0.237	-	97	"	"
	TD-7	Truax AFB Silty Gravelly Sand (3/4" max. size)	88	78	35	21	7.4	119.3	0.423	-	91	14	2
	TD-8		88	78	35	21	13.0	125.6	0.350	-	90	"	"
	TD-9		89	78	35	21	22.0	130.0	0.303	-	100	"	"
	TD-10		88	78	35	21	14.7	134.0	0.265	-	98	"	"
	MFS-13	Manchester Fine Sand Blended with East Boston Till	100	99.5	7	4	3.8	106.4	0.573	7.1	100	Non-Plastic	
	MFS-14		100	99.5	13	6	3.4	105.0	0.594	9.2	100	"	"
	MFS-15		100	99.5	14	6	5.7	110.0	0.520	2.08	100	"	"
	MFS-16		100	99.5	14	7	6.5	110.6	0.513	2.30	100	"	"
Effect of Size and Per Cent Stone (Open System)	LSG-9	Limestone Sandy Gravel (Graded to contain approx. 3% 0.02 mm. with max. sizes as shown) 2"	27	9	4	3	10.7	137.3	0.230	-	100	Non-Plastic	
	LSG-10	1"	27	9	4	3	14.0	135.4	0.248	-	93	"	"
	LSG-11	½"	32	12	5	4	18.5	135.2	0.250	-	100	"	"
	LSG-12	¼"	40	15	7	4	22.3	133.7	0.264	-	95	"	"
	LSG-13	Limestone Sandy Gravel (Samples "scalped" to max. sizes as shown) 2"	24	9	6	5	33.1	134.5	0.256	-	100	24	6
	LSG-14	1"	31	12	7	6	32.0	133.9	0.263	-	96	"	"
	LSG-15	½"	37	14	9	7	17.4	135.0	0.254	-	92	"	"
	LSG-16	¼"	55	23	15	13	56.7	133.9	0.265	-	99	"	"
	TD-11	Truax AFB Silty Gravelly Sand (Coarse aggregate added to give max. sizes as shown) 2"	48	42	18	10	3.8	130.0	0.310	-	92	14	2
	TD-12	1"	65	56	24	14	9.8	130.5	0.302	-	100	"	"
	TD-13	½"	80	69	30	17	10.8	129.2	0.313	-	85	"	"
	TD-14	¼"	96	83	36	20	16.6	128.2	0.319	-	86	"	"
Ice Segregation in Saturated Clay in a Closed System	BC-1	Undisturbed Boston Blue Clay	100	100	100	84	9.5	83.6	1.030	-	100	43	22
	BC-2		100	100	100	84	11.6	83.3	1.037	-	100	"	"
	BC-5		100	100	100	84	8.1	79.4	1.138	-	100	"	"
	BC-6		100	100	100	84	14.3	79.1	1.146	-	100	"	"
Effect of Surcharge (Open System)	NH-13	New Hampshire Silt (Surcharge as shown, lbs/in²) 0	100	99	96	58	155.1	104.7	0.609	0.147	100	27	0
	NH-14	1	100	99	96	58	138.4	105.0	0.605	0.146	100	"	"
	NH-15	2	100	99	96	58	76.7	105.6	0.595	0.135	100	"	"
	NH-16	3	100	99	96	58	50.0	105.6	0.595	0.135	100	"	"

*This table presents data available up to 1 July 1950. Additional tests are in progress.

(1) U.S. Standard Sieve No. 40
(2) U.S. Standard Sieve No. 200
(3) Based on original height of frozen portion
(4) Ratio of volume of voids to volume of solids
(5) Tests made on material passing the U. S. Standard No. 40 Sieve

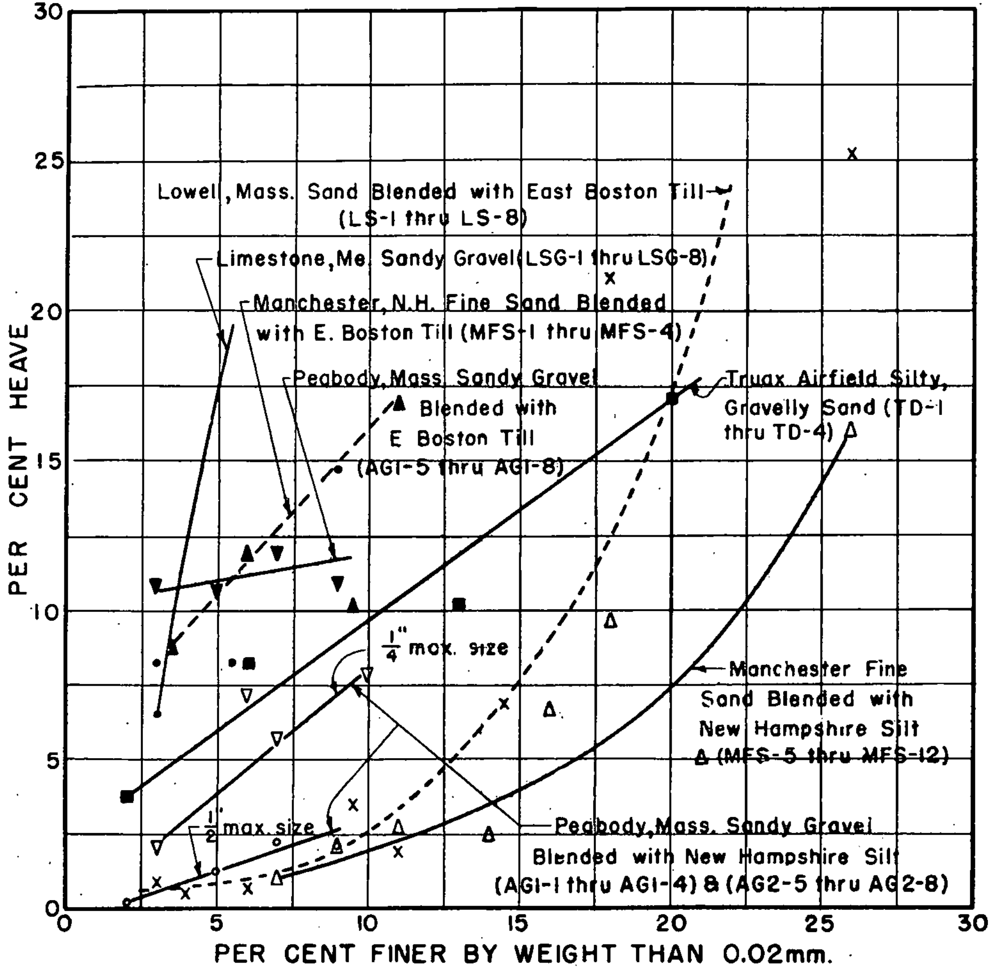


Figure 11. Effect of Percent Finer Than 0.02 mm. Size on Percent Heave

percentage of collodial-clay sizes present in the glacial till. It is also recognized that the chemical composition of these sizes exerts a great influence on ice segregation (13). Tests are being continued with other soils blended with fines of varied character and composition to provide sufficient data for comprehensive analysis. A micropetrographic and chemical analysis will be made of all soils tested.

In general, the test results available in this phase of the investigation indicate that the presently used criterion, which states that well-graded soils with less than 3 percent, by weight, finer than 0.02 mm. are not frost susceptible, has proven to be a useful rule but that other factors, such as the character of the fines, must be considered in recognizing frost susceptible soils with accuracy or in predicting the intensity of ice segregation which may be expected.

Effect of Compaction

In a given soil, dry density (dry unit weight) is a soil property which may be used to study the combined effects of such physical soil characteristics as permeability, void size, and internal structure on ice segregation. Increasing the dry unit weight of a soil by compaction decreases the void size but also decreases the permeability, thereby controlling the rate of growth of ice lenses. Tests for frost action conducted on sandy clay mixtures by Winn and Rutledge (11) indicate "there is one density at which frost action occurs most readily, while at higher or lower densities the action is not so pronounced . . . . . Apparently there is one arrangement of the soil particles, which might be called the critical density, that results in the most favorable combination of capillarity and permeability."

The data thus far available from tests at the Frost Effects Laboratory on the effect of degree of compaction on ice segregation are presented as the second main grouping in Table 2 and are plotted in Figure 12. The data in this figure indicate that heaving increases with increase in original dry density in silt soils such as New Hampshire Silt and Ladd Field, Alaska, subsoil. The tests on East Boston Till show increased heaving with increase in density up to 120 lb. per cu. ft., followed by a rapid decrease in heaving with further increase in density. A similar result is also shown for Truax Drumlin material. However, in each of the latter two cases the indicated trend is dependent upon the position of a single point and additional test results are needed. The tests on the sandy gravel from Limestone show an apparent reverse trend, but the results for this material have thus far proved erratic due to large variations in percent heave with small changes in percent of 0.02 mm. material. It is expected that the reverse trend will be disproved by obtaining additional test points.

It is apparent that many additional tests are needed before final conclusions can be drawn concerning the effect of degree of compaction on percent heave. However, Figure 12 shows that percent heave may either increase or decrease with increase in original density and the effect of density change may be large or small, depending on the density range investigated and the characteristics of the particular soil.

Effect of Size and Percent Stone

In applying the present criteria for frost susceptible soils, questions have frequently arisen concerning the effect of large stones in soil gradations on ice segregation. The inclusion or exclusion of even a small number of stones (say 2 to 4 in. in diameter) in a 25-lb. sample can affect considerably the indicated overall percent, by weight, of sizes finer than 0.02 mm. It may appear that ice segregation should not be affected, since the matrix of the soil (minus 1/4-in. material) has not been altered. However, the presence of stones in a soil gradation may reduce frost heave because of the increased rate of frost penetration due to the higher thermal conductivity of rock, the smaller amount of volumetric and latent heat in the soil mass, the reduced volume of frost susceptible material, and the reduced overall permeability.

Data from tests on four specimens of sandy gravel from Limestone, Maine, (samples LSG-9 to LSG-12, inclusive, in Table 2) show decrease in heave with increase in the maximum-sized stone from 1/4-in. to 2 in. in diameter, the percentages finer than 2.0 mm. ranging from 27 to 40, and the percentages finer than 0.02 mm. equal to 3 and 4. The data obtained from tests of four specimens of pit-run sandy gravel from Limestone, Maine, (samples LSG-13 through LSG-16) wherein the maximum stone sizes were decreased (scalped) each time, allowing the percentage of fines to increase, were inconsistent. However, tests results on four specimens of Truax Drumlin material (samples TD-11 through TD-14) show progressive increase in percent heave with decrease in maximum size and percentage of stone.

Additional tests are being conducted to determine the effect of adding various sizes and percentages of stone to silt and clay subgrade soils.

Saturated Clay in Closed System

Ice segregation can occur only if water can be made available to the growing ice lens. It is possible for such segregation to occur in very fine-grained soils which are very remote from a water table by the withdrawal of pore water from below the zone of freezing, the resulting reduced soil moisture content not going below the shrinkage limit. Sufficient tensile force is developed in the pore water in the process of ice segregation to consolidate the soil, the reduction in volume being equal to the volume of water removed. In such cases heaving may be negligible, although sizeable ice lenses may be formed. The release of water from such lenses in the frost melting period may thus cause subgrade weakening even though there is relatively small pavement heave during the preceding freezing period.

Results of tests on four cylindrical samples, 6 in. high, of undisturbed Boston Blue Clay, 100-percent saturated and tested in a closed system, are given near the bottom of Table 2. All specimens showed considerable ice segregation. The measured amount

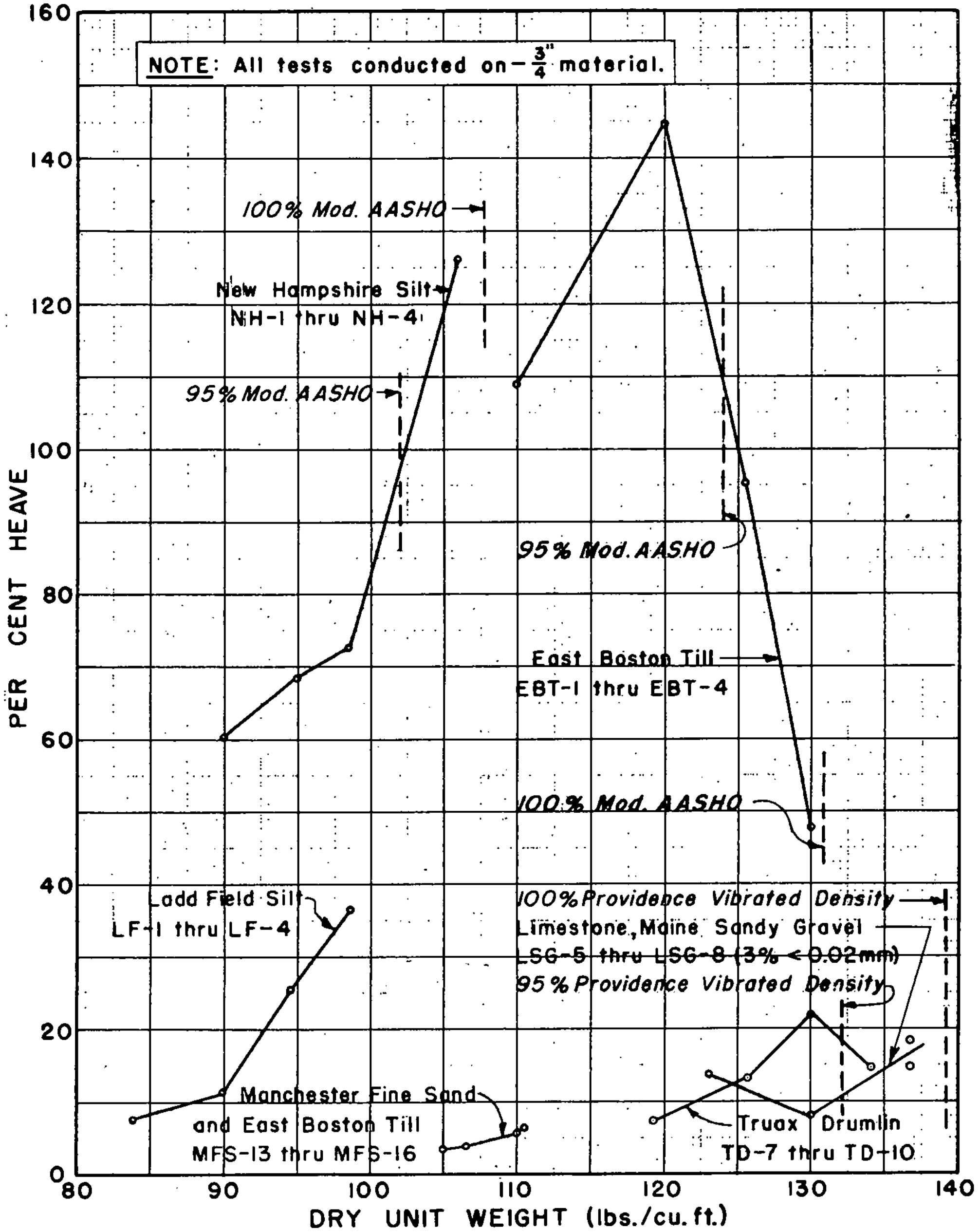


Figure 12. Effect of Degree of Compaction on Percent Heave.

of heave ranged from 8 to 14 percent. It was observed, however, that the lower portions of the samples had become quite dry and brittle, the diameter having shrunk from an average of 4.27 to an average of 4.04 in. in one of the samples.

Effect of Surcharge

A series of tests has been initiated to determine the effect of intergranular pressure on ice segregation in soils of various gradations. Results of four tests completed to date on specimens of New Hampshire Silt are shown at the bottom of Table 2. Surcharge loads of 0, 1, 2, and 3 lb. per sq. in. were used, corresponding approximately to 0-1-2- and 3-ft. thicknesses of pavement and high density base. These preliminary results indicate that for this silt soil heaving decreases with increase in surcharge load. However, much additional testing and study is needed. Tests on several other soils are now in progress.

Penetration of 32 F. Temperature

The rate of penetration of the 32 F. temperature into the samples was obtained from the daily temperature records, plotted as shown in Figure 6. In plotting the penetration versus depth, from these records, as shown in the middle plot of Figure 7, a peculiarity common to practically all specimens was observed. The 32-F. temperature, after progressing into the sample for a distance of 2 to 4 in., suddenly receded, generally from 1 to 2 in., before proceeding downward again. This is illustrated by the curve for sample NH-16 on Figure 7, between 336 and 360 hr. Sample NH-13, also shown on Figure 7, was one of the few specimens which did not show this phenomenon. At first, this dropback in temperature was believed to be the result of either instrument or observational errors or of fluctuation of temperature within the cold room or freezing cabinets. Regular recurrence of the phenomena and close check of temperature measuring equipment indicate, however, that the temperature recession is the result of changes occurring within the soil specimen during the freezing process. It is believed that this phenomenon is due to the release of latent heat of fusion when the soil moisture begins to freeze at the top of the sample as a result of some triggering action, after having become subcooled to below the normal freezing point. It was also observed that heaving commenced only after the temperature recession had occurred.

Temperature Between Frozen and Unfrozen Soil

The freezing point of soil moisture in the various soils tested was obtained by determining the temperatures at the boundary of the frozen and unfrozen layers. These temperatures were obtained by interpolation between thermocouple readings taken immediately prior to removal of the samples from the cabinets at the completion of the tests. The temperature data indicate that soil moisture, in the soils tested, freezes at temperatures ranging from 29.1 F. to 32 F., with the lower values occurring in silty and clayey soils.

Equipment and Test Procedures

It is concluded that the equipment and test procedures devised are satisfactory for the study of ice segregation in soils and that the results may be utilized to establish or modify design criteria. It is also believed that the procedures will be useful for estimating the probable action of specific soils under field conditions. Full evaluation of the testing system must await completion of tests on the base and subbase materials from the considerable number of airfields at which relatively complete observations have been made of actual frost action over several winters and whose frost characteristics under natural conditions are thus known.

Bibliography

1. Taber, S.,"The Growth of Crystals Under External Pressure," American Journal of Science, Vol. 16, pp. 532-556, 1916.
2. Taber, S., "Pressure Phenomena Accompanying the Growth of Crystals," National Academy of Sciences, Vol. 3, pp. 297-302, April 1917.
3. Taber, S., "Ice Forming in Clay Soils Will Lift Surface Weights," Engineering News-Record, Vol. 80, No. 6, pp. 262-263, Feb. 7, 1918.
4. Taber, S., "Surface Heaving Caused by Segregation of Water Forming Ice Crystals," Engineering News-Record, Vol. 81, pp. 683-684, 1918.
5. Taber, S., "Frost Heaving," Journal of Geology, Vol. 37, No. 5, pp. 428-461, July-August, 1929.
6. Taber, S., "Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements," Public Roads, Vol. 11, No. 6, pp. 113-132, August 1930.
7. Taber, S., "The Mechanics of Frost Heaving," Journal of Geology, Vol. 38, pp. 303-317, 1930.
8. Taber, S., "Discussion on Frost Heaving," (Abstracted), Proceedings, Highway Research Board, Vol. 11, Part I, pp. 173-177, 1932.
9. Casagrande, A., "Discussion of Frost Heaving," Proceedings, Highway Research Board, Vol. 11, pp. 168-172, 1932.
10. Beskow, G., "Soil Freezing and Frost Heaving; with Special Reference to Highways and Railroads," Statents Vaginstitut, Meddelande 48, Swedish Geological Society, Series C., No. 375, Stockholm, 1935. 242 pp. (Translated by J. O. Osterberg and published by Northwestern University, Evanston, Ill., November 1947.)
11. Winn, H. F. and Rutledge, P. C., "Frost Action in Highway Bases and Subgrade," Purdue University, Engineering Bulletin Vol. XXIV, No. 2 (Research Series No. 73) Highway Research Bulletin No. 4.
12. Ducker, A., "Experimental Study of Effect of Texture on Freezing of Non-cohesive Soils; Freezing of Texture Fractions of Soils and Their Mixtures," Forschungsarbeiten aus dem Strassenwessen, Bulletin 17, 1939. (In German).
13. Ducker, A., "Soil Colloids and Their Behavior when Subjected to Frost Action" (Uber "Bodenkolloide" und ihr Verhalten bei Frost), Der Bauingenieur, pp. 235-237, August 1942. (Translated by Engineer Department, Research Center, U. S. Waterways Experiment Station, Vicksburg, Mississippi. TR. 141. 44-40).