CORPS OF ENGINEERS
U.S. ARMY

FROST INVESTIGATIONS

FISCAL YEAR 1951

COLD ROOM STUDIES

SECOND INTERIM REPORT OF INVESTIGATIONS

PREPARED BY
FROST EFFECTS LABORATORY
CORPS OF ENGINEERS, U. S. ARMY
NEW ENGLAND DIVISION, BOSTON, MASS.
FOR
OFFICE OF THE CHIEF OF ENGINEERS
AIRFIELDS BRANCH
ENGINEERING DIVISION
MILITARY CONSTRUCTION

JUNE 1951

IN TWO VOLUMES

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SYNOPSIS

This report presents the results of cold room studies of frost action in soils which were performed between February 1950 and the end of Fiscal Year 1951 by the Frost Effects Laboratory, New England Division, Corps of Engineers. The investigations are being conducted for the Airfield Branch, Office of the Chief of Engineers, Department of the Army, as part of a continuing program of frost investigations aimed toward establishing and improving engineering design and evaluation criteria for roads, highways and airfield pavements constructed on soils which are subject to seasonal freezing and thawing. The studies are being conducted chiefly to determine the effects of each of the individual factors which influence ice segregation in soils, including gradation, per cent finer than 0.02 mm., per cent and size of aggregate greater than 2.0 mm., degree of compaction, surcharge pressures, initial degree of saturation in a closed system, alternate cycles of freeze-thaw, admixtures, capillarity, condensation, proximity of water supply, rate of penetration of 32°F. temperature, mineral composition of fine soil fraction, and permeability.

To investigate the effects of several of the factors listed, tests have been performed on a large number of natural soils of various types, obtained from several locations in the Northern United States and Alaska, and on specimens prepared by blending various fine and coarse soil fractions in proportions to give desired investigational gradations. The purpose of this report is to consolidate and summarize all test results obtained to date to permit review by the Board of Consultants and to aid in formulating the direction and scope of the future investigations.

Available test data from the phases of the investigation which are substantially complete indicate (1) The intensity of ice segregation in soils is dependent not only on the per cent of grains finer than 0.02 mm. but also on the grain size distribution and/or physico-chemical properties of these fines; (2) Fine soil fractions with a high percentage of fine clay sizes appear to be more potent than silt sizes in producing ice segregation in soils of near borderline frost susceptibility; (3) Soils in similar soil groups, when classified by the Department of the Army Uniform Soil Classification System, show approximately the same rates of heave for corresponding percentages finer than 0.02 mm.; (4) The percentage of material finer than 0.02 mm. for which a given rate of heave is obtained increases progressively with each group from Sandy Gravel and Gravelly Soils (GW) toward the fine-grained soils, Gravelly Sandy Clay and Clay (CL); (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 already existing in the voids of the soil underlying the surface of freezing; and (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 inches per day. However, the heave per unit depth of frozen material is in inverse proportion to the rate of penetration of the freezing temperature.

PART I. INTRODUCTION

1-01. Background and Purpose. 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 non-uniform heaving of the pavements, loss of pavement 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, define

define pumping, and subsequent pavement break-up 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 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", dated June 1951, unifies and summarizes the principal results of observations and tests made and presents design and evaluation criteria for both airfield and highway pavements resulting from a study of the accumulated data.

The field studies have shown a need for comprehensive laboratory investigations, under controlled conditions, to study the effect of each of the variables of soil characteristics, water supply, and temperature conditions 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. Studies which are being conducted with its specially-designed facilities will give a clearer understanding of frost action in soils, and will result in the development of improved criteria for the design and evaluation of pavements, not only of airfield runways, taxiways and aprons, but also of roads and highways. An unpublished report entitled "Interim Report of Cold Room Studies", dated July 1950, contains the results of cold room studies which had been completed up to 15 June 1950.

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 their behavior under freezing conditions. The more precise determination of degree of frost susceptibility thereby made possible will aid in the selection of satisfactory base materials which will not lose strength during frost melting. 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 laboratory tests.

1-02. Overall Program of Cold Room 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 planned program includes tests to determine the following:

a. Effect of particle size distribution on ice segregation in soils.

b. Effect of degree of compaction on ice segregation in frost susceptible soils.

c. Effect of surcharge or overburden pressure on ice segregation in frost susceptible soils.

d. Effect of per cent and size of aggregate greater than 2.0 mm. in soil gradations on ice segregation.

e. Effect of initial degree of saturation on ice segregation in a frost-susceptible soil in a closed system, i.e., a system in which no water is made available to the bottom of the sample during freezing.

f. Effect of alternate freezing and thawing on permanence of initial compacted dry density and on strength of soils.

g. Relationship between ice segregation and soil properties such as void ratio, permeability, and capillarity.

h. Effect of admixtures in preventing or retarding the formation of ice lenses in frost-susceptible soils.

i. Frost susceptibility or non-frost susceptibility of base and subgrade soils from various airfields in the northern United States.

j. Effect of proximity of water table on ice segregation in frost-susceptible soils.

k. Effect of frost melting on strength characteristics of soils, including time required for weakened soils to return to normal strength after thawing.

l. Effect of the chemical nature of the soil minerals and of the dissolved salts in the pore water on ice segregation.

m. The nature of physical laws governing ice segregation in soils, an understanding of which is needed to aid the development of design criteria.

1-03. Scope of Studies Presented in This Report. This report presents the results of all cold room investigations conducted since the initiation of the program in February 1950, up to the end of Fiscal Year 1951. The investigation has dealt exclusively with Items (a) through (i) of the "Overall Program of Cold Room Tests" listed in Paragraph 1-02, above. Special equipment has been designed and constructed to accomplish Item (j) but testing is not scheduled to commence until Fiscal Year 1952.

Items (k) through (m) of the previously listed program either have not been initiated or are in a preparatory stage and are, therefore, not covered in this report.

1-04. Authorization. Frost Investigations during Fiscal Year 1951 were authorized and funds allocated by Directive NED MIC 51-2, dated 11 October 1950, from the Chief of Engineers to the Division Engineer, New England Division. Instructions and Outline for Cold Room Studies were transmitted as inclosure with letter, dated 23 October 1950, from the Chief of Engineers to the Division Engineer, New England Division, Subject: "Instructions and

Outlines for Investigational Projects, Fiscal Year 1951".

1-05. Presentation of Report. The results of the cold room studies completed up to the end of Fiscal Year 1951 are presented in two volumes consisting of the following:

Volume 1: The main report entitled "Cold Room Studies, Second Interim Report of Investigations" in which the results of the studies are summarized and discussed.

Volume 2: Appendices to the main report entitled "Appendix A: Equipment and Test Procedures", in which are described the cold room, freezing equipment, specimen preparation, and test procedures; and "Appendix B: Investigational Data", in which are included plots of freezing-temperature penetration, heave and water content distribution for all samples, and tabulations of the basic test conditions and results.

The items investigated to determine the effect of Variable or relationship of the following on the intensity of ice segregation are grouped in the following order of presentation: poorly written

a. Per cent finer than 0.02 mm.
b. Degree of compaction
c. Surcharge
d. Per cent and size of aggregate greater than 2.0 mm.
e. Initial degree of saturation (closed system)
f. Alternate cycles of freeze-thaw
g. Admixtures
h. Height of Sample
i. Capillarity and condensation
j. Rate of freezing-temperature penetration

k. Mineral constituents in fine soil fraction

l. Permeability

m. Natural soil gradations

The results of the investigation are summarized in this report in the order listed and the pertinent test data for each sample are presented in Tables B1 through B14 in Appendix B, Volume 2. The plates containing the heave, temperature penetration, and water content distribution data for each sample are cross-referenced on Tables B1 through B14.

1-06. Definitions. Description of tests and analysis of results involve specialized use of certain terms ~~and words~~. Definitions of these words and terms as employed in this report are as follows:

Frost heave is the raising of ~~the~~ a 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.

non-Frost susceptible

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 per cent 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 per cent 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

such soils separately, because of their rarity and tendency to occur intermixed with other soils.)

Frost action is a general term used in reference to freezing of moisture in materials and the resultant effects on 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.

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

Degree hour is a variation of one Fahrenheit degree from 32°F. for a period of one hour. The degree hour is negative if below 32°F. and positive if above 32°F.

Closed system is a test condition in which no free water is made available from outside the specimen during the freezing process.

Open system is a test condition in which free water is made available from outside the specimen during the freezing process.

1-07. Acknowledgements. The Frost Investigations, of which these Cold Room Studies are a part, are being conducted by the Frost Effects Laboratory for the Airfields Branch, Engineering Division, Military Construction, Office of the Chief of Engineers. The studies are under the administration of Mr. Gayle MacFadden, Chief, Airfields Branch, assisted by Mr. Thomas B. Pringle, Head, Runways Section, and by Mr. Frank Hennion.

Colonel H. J. Woodbury is the Division Engineer, New England Division, Corps of Engineers, U. S. Army. Mr. John E. Allen is Chief of the

Engineering Division to which the Frost Effects Laboratory is attached. Mr. Kenneth A. Linell is Chief of the Frost Effects Laboratory. The studies are under the direct supervision of Mr. James F. Haley, Assistant Chief, Frost Effects Laboratory.

Dr. Arthur Casagrande of Harvard University, Dr. P. C. Rutledge of Northwestern University and Prof. K. B. Woods of Purdue University are the investigational consultants.

Dr. T. William Lambe of the Massachusetts Institute of Technology performed tests to determine the mineral composition and surface area of the minus 200 mesh fraction of several of the soils. Dr. Lambe also supplied the materials and rendered technical assistance in the cold room tests to determine the effectiveness of admixtures of calcium acrylate in preventing or retarding ice segregation in frost susceptible soils.

PART II - FROST CLASSIFICATION, SOILS AND PROCEDURES

2-01. General. The Frost Investigations which had been accomplished in this program prior to the initiation of the Cold Room Studies were principally field studies at airfield sites located throughout the northern United States. From the results of these field studies and empirical knowledge gathered by other investigators, the existing Corps of Engineers design criteria for frost conditions (Chapter 4, Part XII, Engineering Manual, Military Construction) was evolved. Field investigations at even a large number of sites do not offer sufficiently diversified conditions of soil, ground water, and temperature; also, since the variables effecting frost action cannot be controlled, it is difficult to isolate the variables being investigated.

The cold room studies, in which conditions can be controlled and varied as desired within small limits, have been designed to simulate field conditions as closely as practical. The soils are generally compacted to average field density conditions and the rate of penetration of the freezing temperature into the samples averages 1/4 inch per day, which is considered to be representative of field conditions. The majority of the tests performed in this investigation have had an unlimited supply of water available at the base of the specimens, which is a severe condition insofar as water availability is concerned and which generally results in virtually the maximum rate of ice segregation and heave which the soils could exhibit under natural field conditions. The results are therefore not usually quantitatively applicable. The cold room test procedures are considered satisfactory, however, for determining the relative degree of frost susceptibility of of various soils.

Rutledge

2-02. <u>Measures of Frost Susceptibility.</u> To classify soils tested in the cold room as to their degree of frost susceptibility, Dr. A. Casagrande has proposed the following criteria:

Total Per Cent Heave	Frost Susceptibility Classification
0 - 5	Negligible
5 - 10	Very Low
10 - 20	Low
20 - 40	Medium
40 - 80	High
> 80	Very High

The value of the total <u>per cent heave</u> varies inversely with the rate of penetration of the freezing temperature into the cold room specimens. It has been found that the rate of freezing of the test specimens, for which it is desired to compare test results, is difficult to maintain constant because of fluctuations in the freezing-cabinet temperature over the entire duration of a particular test or variations in temperatures between the various cabinets. Since <u>rate of heave</u> has been found to be relatively independent of rate of freezing, over the range of the rates of freezing employed in the investigation, the <u>average rate of heave</u> has been utilized as the basis for comparison of the test results.

Based on Dr. Casagrande's proposed frost susceptibility classification the following tentative scales of <u>average rate of heave</u> have been adopted for rates of freezing between 1/4 and 3/4 inch per day.

Average Rate of Heave mm./day	Frost Susceptibility Classification
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

2-03. Soils Selected for Tests. The descriptions, classifications, and sources of soils which have been subjected to testing in this investigation are summarized in Table 1. As shown therein, the soils have been divided into the following three groups: (a) nine basic soils ranging from a well graded sandy gravel (GW) to a medium plastic clay (CL), chosen for testing both at their natural gradations and after blending with one another to give desirable percentages of finer soil fractions for testing, (b) base and subgrade soils obtained from 14 airfields in the northern United States, and (c) samples of proposed base course borrow materials for use on Alaskan highways. The soils under group (b) are being tested for degree of frost susceptibility for correlation with field data available in the Frost Investigational Reports and/or Pavement Failure Reports.

2-04. Testing Procedure. The soil specimens were generally prepared for freezing tests in a 5.91-inch inside diameter steel molding cylinder to an approximate height of 6-inches and to a predetermined density by means of a static load and/or vibration.

The specimens were ejected from the molding cylinder and placed in heavy cardboard containers, the interiors of which were greased to prevent friction between the specimens and the container walls during heaving. The molded samples were allowed to temper for at least 24 hours at 38°F. before the start of the freezing tests. Thermocouples were inserted at intervals along the length in at least one sample in each freezing cabinet to measure the temperature changes. The samples were placed in a freezing cabinet and granulated cork was placed around the sides for the full height of the specimens. A free water surface was maintained approximately 1/8-inch above a porous stone at the bottom of each sample. A surcharge weight of 0.5 lbs. per sq. in. was placed on top of each sample. The samples were frozen from the top by gradually decreasing the temperature above the samples in the freezing cabinet, while the bottoms of the samples were exposed to the cold room temperature which was maintained between 35 - 38°F. The temperature in the test cabinet was lowered to obtain approximately 1/4-inch per day penetration of the 32°F. temperature into the samples. Heave measurements were taken daily. At the completion of the test, usually after 24 days, the samples were removed from the freezing cabinet, measured, split longitudinally, photographed, examined for ice segregation, and, finally broken up to determine the water content distribution. Photographs of typical specimens after splitting are shown on Plates 16 to 22 inclusive of this report.

A more detailed description of specimen preparation and freezing procedures is presented in Volume II, "Appendix A: Equipment and Test procedures". The heave data, the penetration of the 32°F. temperature, the cumulative degree-hours below 32°F., and the test cabinet temperatures all plotted versus time, and the water content distribution in each sample, before and after testing, for each test series, are presented in Volume II, "Appendix B: Investigational Data".

PART III - COLD ROOM INVESTIGATIONS

obtain more undisturbed samples to get natural conditions woods

3-01. Effect of Per Cent Finer Than 0.02 mm. An extensive series of tests was performed to check the validity of the present criteria for frost susceptible soils and to determine, for 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 ice segregation will occur. The basic soils selected for this investigation were Limestone Sandy Gravel, Peabody Sandy Gravel, Lowell Sand, Truax Drumlin Soil, Manchester Fine Sand, East Boston Till, and New Hampshire Silt. Gradation curves of these soils are shown on Plate 1. In addition, the minus 100-mesh fraction of Limestone Sandy Gravel, referred to as Chapman Pit Fines, was used in this series of tests.

Can we get proper mixing

The above basic soils were graded into coarse and fine soil fractions for the preparation of various specimen gradations. The gradation curves of these soil fractions are grouped on Plates 2 and 3 as "Gradation Curves for Coarse Soil Fractions", and "Gradation Curves for Fine Soil Fractions", respectively. New Hampshire Silt, East Boston Till, and Chapman Pit fine soil fractions were each artificially blended into the Peabody Sandy Gravel, Lowell Sand, and Manchester Fine Sand coarse soil fractions to give in each instance the desired percentage of fines in the latter soils. Limestone Sandy Gravel and Truax Drumlin Soil test specimens were also prepared, by first splitting into fine and coarse fractions and recombining the two fractions to give the desired per cent finer than 0.02 mm.

The test results are summarized on Plates 2 and 3 in plots of average rate of heave versus per cent finer by weight than 0.02 mm. The test data for all samples are presented in Table B1, Appendix B.

Examination of Plates 2 and 3 reveal that for equal percentages of material finer than 0.02 mm., relatively large variation in the average rates of heave ~~were~~ was recorded. The average rates of heave in millimeters per day when 10 per cent of the soil grains were finer than 0.02 mm. are as follows:

	Fine Fraction		
Coarse Fraction	Chapman Pit	East Boston Till	New Hampshire Silt
Limestone Sandy Gravel	4.0	-	-
Peabody Sandy Gravel	2.5	1.8	1.0
Lowell Medium to Fine Sand	1.3	0.25	0.50
Manchester Uniform Fine Sand	2.0	1.4	0.25

The fine soil fraction designated Chapman Pit is the minus 100 mesh portion of Limestone Sandy Gravel fines, and constitutes the most potent fine soil fraction tested in this test series. When blended with the two sandy gravels and the two coarse sand fractions, it resulted in greater average rates of heave than when the East Boston Till or New Hampshire Silt fines were used. In two out of three instances the East Boston Till fines were more effective in producing heave than New Hampshire Silt fines.

Based only on the grain size distribution, it appears that the finer the grains or the ~~more~~ higher the percentage of colloidial sizes contained in the finer soil fraction, the more effective the finer soil fraction is in producing ice segregation. The Limestone Sandy Gravel fines when recombined with Limestone Sandy Gravel to give 3 per cent finer than 0.02 mm. produced average rates of heave of 1.0 mm. per day. Such a soil, at the borderline according to existing criteria, would nevertheless be classified as a soil of low frost susceptibility in accordance with the scale presented in Paragraph 2-02. For a freezing test of 18 days duration, a 6-inch high sample, when frozen to the bottom, would heave approximately 3/4 of an inch. By comparison when the coarse and fine fractions of Truax Drumlin soil were blended together to give 3 per cent finer than 0.02 mm. an average rate of heave of 0.35 mm./day resulted. Such a soil in accordance with Paragraph 2-02 would be classified as a soil of negligible frost susceptibility.

Definite horizontal ice lenses usually were not discernible to the naked eye in the gravelly soils ~~of this~~ test series which heaved less than 15 or 20 per cent. Occasionally, thin ice coatings were present o ~~either~~ on the top and more frequently on the ~~or~~ bottom sides of the stones in these soils and were somewhat more frequently located on the underside of the stones.

3-02. Effect of Degree of Compaction. In a given soil, dry density (dry unit weight) is a soil property which may be used to study the combined effect on ice segregation of such physical soil characteristics as permeability, void size, and internal structure. Increasing the dry unit weight of a soil by compaction decreases the void size and also decreases the permeability, thereby affecting the rate of growth of ice lenses. Tests for frost action conducted on sandy clay mixtures by Winn and Rutledge (11) indicate that, for that soil: "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".

Plots of rate of heave vs. degree of compaction, together with the gradations of the soils used in this test series, are shown on Plate 4 of this report. The gradation and per cent of fines in the samples were constant while the density of the specimens was varied as desired. The test data for all samples are tabulated in Table B2, Appendix B. The results indicate that heaving increases with increase in original dry density for silt soils as New Hampshire Silt and Ladd Field subsoil. Tests on East Boston Till show increased heaving with increase in density up to 120 lbs. per cu. ft. followed by a rapid decrease in heaving with further increase in dry density. Rerun tests on this soil showed lesser rates of heave but with heaving increasing up to the maximum test density of 120 pcf. It is noted that the initial degree of saturation of two of the rerun test samples (EBT 23 and 24) was 88 per cent compared to that of the original test samples which was 100 per cent. Truax Drumlin Soil and Limestone Sandy Gravel show increased heaving with increase in dry density up to approximately 132 lbs. per cu. ft. followed by a gradual decrease in heaving with further increase in dry density. The results from tests on sandy soils, such as Manchester Fine Sand, Indiana Dune Sand and Alaskan Silty Fine Sand, show negligible variation in heave with change in density. Clayey gravelly sand (subbase) from Fargo AFB shows an apparent decrease in heave with increase in density, however, this is based on the results of tests on two samples and is not considered conclusive.

In general, Plate 4 indicates that for well graded soils such as East Boston Till, Truax Drumlin Soil and Limestone Sandy Gravel the rate of heave increases with density to a critical density above which the rate of heave is inversely proportional to density. This is similar to the results of Winn and Rutledge (11) for sandy clay soil.

Variation in density of uniform fine sands of borderline frost susceptibility such as Indiana Dune Sand, Manchester Fine Sand (blend), and

Alaska Fine Sand has negligible influence on rate of heave. Inorganic silt soils of medium to very high frost susceptibility are rendered more frost susceptible by increase in density up to the maximum laboratory compacted density.

There appears to be no advantage, from the standpoint of decreasing the effects of frost action, in compacting the soils tested in this test series except possibly the well-graded soils. The advantage of compacting these latter soils is also questionable because, if the soils are not made virtually non-frost susceptible by the compaction a loosening of the soils might must result, after a few freezing cycles.

3-03. Effect of Surcharge. A series of tests ha~~ve~~s been performed to determine the effect of surcharge omit or overburden pressures on ice segregation in soils of various gradations. Surcharge loads of 0, 1/2, 1, 2, 3, 4 and 6 pounds per square inch were placed on 6 inch diameter specimens during freezing. These surcharge weights correspond approximately to 0, 1/2, 1, 2, 3, 4 and 6 foot thicknesses of pavement and high density base course respectively.

Plots of average rates of heave vs. intensity of surcharge and gradations of the soils used in this test series are shown on Plate 5 of this report. The detailed test data for all specimens are tabulated in Table B3 of Appendix B. The original height of all samples tested was 6 inches except that New Hampshire Silt samples both 6 inches and 12 inches in height were tested with similar surcharge loads.

The test data indicate that, for the soils tested, the average rate of heave decreases with increase in surcharge load. Since the semi-logarithmic plot of the data results in a series of lines nearly parallel, the following equation is obtained from the average data:

$$\log r_s = \log r_o - \frac{s}{6}$$

where -

s = surcharge stress in lbs. per sq. in.

r_s = rate of heave in mm/day with a surcharge stress of s.

r_o = rate of heave in mm/day with a zero surcharge stress.

All logarithms are common logarithms.

Since a surcharge of 0.5 lbs. per sq. in. has been generally used in the cold room investigations, the effect of overburden pressures in decreasing the frost susceptibility which was indicated by the results of the standard tests may be determined by the following equation:

$$\log r_s = \log r_{0.5} - \frac{(s-0.5)}{6}$$

where $r_{0.5}$ = rate of heave in mm/day with a surcharge stress of 0.5 psi.

Additional testing of a wider range of soil gradations is believed necessary before attempting to generally apply the relationship 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 per cent 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 balanced by a closer approach to a ground water table. Also, the total heave per unit of depth in the field usually increases with depth as the rate of frost penetration is reduced.

3-04. Effect of Per Cent and Size of Aggregate 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 per cent and gradation of the coarse soil fraction on ice segregation. The inclusion or exclusion of even a small number of stones (say 2 to 4 inch diameter) in a 25 pound sample from a proposed base course borrow area or a construction control sample can appreciably affect the indicated overall per cent, by weight, of sizes finer than 0.02 mm.

Six series of tests were performed in which the maximum size and/or per cent of the coarse fraction was altered. The gradations of the samples or of the materials which were combined to make the test samples are shown on Plate 6 of this report. The pertinent test data obtained are included in Table B4 Appendix B.

A series of freezing tests were performed on four specimens of Limestone Sandy Gravel, the gradations of which are shown on Figure 1, Plate 6. The maximum size aggregate was varied from 2-inches to 1/4-inch in diameter and the weight of grains finer than 0.02 mm. ranged from two to four per cent.

In a second series of tests nine samples of Limestone Sandy Gravel and five samples of Truax Drumlin Soil were regraded by scalping the maximum size aggregate in increments from the 2-inch down to the No. 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. ranged from 3 to 22 percent. The gradations of the samples are shown in Figures 2, 3, and 6, Plate 6. The average rates of heave recorded for these tests plotted in relation to per cent finer than 0.02 mm. are shown in Figure 7 of Plate 6.

There does not appear to be any effect of maximum size or per cent of coarse fraction within the range of gradations tested. When the per cent finer than 0.02 mm. is kept nearly constant as in Figure 1, Plate 6, the rate of heave does not change appreciably, all other conditions being equal. In the case where the per cent of the total sample finer than 0.02 mm. is increased by the removal of stone, the rate of heave increases in the same manner as if the coarse fraction was kept constant and fines were added to increase the per cent finer than 0.02 mm. This is illustrated by comparing the plots of average rate of heave vs. per cent finer than 0.02 mm. on Plate 3 with Figure 7 of Plate 6. Both sets of curves are shown in latter figure.

Two test series were performed using New Hampshire Silt and Ladd Field Subsoil to which were added varying percentages of ~~minus~~ 2-inch to ~~plus~~ 3/4-inch gravel sizes. Gradations of these soils are shown in Figures 4 and 5 of Plate 6. The results using New Hampshire Silt showed no consistent trends, but the results using Ladd Field Subsoil showed a decrease in average rate of heave as the per cent of stones were increased, which in effect decreased the per cent finer than 0.02 mm. in the total sample as shown in Table B4, Appendix B.

The inconsistent results obtained in the series using New Hampshire Silt are attributed to the non-uniform gradation of the samples as the stones floating in the matrix of fine highly frost susceptible silt resulted in the development of large voids in the frozen soil structure which was not typical in other series using natural soil gradations.

It would seem that in these tests the combined effects of change in permeability, change in overall thermal properties, and change in total proportion of soil material susceptible to dispersion by frost action, produced by changing the proportion of the coarse fraction while holding the per cent finer than 0.02 mm. constant, were negligible. On the other hand, simple addition of coarse sizes to a given soil will result in proportionate decrease in percentage finer than 0.02 mm., with consequent decrease in overall heave potential. Whether such lesser overall heave represents also lesser reduction in bearing capacity in the spring is a matter for further consideration.

3-05. 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 susceptible soils in a closed system, i.e., a system in which no water is made available to the bottom of the sample.

The materials selected for testing were Truax Drumlin Soil, New Hampshire Silt, East Boston Till, Dow A.F.B. Clay, Dow A.F.B. Sandy Clay Subgrade, and ten (10) base and subgrade materials from airfields in northern United States as shown in Table B5 of Appendix B. Gradation curves for these soils are shown on Plate 7. Samples were prepared at approximately 70, 80, 90 and 100 per cent saturation except for those airfield materials which were tested only at 100 per cent saturation, and were prepared from remolded materials. For test series wherein the degree of saturation was varied, the samples were prepared at approximately the same densities.

The pertinent test data from these series of tests are presented on Plates B142 through B150 in Appendix B which show the water content distribution in the specimens before and after freezing. These plots indicate that, as the top of a sample of frost susceptible soil is frozen, a considerable increase in water content results in that zone as water is drawn up out of the bottom of the sample. The results of the tests in which the initial degree of saturation was varied are summarized in the following table:

Soil	Sample No.	Before Freezing		Water Content After Freezing	
		Degree of Saturation	Water Content	Top of Sample	Bottom of Sample
East Boston Till	EBT-5	69.9	9.5	10.6	6.4
	-6	81.4	10.9	13.7	7.1
	-7	90.4	12.2	13.7	8.3
	-8	100.0	12.9	20.9	7.1
Dow AFB Clay	DFC-2	68.2	13.3	18.3	11.6
	-3	82.2	15.2	21.5	13.0
	-4	92.4	17.1	20.8	13.6
	-5	100.0	16.3	23.9	14.0
	-1	100.0	18.0	23.1	14.9
New Hampshire Silt	NH-5	67.6	17.5	24.7	6.5
	-6	78.7	20.0	27.1	6.1
	-7	87.6	22.5	28.0	5.2
	-8	100.0	25.4	36.0	5.5
Truax Drumlin Soil	TD-15	70.0	7.8	8.3	5.6
	-16	68.9	7.7	9.3	6.3
	-17	87.5	9.7	10.1	8.0
	-18	99.0	10.9	13.7	6.5

The tabulated data indicates 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 decreases to a relatively constant value which appears to be independent of the initial degree of saturation within the range tested. Additional testing is scheduled to determine the relationship between the water content at the bottom of the sample and the shrinkage limits for the various materials.

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 of the moisture content of the material directly underlying the zone of freezing. The increase in water content at the top of the samples in the cold room tests is not necessarily considered quantitatively representative of the results that would occur in nature since the samples were only six inches in height, while in nature water may be supplied for ice segregation from soil at much greater depths. Plastic soils tested in the closed system exhibited a tendency to shrink in diameter and pull away from the container at the lower portions of the specimens. Presence of an appreciable consolidating force in the lower portions of all samples is indicated by the marked decreases in water content in bottoms of samples as compared with the original water contents. In nature it is visualized that vertical shrinkage cracks would tend to develop, in plastic soils, particularly during the initial freezing cycle.

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3-06. Tests on Saturated Undisturbed Clay in Closed and Open Systems.

Results of tests on undisturbed samples of Boston Blue Clay, 100 per cent saturated and tested in both open and closed systems, are presented in Table B6 of Appendix B. The water content distribution in the specimens before and after freezing are shown on Plates B149 and 150. All samples tested in the closed system showed considerable ice segregation near the tops of the samples. It was observed, however, that the lower portions of the samples had become quite dry and brittle, the diameter having shrunk from 4.27 inches to an average of 4.04 in one of the samples.

The water contents of the undisturbed samples before freezing ranged from 38 to 44 per cent. In the closed system, the water contents increased at the tops of the specimen to from 48 to 100 per cent. At the bottoms of the samples the water contents decreased to between 21 and 29 per cent in all samples which were frozen for more than 2/3 their height. The shrinkage limit of the clay tested is 22 per cent or slightly less than the water content at the bottom of the samples at end of freezing.

Thus the shrinkage limit represented the approximate lower limit of water content reduction due to ice segregation in this undisturbed clay in this series of tests.

3-07. <u>Effect of Alternate Cycles of Freeze-Thaw.</u> A series of tests was performed on materials that had been used as base and subbase materials at various airfields, to determine if highly compacted frost-susceptible gravel and sand soils maintain their original densities; also to determine if the intensity of ice segregation becomes progressive when soils are subjected to alternate cycles of freezing and thawing. The gradation curves of the materials used in the test series are shown on Plate 8. Test results are shown in Table B7 of Appendix B and plots of heave vs. time are shown on Plates B61 through B64.

A sample of Fargo Airfield Clayey Sand subbase and two samples of Truax Drumlin Soil were subjected to three alternate cycles of freeze-thaw. The samples were molded 6-inches in diameter and 6-inches in height. The measured heaves of these samples after each freezing cycle are summarized in the following table:

Sample No.	Soil Type	Heave After Freezing in Inches		
		1st Cycle	2nd Cycle	3rd Cycle
FA-3	Fargo Airfield Clayey Sand	2.6	3.1	3.4
TD-28	Truax Drumlin Soil, Silty Gravelly Sand	2.8	2.8	2.6
TD-29		1.1	2.6	3.0

The densities of the Truax Drumlin Soil samples (TD-28 and 29) after the third thaw cycle were 128 and 118 pcf compared with 136 and 135 pcf respectively at the start of the test. The Fargo Clayey Sand sample was split for observation of ice lens formation; therefore, the final thawed density was not obtained.

Four samples were prepared 12 inches in height of which the top 6 inches was composed of a base material and the lower 6 inches a relatively impervious subgrade material. The base materials used were Truax Drumlin Soil, gravelly sand from Spokane AFB, clayey sandy gravel from Great Falls AFB, and Limestone Sandy Gravel. The subgrade for each sample was East Boston Till except that Limestone Sandy Gravelly Clay was used in conjunction with Limestone Sandy Gravel. The samples were subjected to three cycles of freeze-thaw in which the sample was frozen each cycle to approximately a 6-inch depth.

As shown on Plates B63 and B64, Appendix B, the base materials had decreased in density between 2 and 8 per cent after the third thaw cycle and showed a progressive increase in heave for each freezing cycle, except the Limestone Sandy Gravel which showed a slight progressive decrease in heave with cycles of freezing.

As indicated in Table B7, Appendix B, the densities at the end of all tests were less than the original densities. However, the laboratory tests in 6-inch diameter cylinders do not ideally simulate field conditions because the subsidence of the sample during thawing is undoubtedly restrained by the friction on the walls of the cylinder, which prevents the sample from returning to its original density. A method of test is needed which avoids this source of error, and before final conclusions are made, this friction should be investigated to determine its effect upon the results of these tests.

Effect of Density on Change
Thawing Freezing

3-08. <u>Effect of Admixtures.</u> A series of tests was performed on New Hampshire Silt and Fort Belvoir Clay to determine the effectiveness of the admixture of calcium acrylate in preventing or retarding the formation of ice lenses in these frost susceptible soils, and to determine whether alternate cycles of freeze-thaw result in progressive heaving in the treated soils.

An extensive research program, sponsored by the Engineer Research and Development Laboratories, Fort Belvoir, Virginia, is being currently conducted at the Massachusetts Institute of Technology under the supervision of Dr. T. William Lambe, Assistant Professor of Soil Mechanics, with the objective of developing methods of solidifying soils by the use of chemicals. The most promising admixture developed to date is calcium acrylate. When this chemical is mixed with a soil in correct proportions, it forms a flexible product with significant tensile strength which can withstand the effect of water. Its successful development as a feasible and economical method of soil stabilization might also lead to its utilization in the treatment of frost susceptible soils to prevent or minimize the effects of frost action, if found suitable.

In this test series to determine the effectiveness of the admixture of calcium acrylate in preventing or retarding ice lens formation, varying percentages of calcium acrylate (0, 5, 7.5 and 10 per cent, respectively) were blended into the dry soil of samples numbered NH-29-A through NH-26-A, and FB-1-A through FB-4-A. In the test series to determine the effectiveness of this admixture with alternate cycles of freeze-thaw, five per cent of calcium acrylate was blended into the dry soil of samples numbered NH-33-A, NH-34-A, FB-5-A, and FB-6-A. Latter percentage of admixture was selected because the former test series indicated that a 5 percent admixture of calcium acrylate was the minimum required to reduce or prevent ice lens formation in these soils.

Samples for the above test series were prepared in the following manner: The desired percentages of calcium acrylate, based on the dry weight of the soil, were first thoroughly blended into the dry soils. A five per cent admixture of sodium thiosulphate activator, based on molecular weights of sodium thiosulphate and calcium acrylate, was added together with the molding water. Immediately prior to compacting the specimens, a catalyst, ammonium persulfate, was added with a small amount of water, retained from the measured amount of molding water, to act as a dispersing agent. The quantity of ammonium persulfate was determined as five per cent of the calcium acrylate, based on molecular weight. The total water added to the samples was sufficient to give 100 per cent saturation at the predetermined densities.

The test data and results for this test series is given in Table B8 of Appendix B and the gradation curves of the soils are shown on Plate 9 of this report.

The cellular structure of Diatomaceous Earth led to the belief that this soil might act as an air-entrainment agent when blended with frost susceptible soils, and would reduce the ice lens formation in these soils. Prior to blending with frost susceptible soils, two samples of Diatomaceous Earth were subjected to freezing tests. The test results for these samples, DTE-1 and 2, as shown in Table B8 of Appendix B, indicated that this soil was in itself extremely frost susceptible, so the tests using this material as an admixture were not initiated.

Test results indicate that calcium acrylate is very effective in preventing the formation of ice lenses in Fort Belvoir Clay, as the rate of heave was reduced from 14 mm. per day in the untreated soil to 0.1 mm/day or less for admixtures of 5, 7.5 and 10 per cent calcium acrylate. The Fort Belvoir material with admixtures of calcium acrylate showed no segregated ice after freezing and specimens with 5 per cent calcium acrylate exhibited no increase in rate of heave after two cycles of freezing.

When mixed with New Hampshire Silt, the calcium acrylate was not as effective in reducing frost action. The admixture of 5, 7.5 and 10 percent calcium acrylate reduced the rate of heave to 4.5, 2.0, and 0.5 mm. per day, respectively, as compared to a rate of heave of 14 mm. per day in the untreated soil. Samples of New Hampshire Silt with 5 per cent calcium acrylate were subjected to two cycles of freezing and thawing and did not show an increase in rate of heave during the second cycle of freezing. All New Hampshire Silt samples contained ice lenses after freezing. These lenses varied from hair-line to 1/8-inches in thickness for the sample height.

A significant observation during the test was that the specimens with calcium acrylate admixture retained their original tough rubbery texture during freezing and it was difficult to distinguish between the frozen and unfrozen material except where actual ice lenses were present. In addition, there was no observed weakening upon thawing in the New Hampshire Silt specimens that had heaved. As shown on Plates B67 and B68 of Appendix B, the specimens returned to virtually their original heights in the thaw period between freeze cycles.

A considerably greater number of test cycles would be required to demonstrate the permancence of this effective reduction in frost action.

3-09. Effect of Height of Sample. A series of tests was performed to determine the effect of test sample height on ice segregation.

The materials selected for testing were Truax Drumlin Soil (Samples

TD 19, 20, and 21), Limestone Sandy Gravel (Samples LSG 22, 23, and 24), Manchester Fine Sand blended with New Hampshire Silt (Samples MFS 18, 20, and 22) and Manchester Fine Sand blended with East Boston Till (Samples MFS 17, 19, and 21). Sample heights were varied between 4 and 12-inches with a constant diameter of 5.91-inches. Test results are given in Table B9 of Appendix B and results are presented in plot form as per cent of heave vs. height of sample together with soil gradations on Plate 10 of this report.

Results indicate that the per cent heave and rate of heave increases with decrease in sample height over the test height range investigated. The plots of heave versus time, and water content distribution in the samples, are shown on Plates B70 through B72 and B158 through B160, respectively, of Appendix B. These referenced plates indicate that the lower 4-inch portion of the 8 or 12 inch high samples did not heave comparable to the 4-inch high samples although the latter samples were located in the same relative position in reference to the water level. There does not appear to be any obvious explanation of the considerably lesser amount of heave in the lower portion of the taller samples except that the slight additional weight of material and possible side wall friction in the containers during heaving may have resulted in an effective surcharge on the lower portions of the samples. Further study is needed to clarify this point.

Hold Air Vent

3-10. <u>Effect of Capillarity and Condensation</u>. Theories exist that a principal source of moisture accumulation in the base course is through the condensation of vapor in the soil atmosphere due to either changes in temperature or in pressure, assuming that both the pavement and subgrade are relatively impervious. A series of tests was performed to obtain information on the effect of capillarity and vapor condensation in producing changes in moisture in a very pervious base material overlying a relatively impervious subgrade and in a relatively impervious base overlying a very pervious subgrade.

The test samples were 6 inches in diameter and 12 inches in height with the upper half of each sample consisting of base material and the lower half subgrade material. Samples of oven-dried materials were prepared using Peabody Sand (-#10 mesh to +#65 mesh) and Pea Gravel (-3/8-inch to +1/4-inch) as base materials over new Hampshire Silt subgrade. In another test series, the New Hampshire Silt was used as the "base" material over the Peabody Sand in one instance and Pea Gravel in another.

Samples to study the effect of capillarity were molded in lucite cylinders to facilitate observation of the boundary between dry and moist material. The samples were placed in the cold room with the temperature maintained at a steady temperature between plus 35°F. and plus 38°F. The sample bases were placed in water and the water levels maintained 1/4-inch above the bottoms of the samples. The tops of the samples were sealed to prevent evaporation, using a spray coat of vinylite plastic and a coating of petrolatum. The capillarity samples were allowed to stand for either 20 or 40 days and then were extracted from their containers and water content distribution was determined.

The samples to study the effect of condensation were prepared in cardboard containers and water was supplied to the bottoms of the samples. The tops were sealed in the same manner as the capillarity samples. The samples were placed in the freezing cabinets in the cold room with the sides of the samples insulated, with granulated cork, for their full height. The tops of the samples were exposed to alternate 12 hour periods of 32°F. and

110°F. for either 20 or 40 cycles while the bottoms of the samples were exposed to the cold room temperature which ranged from plus 35°F. to 38°F. The 110°F. temperature was obtained by the use of a 100 watt electric light bulb. The samples were removed from the freezing cabinet at the end of the test and water content distribution was determined.

The gradation curves of the material used in this test series are shown on Plate 11 of this report. The test results are shown in Table B10, Appendix B. The degree of saturation in the materials at the end of each test series is presented in the following table:

Material		Degree of Saturation at End of Test		
		Capillarity	Condensation	
			20 cycles	40 cycles
Base	New Hampshire Silt	97 (1)	95	94
Subgrade	Peabody Sand	55	68	81
Base	Peabody Sand	24 (1)	34	35
Subgrade	New Hampshire Silt	96	90	92
Base	New Hampshire Silt	1 (2)	1	2
Subgrade	Pea Gravel	7	4	3
Base	Pea Gravel	3 (2)	4	2
Subgrade	New Hampshire Silt	96	100	100

(1) Duration of test 20 days

(2) Duration of test 40 days

The test using New Hampshire Silt over Peabody Sand showed somewhat greater degrees of saturation in the base material when the surface temperature was varied than when the temperature was held constant, but in all other tests the moisture accumulation in the subgrade material was not appreciably influenced by changes in surface temperature. The data indicates that the movement of moisture up through the specimens was principally through the liquid phase rather than transfer by soil vapor. The New Hampshire Silt remained practically free of water when placed over the Pea Gravel, but when placed over the Peabody Sand the New Hampshire Silt attained practically full saturation, water being supplied by capillary movement up through the sand. It is believed that the degree of similitude between this kind of test and natural field conditions should be further explored before final conclusions are drawn as to the significance of the tests.

3-11. Effect of Rate of Penetration of 32°F. Temperature. A series of tests have 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. Design penetration rates of 1/4, 1/2, 3/4 and 1-inch per day were used in the tests. The materials selected for testing were silty sandy gravels from Mansfield Hollow Dam, Mansfield Hollow, Connecticut and from proposed site of Ball Mountain Dam, Jamaica, Vermont (these are not included in the selected list of soils shown on Table 1); Spokane AFB Gravelly Sand, Lowry AFB Clayey Sand, New Hampshire Silt, East Boston Till, Boston Blue Clay (undisturbed), Dow AFB Clay (undisturbed) and Limestone Sandy Gravel. Plus 3/4-inch sizes were removed from the coarse-grained materials.

The test results are summarized in Table B11 of Appendix B and are shown on Plate 12 of this report as a plot of rate of penetration vs. rate of heave. The gradations of the various soils are also shown on Plate 12. The rates of penetration shown on Plate 12 are the actual values from the tests, which varied slightly from the design values chosen. The single test performed on Limestone Sandy Gravel at 1/2-inch rate of penetration is not plotted.

The results for 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 (1/4 to 1-3/4 inches per day). Though the data for Dow AFB Clay shows the rate of heave to apparently decrease with increase in rate of freezing-temperature penetration, the undisturbed samples of Dow Clays 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 per cent of heave of the frozen material and the intensity of ice segregation should vary directly with rate of freezing, as has been observed. (In field explorations it is found that 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 half, with the heave per day remaining constant, the heave for any one day will represent the freezing of only one half as much depth of original soil, and the expansion of that soil per unit of depth must be doubled, with twice as much segregated ice, in order to maintain the rate of heave.

Further plots and analysis of the data from this test series might prove instructive; for example, a plot of rate of penetration of 32°F. temperature vs. the per cent heave of the depth frozen, per day.

3-12. Frost Action In Minus 200 Mesh Soil Fractions Alone. The magnitude of ice lens formation in the minus 200 mesh soil fractions of Limestone Sandy Gravel (Chapman Pit), Peabody Sandy Gravel, East Boston Till, and Truax Drumlin Soil (Samples LSG-25-F, PSG-1, EBT-12-F and TD-27-F, respectively,) was determined by freezing tests in the cold room. Gradations of the soils are shown on Plate 12A. The results of the tests are shown in Table B12 of Appendix B. The samples prepared from the fine soil fractions of the four soils had substantially the same average rates of heave ranging from 15.0 to 17.5 mm. per day. This contrasts with the results from the tests for effect of per cent finer than 0.02 mm. reported in Paragraph 3-01, where the Chapman Pit fines were found more potent than East Boston Till and New Hampshire Silt fines, in combination with various coarse fractions. It contrasts also with the markedly different rates of heave obtained for Limestone and Truax soils in the tests for effect of per cent and size of coarse aggregate, as shown in Figure 7 on Plate 6. However, if the data for these two soils shown in Table B12 were plotted on Figure 7, Plate 6, and the solid lines thereon were drawn so as to show somewhat greater convergence, then the results would not appear too unreasonable.

3-13. Effect of Mineral Composition of Fine Soil Fraction. The tests performed to determine the effect of per cent finer than 0.02 mm. on ice segregation in soils (Paragraph 3-01) indicated that the particle size and distribution or the nature of the fines (minus 200 mesh) influenced the formation of ice lenses in a soil. To explore the relation between the mineral and chemical composition of the fines and the soil frost susceptibility, the Frost Effects Laboratory contracted with Dr. T. William Lambe of the Massachusetts Institute of Technology, Cambridge, Mass., to perform the following tests on selected frost susceptible soils:

a. Identify each of the mineral constituents present in the portion of the soil passing the 200 mesh sieve.

b. Determine the percentage of each such mineral constituent by differential thermal analysis.

c. Determine the surface area per unit mass of the minus 200 mesh soil fractions.

The soils selected for testing were:

a. Limestone Sandy Gravel
b. Peabody Sandy Gravel
c. East Boston Till
d. Limestone Glacial Till
e. New Hampshire Silt
f. Ladd Field Silt
g. Truax Drumlin Soil
h. Lowry AFB Clayey Sand
i. Patterson AFB Clayey Sandy Gravel
j. Clinton AFB Clayey Sandy Gravel
k. Dow AFB Clay
l. Dow AFB Till
m. Boston Blue Clay

The total surface area per mass of soil was determined by the Ethylene Glycol Retention Test.* A soil sample of approximately 1.2 gms. was used for the test which was performed as follows:

a. The soil sample was dried to a constant weight over phosphorus pentoxide (P_2O_5) in an atmosphere of less than 0.1 mm. Hg. absolute pressure.

b. The soil sample was weighed.

c. Approximately 3/4 gm. of ethylene glycol was added to the dry sample and allowed to soak for 24 hours.

d. The glycol-soil mixture was put over calcium chloride ($CaCl_2$) and subjected to an absolute pressure of less than 0.1 mm. Hg. until it reached a constant weight.

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* A detailed presentation of this test can be found in "Total Surface of Clays in Polar Liquids as a Characteristic Index", R. S. Dyal and S. B. Hendricks, Soil Science, Vol. 69, June 1950.

e. The samples were weighed and the weight of glycol retained per gram of soil was calculated.

The total surface area per mass of soil was approximated from the glycol retention since the area covered by one gram of ethylene glycol is approximately 0.3204 sq. meters. The computed surface area is approximate because it has not yet been shown that the retained glycol forms a single molecular layer on all minerals. The degree to which the glycol penetrates the interior of certain mineral particles is also unknown. However, Hendricks has proved that glycol retention gives an excellent measure of the total surface area of the expanding lattice minerals.

As a preliminary step to differential thermal analysis, the soil sample was brought to an equilibrium moisture content in an atmosphere of 50 per cent relative humidity. Since this moisture content has been found indicative of the composition and properties of a soil, this moisture was measured and recorded.

The soil mineral composition of each of the soils was determined by differential thermal analysis. This analysis was performed with a differential thermal analyzer similar to that used by Kerr and Kulp.* Each soil was brought to an equilibrium water content at 50 per cent relative humidity before testing in order that the absorbed water deflection on the thermogram could be used in the analysis. The thermograms for all the soils tested are shown on Plate 13 of this report. The solid lines, thereon, are the initial runs and the broken lines are the reruns used to detect minerals with reversible reactions. These thermograms were compared with ones of Know minerals for identification of the various components in each soil.

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

Since thermal analyses showed the presence of carbonates in many of the soils, dilute hydrochloric acid was added to each soil to test for carbonates.

The results of the above studies are summarized in Table 2 of this report. The soils investigated have been grouped in the summary and on Plate 13 so that soils of approximately similar composition are together i.e.: sample numbers 1 through 4 which contain a significant amounts of carbonate, next the group of clayey soils, and finally the group of silty soils. The original thermogram obtained for the minus 200 mesh fraction of East Boston Till was such that it was thought desirable to isolate the minus 2 micron fraction by centrifuging and then analyzing it with the differential thermal analyzer. Even though the thermal tests on the minus 2 micron fraction (the thermogram of which is shown on Plate 13) did not make a positive analysis of the Till possible, it did aid in interpreting the original thermogram.

The following comments on this investigation have been submitted by Dr. T. William Lambe: "Generally, soils having high surface area and high water content at 50% relative humidity are the more 'active' soils. For example, it would be expected that Lowry AFB Clayey Sand would be a very difficult soil to work with. This is indicated by the high surface area and high water content at equilibrium, plus the high percentage of the expanding lattice mineral montmorillonite which is the most troublesome clay mineral commonly found in soils, followed by illite and kaolinite." Dr. Lambe's experience is that a great number of the glacial clays contain illite, which seems to be substantiated by the results for soils of this type tested for this study.

Examination of the test data presented on Table 2 indicates a direct relationship between the combined percentage of montmorillonite and illite and the surface area and water content at 50 per cent relative humidity.

Peabody Sandy Gravel, New Hampshire Silt, and Ladd Field Silt contained at the most only traces of clay minerals. Quantitative analyses on these soils were not made for the feldspars, micas, amphiboles, etc., because the differential thermal analyzer does not lend itself to this analysis as well as other methods. Dr. Lambe did not think it justified to try to make quantitative analyses for these minerals by other methods because their contributions to the physico-chemical properties of the soils appear to be negligible.

In a paper presented before the Annual Meeting of the Highway Research Board, January 1951, Grim* analyzed the possible effects of clay mineral composition on frost action in soils, although substantiating field or laboratory data of frost heaving characteristics are not included. Two considerations were used by Grim in evaluating the potential of various clay mineral types in developing ice segregation in soils. The first consideration was that a movement of water through the soil was necessary to supply the growing ice crystal. The second consideration was that "very fine colloid-sized clay minerals show very little or no ice segregation on freezing". Grim reasons that those clay minerals which adsorb a large quantity of water in a definite molecular pattern immobilize the water adjacent to the adsorbing surface, thus reducing the permeability and the ability of the soil to supply water for ice segregation.

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* Grim, Ralph E., Illinois State Geological Survey, "Relation of Frost Action to the Clay Mineral Composition of Soil Materials".

A somewhat similar concept is held by Winterkorn* who states, "Directly adjacent to the adsorbing soil, solidly adsorbed water is found, the center of the pore space is occupied by ordinary water freezing at about 0°C., and between the ordinary water and the solidly adsorbed water there is a zone of liquid water possessing a melting point down to -22°C. which serves as a passageway for the conduction of water to freezing centers."

The adsorption characteristics of the various types of clay minerals toward water and various ions and organic molecules were discussed by Grim together with possible effects on frost action as follows:

a. "Montmorillonite Soils." "In montmorillonite, adsorption water penetrates between individual molecular layers, and as a consequence such material has tremendous adsorptive surface and enormous water adsorption capacity." "....The water adsorbed on the surface of montmorillonite particles would consist of water molecules in a definite pattern, and ... therefore, the water would not be fluid or mobile". "....the water initially adsorbed is rigid rather than mobile or fluid and ... at varying distances from the adsorbed surface the rigid water changes to liquid water".

"Montmorillonite has high adsorption capacity for certain cations, anions, and organic molecules". "....The tremendously significant fact is that the character of the adsorbed ion to a very considerable extent controls the perfection of orientation of the water molecules and the thickness of the water layers, showing a definite configuration, and, as a consequence, exerts an enormous influence on the properties of clay-water systems".

"In montmorillonite carrying sodium as the adsorbed ion, water can enter easily between all the unit layers, and in the presence of an

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* Winterkorn, H. "The Condition of Water in Porous Systems". Soil Science, Vol. 56 (1943).

abundance of water adsorbed water layers with a definite configuration of water molecules can build up to great thicknesses". "Thus even in the presence of large amounts of water in which the water content would be in excess of the clay mineral content, there would be no fluid water. Such clays are, therefore, substantially impervious, and on freezing there is little or no concentration of ice in layers".

"In montmorillonite carrying calcium, magnesium, or hydrogen as the exchangeable ion, the situation would be quite different than for a sodium montmorillonite. When the alkaline earths or hydrogen are present as adsorbed ions, water enters between the unit layers with some difficulty and forms relatively thin layers of rigid adsorbed water. In such clays, water present beyond a certain relatively small amount (about 40 per cent of the dry clay), in comparison with Na/ montmorillonite clay, is fluid. In such clays, therefore, concentration of ice in layers may develop on freezing only if the moisture content is fairly high."

"In montmorillonite clays containing potassium, there is very little adsorption of water with a definite configuration. Therefore, in the presence of even small amounts of water, some fluid water would be present."

b. <u>"Kaolinite Soils"</u>. "In soil materials composed of kaolinite, the kaolinite particles occur in relatively large units - 100 to 1000 times the size of the montmorillonite units in a montmorillonite soil - and consequently the surface area is relatively small. Also because of the nature of the crystalline structure of kaolinite only about half the total surface seems particularly likely to develop adsorbed water with a definite configuration, i.e., rigid water. It may therefore be concluded that at even relatively small water contents kaolinite soils would contain some fluid water. Kaolinite soils therefore are not particularly impervious, and should readily show a concentration of water in ice layers on freezing."

c. "Illite Soils". "Many soil materials are primarily composed of the mica type of clay minerals like illite and chlorite. The characteristics of such soils range between those of kaolinite soils and montmorillonite soils, but usually are closer to the former than the latter." "Somewhat more adsorbed water would be immobilized in illite clays than in kaolinite clays, but the total quantity would still be relatively small, and at relatively low water content illite clays would be expected to contain fluid water. Illite clays are not impervious, and should show readily the concentration of water in ice layers on freezing."

"Many illite soils contain small amounts of montmorillonite interlaminated with the illite layers." "....small amounts of such montmorillonite can have an effect on physical properties out of all proportion to the amount actually present. This conclusion should also apply to frost action. A small amount of montmorillonite would, particularly if adsorbed sodium ions were present, greatly increase the amount of water immobilized and as a consequence increase the imperviousness and decrease the tendency for water to concentrate in ice layers on freezing."

Correlation of the mineral composition of the minus 200 mesh soil fraction with the intensity of ice segregation in natural soils is complicated not only by the fact that there are usually several types of minerals present, but also by differences in the other variables, such as grain size distribution of the fine or coarse fraction or the total percentage of fines present, in the soils being compared. In order to determine the specific effects of mineral composition on ice segregation, it is believed necessary to obtain fine soil fractions which are as nearly as practical of one type mineral. Specimens can then be prepared and the relative effect of each mineral on ice segregation can be evaluated.

The minus 200 mesh fraction of Lowry AFB Clayey Sand contained 25 per cent montmorillonite and 65 per cent illite; this was the highest per cent of these constituents present in any of the samples tested. The gradation and relationship between rate of heave and per cent finer than 0.02 mm. for two samples of Lowry Clayey Sand (LA-1 and LA-2) are shown on Plate 15 of this report with the test results of other natural soils. The results indicate that the rates of heave for the Lowry samples are reasonably consistent with the results obtained for soils of similar gradation in the group identified as "Silty Sand and Silty Gravelly Sand" on Plate 15. The Truax Drumlin soil (Samples TD-5 and TD-6), whose minus 200 mesh fraction has 65 per cent illite, also shows results consistent with those of soils of similar classification and gradation. It is also noted on Table B-13 of Appendix B that, although containing montmorillonite, the Lowry Clayey Sand was generally more pervious than other soils with equivalent percentages of fines. This seems to indicate that the montmorillonite contained adsorbed ions of a type conducive to high rather than low permeability, and that, as a general conclusion, it is necessary to know not only the type of soil mineral but the <u>kind</u> of its adsorbed ions, if a correlation is to be obtained between mineral composition and frost susceptibility.

In the series of tests discussed in paragraph 3-01, the fines from Limestone Sandy Gravel (Chapman Pit) were found to be more potent in producing ice segregation than the fines from East Boston Till and New Hampshire Silt. The Limestone Sandy Gravel had 40 per cent kaolinite and 20 per cent illite; the East Boston Till 20 per cent kaolinite and 40 per-cent illite; and the New Hampshire Silt had no kaolinite, montmorillinite 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 by Plate 2, which also may account for the difference in ice segregation in the specimens into which they were blended.

There must also be considered the results of tests on minus 200 mesh fractions of soils reported in Paragraph 3-12, which may be compared as follows:

Source of Minus 200 Mesh Fraction	Avg. Rate of Heave from Table B12 mm/day	Principal Minerals from Table 2	
		Mineral	Per Cent
Chapman Pit (Limestone Sandy Gravel)	15.5	Kaolinite Illite	40 20
East Boston Till	15.0	Kaolinite Illite Quartz	20 20 30
Truax Drumlin Soil	17.5	Illite Quartz Dolomite	65 15 20
Peabody Sandy Gravel	17.0	Quartz	40

Gradations are shown on Plate 12A. As pointed out previously, these rates of heave are not substantially different from one another. It may be that the susceptibilities of these materials are so high that the maximum rates of heave are limited by other factors, such as the rate of heat removal, and that in these materials the relative susceptibilities of the minerals themselves only become important as the percentage of material finer than 0.02 mm. in a soil drops toward the boundary between susceptibility and non-frost susceptibility.

The theories presented by Grim relative to the effect of mineral composition on the soil permeability may or may not be of practical significance in soils of borderline frost susceptibility. Since soils of this type do not have a high percent of fines they are sufficiently pervious to supply water for ice segregation and it is believed that variations in the mineral composition of the fines in these soils would not render them sufficiently impervious to restrict the formation of ice lenses. On the other hand, presence of a small percentage of the proper type of clay minerals might have a very large effect on borderline soils by making frost action possible in otherwise non-susceptible material. In soils containing high percentages of colloidal grains the permeability theories may be valid as the mineral composition has a marked influence on the permeability and the ability to supply water for growth of segregated ice. Cold room tests performed on Boston Blue Clay and Dow Field Clay have demonstrated that these soils are highly frost susceptible, and also that appreciable ice segregation will occur without an outside water source as water is pulled from the soil voids beneath the zone of freezing. Additional tests are scheduled using more impervious clay soils including bentonite. Whether or not the more impervious clays are non-frost susceptible is still open to question.

It is visualized that a relatively small amount of ice segregation in such soils would cause a weakened condition during the frost melting period as considerable time would be required for the water from the ice lenses to redistribute itself through the soil. However, the point is worth investigating, as there would be obvious advantages in being able to identify certain types of impervious soils as being non-frost susceptible.

3-14. Effect of Permeability. The coefficients of permeability and the void ratios of the cold room test materials are shown on Tables B1 to B14 inclusive. The relationship between the coefficient of permeability and average rate of heave is shown on Plate 14 of this report. Lines have been drawn through a series of points where specimens of one material were prepared at several initial densities.

The test results indicate that soils with coefficients of permeability between 100 x 10^{-4} and 10 x 10^{-4} cm. per sec. are from negligible to low frost susceptibility, and that the frost susceptibility increases as the coefficient of permeability decreases, until maximum rate of heave is obtained between approximately 0.1 x 10^{-4} and 0.001 x 10^{-4} cm. per sec.

The degree of frost action which actually occurs in a soil in the field may not correspond with the degree of relative frost susceptibility determined in the cold room tests. The unlimited supply of water at the bottoms of the six inch high cold room samples does not, nor is it intended to simulate most common field conditions of moisture supply. In a very impervious soil of considerable depth, water must principally be obtained from that existing in the soil voids and ice segregation is thereby limited. However, by virtue of its impermeability such a soil will reabsorb water from melting ice lenses relatively slowly, thus tending to prolong the weakening, especially if the rate of thaw is rapid. In a less impervious soil, such as a silt, because of its higher permeability, more water may be available and more ice segregation may occur, and also the melt water is more readily carried away particularly when thawing is slow. Further study is needed to evaluate the combined effects of frost susceptibility, permeability, distance to water source, rate of thaw and surcharge upon the soil bearing capacity during frost melting.

3-15. Frost Susceptibility of Various Airfield and Highway Base and Subgrade Soils. Tests were performed to determine the relative frost susceptibility of base and subgrade soils from various airfields in the northern United States and of proposed select borrow base course materials for Alaskan highways.

Data from these tests are shown in Table B13 and B14 of Appendix B. Plots of average rate of heave vs. per cent finer than 0.02 mm. and gradations of the various materials are shown on Plate 15 of this report. To present this data in plot form, the base and subgrade soils have been divided into soil types in accordance with the Department of the Army, Uniform Soil Classification.

The data in these plots indicate that, for the coarse-grained airfield base and subgrade soils (GW, GM, SM), the rate of heave increases with increase in per cent finer than 0.02 mm. The Alaskan silty fine sand (Samples AFS-1 and AFS-2) and the material from Seward and Kenai Highways, Alaska, (Samples BPR-1 to 5) gave results "out of line" when compared with corresponding soil types from airfields. Although the per cent of material finer than 0.02 mm. in the fine fraction of these soils is relatively low, the portion of material passing the 200-mesh sieve consists principally of clay sizes which may be the reason for the relatively high rates of heave with small percentages of fines. All these coarse-grained soils were tested in the remolded state.

Only a few fine-grained type airfield and highway base and subgrade soils have been investigated. These are identified on Plate 15 as "Sandy Gravelly Clay and Sandy Clay (CL)" soils. Subgrade soil samples from Limestone were tested in both the undisturbed state (Samples LST-2 and LST-3) and in the remolded state (Samples LST-4 and LST-5). Dow Field Till samples (Samples DFT-1 and DFT-3) were remolded before testing. The data from these tests, together with results of tests on some other soils having appreciable clay content, are shown on Plate 15; the general trend is that the rate of heave increases with increase in per cent finer than 0.02 mm.

Results of tests on a number of other base and subgrade soils which do not fall into one or the other of the larger classification groupings are also shown on Plate 15.

An examination of Plate 15 reveals that for an average sandy gravel or gravel (GW) soil with 3 per cent of 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 per cent finer than 0.02 mm. and by a silty sand and silty gravelly sand (SM) having 18 per cent 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 per cent of grains finer than 0.02 mm. It is also noteworthy that Alaska Sandy Gravel (BPR-1, BPR-3, and BPR-5) with one per cent of grains finer than 0.02 mm. had average rates of heave of 1.0, 1.0, and 0.5 mm. per day, respectively. By the Frost Susceptibility Classification System presented in Paragraph

2-01 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 such soils would be quickly drained or redistributed through the soil so that weakening would be slight.

PART IV - CONCLUSIONS

4-01. Conclusions presented below cover those phases of the cold room studies which have been essentially completed up to the end of Fiscal Year 1951. Except for a few results derived from closed system tests, all conclusions are drawn for the case of a soil with free access to water. The conclusions cover only the most obvious results and are subject to modification or amplification on basis of additional tests and further analysis. Some test series for which the results are considered inconclusive, or not sufficiently explained at present, are not covered.

a. Effect of Per Cent Finer than 0.02 mm. The intensity of ice segregation in soils is dependent not only on the per cent of grains finer than 0.02 mm. but also on the grain size distribution or properties of these fines. Fine soil fractions with a high percentage of fine clay sizes appear to be more potent than silt sizes in producing ice segregation in soils of borderline frost susceptibility.

b. Effect of Degree of Compaction. The following is true for the soils tested to date:

(1) In the well-graded frost susceptible gravelly soils the intensity of ice segregation increases moderately with initial density up to a critical density, which is of the order of 95 per cent of Modified A.A.S.H.O. Density, above which there is a decrease in ice segregation with increase in density.

(2) In the uniformly-graded frost susceptible sands the initial density has negligible influence on intensity of ice segregation.

(3) In the inorganic silt soils the intensity of ice segregation increases with initial density up to 100 per cent Modified A.A.S.H.O. Density.

c. Effect of Surcharge. 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.

d. Effect of Per Cent and Size of Aggregate Greater Than 2.0 mm. in Soil Gradation. The test results ~~do not~~ show no ~~any~~ appreciable effect of per cent and maximum size of coarse aggregate on the rate of heave, when the per cent finer than 0.02 mm. is held constant. When coarse material is added or removed without holding the per cent finer than 0.02 mm. constant, the rate of heave which occurs is in proportion to the per cent finer than 0.02 mm. which results, the coarse material acting as a filler to increase the total height of material for which the heave, produced by the fines, is measured.

e. Effect of Availability of Water.

(1) Although a supply of water is a requisite for occurrence of ice segregation in soils, the source may consist of free water existing within the voids of the underlying soil, as well as a close underlying ground water table or aquifer.

(2) 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 already existing in the voids of the soil underlying the surface of freezing.

(3) In clay soils the water content of the soil directly below the zone of freezing may be reduced to approximately its shrinkage limit as the water is drawn to the segregated ice.

f. Effect of Alternate Cycles of Freeze-Thaw. Tests showed some, though not entirely consistent, tendency for progressive increase in heave and decrease in density up to 3 freeze-thaw cycles. However tests of longer duration using improved procedures are required.

g. Effectiveness of Calcium Acrylate in Preventing Frost Action in Soils. Calcium acrylate was found to be very effective in preventing ice segregation in a clay soil but was not as completely successful in a silt soil. The effectiveness was not reduced by two cycles of alternate freezing and thawing.

h. Effect of Rate of Penetration of 32°F. Temperature. The rate of heave of the surface is generally independent of rate of freezing within the range of 1/4 to 1-3/4 inches per day. However, the heave per unit depth of frozen material is inversely proportional to the rate of penetration of the freezing temperature.

i. Frost Action In Minus 200-Mesh Soil Fractions. The minus 200-mesh fractions of four quite different soils showed nearly equal rates of heave, although the fines of two of these soils showed distinctly different frost susceptibilities when mixed with various coarse fractions in proportions to approach borderline frost susceptibility.

j. Effect of Mineral Composition of Fine Soil Fraction. The influence of mineral composition of the fine soil fraction on ice segregation in the tests performed to date is largely masked by fluctuations in other factors (define or enumerate), by the presence of several minerals in each soil fraction and by a lack of sufficient information on the nature of the adsorbed ions in the clay fractions.

k. Effect of Permeability. Soils with coefficients of permeability between 100×10^{-4} and 10×10^{-4} cm/sec. are from low to negligible frost susceptibility, and frost susceptibility increases until maximum rates of heave are reached in the range of permeability between 0.1×10^{-4} to 0.001×10^{-4} cm/sec.

1. Frost Susceptibility of Various Airfield and Highway Base and Subgrade Soils. Soils in similar soil groups, when classified by the Department of the Army Uniform Soil Classification System, show approximately the same rates of heave for corresponding percentages finer than 0.02 mm., and the percentage of material finer than 0.02 mm. for which a given rate of heave is obtained increases progressively with each group from Sandy Gravel and Gravelly Soils (GW) toward the fine-grained soils, Gravelly Sandy Clay and Clay (CL).

PART V - RECOMMENDATIONS

5-01. Since the investigations covered in this report include the results of tests performed up to the end of June 1951 and the volume of data is large, time has permitted only relatively rapid analysis. It is therefore recommended that further and more searching analysis of the data presented herein be performed before other than limited testing is resumed in Fiscal Year 1952, and that the results of this study then be used to revise and readjust in detail the subsequent testing program. These studies should aim particularly at tracing out more precisely the physical explanations of some of the observed results and interrelating more closely the results of the different phases of the investigation.

5-02. It is recommended that the following specific phases of the cold room studies be continued or investigations be initiated to determine:

a. The relative frost susceptibility of typical subgrade and base course materials covering the full range of soil types and gradations and obtained from locations with wide geographical distribution.

b. The effect of grain size distribution and mineral composition of fine soil fraction on frost action.

c. The effect of proximity of water table on ice segregation in frost susceptible soils.

d. The effect of admixtures in preventing or minimizing ice segregation in frost susceptible soils.

e. The minimum degree of saturation at which ice segregation is possible in various soil types without an outside source of water.

f. The effect of freezing point of soil moisture on ice segregation in soils.

g. The effect of frost melting on strength characteristics of soils, including studies of the relationships between rate of thaw, amount of segregated ice, permeability and surcharge.

h. The effects of alternate freezing and thawing in altering frost susceptibility characteristics. of High Density materials

i. The frost characteristics of undisturbed fissured clays.

j. The nature of physical laws governing ice segregation in soils, an understanding of which is needed to aid the development of design criteria.

k. Moisture movement in vapor phase

l. Effect of surcharge load temperature & Pressure effects

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COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEARS 1950 - 1951

TABLE 1
SOILS SELECTED FOR COLD ROOM TEST PROGRAM

TEST IDENTIFICATION SYMBOL	SOURCE	DESCRIPTION	CORPS OF ENGINEERS UNIFORM SOIL CLASSIFICATION	SPECIFIC GRAVITY		% FINER THAN		MAXIMUM DRY DENSITY
				+ #10 SIEVE	- #10 SIEVE	#200 SIEVE	0.02 mm.	
(a) BASIC SOILS								
LSG	Limestone AFB, Limestone, Maine	Sandy Gravel Base	GW	2.70	2.73	6	5	139(1)
AG	Peabody, Massachusetts	Clean Sandy Gravel	GW	2.71	2.69	<1		130(2)
LS	Lowell, Massachusetts	Well-graded Sand	SW		2.68	3		110(2)
MFS	Manchester, New Hampshire	Uniform fine Sand	SP		2.68	8	1	109(2)
NH	Goff's Falls, New Hampshire (Referred to as New Hampshire Silt)	Silt	ML		2.70	85-96	58-73	107(3)
EBT	Governor's Island, East Boston (Referred to as East Boston Till)	Gravelly Sandy Clay (Glacial Till)	CL		2.76	49	43	131(3)
BC	North Cambridge, Massachusetts (Referred to as Boston Blue Clay)	Clay	CL		2.72-2.81	99	84-90	77-84(5)
TD	Truax AFB, Madison, Wisconsin	Drumlin Soil, Silty Gravelly Sand Base and Subbase	SM	2.76	2.71	28-30	16-18	139(3)
LF	Ladd Field, Fairbanks, Alaska	Silt Subsoil	ML		2.74	91	37	100(4)
(b) TYPICAL BASES AND SUBGRADES FROM VARIOUS AIRFIELDS								
CA	Casper AFB, Casper, Wyoming	Silty Gravelly Sand Base	SM	2.64	2.65	23	15	
		Silty Sand Subgrade	SM	2.64	2.65	21-39	16-18	
CL	Clinton County AFB, Wilmington, Ohio	Clayey Sandy Gravel Base	GC	2.75	2.72	20	14	
DFC	Dow AFB, Bangor, Maine	Clay Subgrade	CL		2.75-2.79	93-100	72-89	
DFT		Sandy Clay Subgrade	CL		2.71	80	64	
FA	Fargo Municipal Airfield, Fargo, North Dakota	Clayey Sand (Subbase)	SC	2.69	2.70	16	9	
GF	Great Falls AFB, Great Falls, Montana	Clayey Sandy Gravel Base	GC	2.65	2.67	22	17	
HF	Hill AFB, Ogden, Utah	Silty Sand Subgrade	SM		2.64	27	13	
LST	Limestone AFB, Limestone, Maine	Sandy Gravelly Clay Subgrade	CL	2.68	2.72	45-61	30-48	
LA	Lowry AFB, Denver, Colorado	Clayey Sand Subgrade	SC		2.64	36-42	24-31	
PT	Patterson Field, Fairfield, Ohio	Clayey Sandy Gravel Base	GC	2.76	2.71	22	15	
PA	Pierre Airfield, Pierre, South Dakota	Silty Gravelly Sand Base	GM-SM	2.77	2.69	17	9	
RC	Rapid City AFB. Rapid City, S.D.	Silty Sandy Gravel Base	GM	2.76	2.76	12	8	
SF	Sioux Falls Airfield, Sioux Falls, South Dakota	Silty Sandy Gravel Base	GM	2.74	2.70	15	9	
SPK	Spokane AFB, Spokane, Washington	Gravelly Sand Base	SP-GP	2.92	2.71	6	4	
WN	Wendover AFB, Wendover, Utah	Silty Sandy Gravel Base	GM	2.67	2.74	14	9	
(c) SELECT BORROW BASE MATERIALS FOR ALASKAN HIGHWAYS								
ACR	Alaska Highway, Section C, Tok Junction to the Alaska-Yukon Boundary	Alaska-Canadian Rock	GM	2.69	2.74	11	7	
AMS		Mica Schist	GW	2.71	2.76	5	3	
ADG		Decomposed Granite	GW	2.63	2.68	3	2	
AFS		Silty Fine Sand	SM		2.79	26	3	
BPR	Seward Highway and Kenai Highway, Alaska	Sandy Gravel	GW-GP	2.72-2.77	2.44-2.77	2-5	1-3	
		Silty Sandy Gravel	GM	2.72	2.72	27	11	

NOTES:
(1) Providence Vibrated Density on minus 3/4-inch material.
(2) Providence Vibrated Density on minus 1/2-inch material.
(3) Modified AASHO Method.
(4) Standard Proctor Method.
(5) Undisturbed Dry Density.

TABLE I

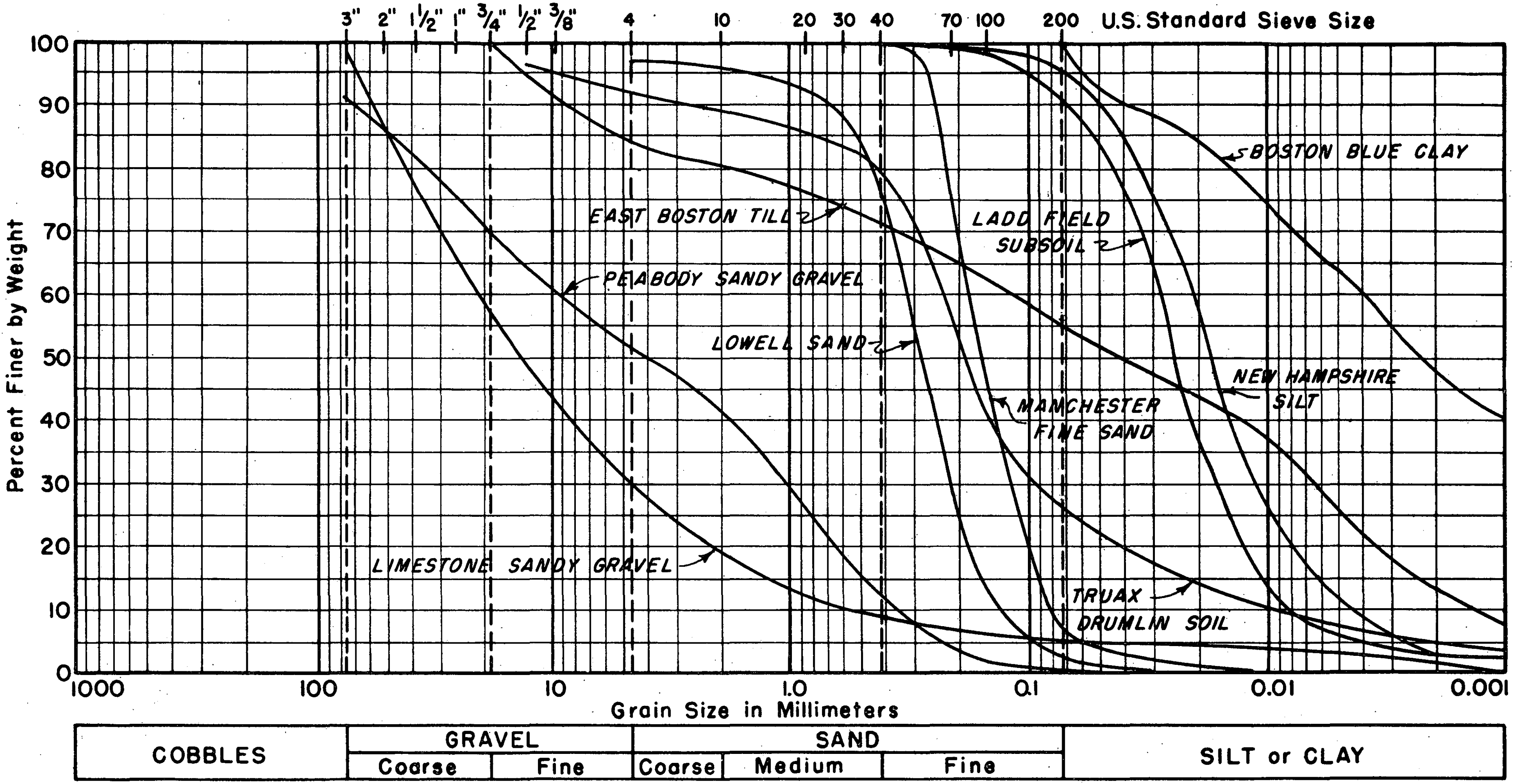
COLD ROOM STUDIES FOR FROST ACTION IN SOILS
FISCAL YEARS 1950 - 1951

TABLE 2

SUMMARY OF RESULTS
MINUS 200 MESH FRACTION SOILS

SAMPLE NO.	SOIL TYPE	ETHYLENE GLYCOL RETENTION IN g. GLYCOL/g. SOIL	APPROX. SURFACE AREA IN SQ. m/g SOIL	WATER CONTENT AT 50% RELATIVE HUMIDITY IN %	CARBONATE SPOT TEST	COMPOSITION IN %	
						MINERAL	PER CENT
1	Truax Drumlin Soil	21.2	68	2.8	Positive	Illite Dolomite Quartz	65 20 15
2	Patterson Field Clayey Sandy Gravel	13.0	42	1.6	Positive	Illite Quartz Dolomite Limonite	40 35 20 5
3	Clinton AFB Clayey Sandy Gravel	19.8	64	2.2	Positive	Illite Quartz Dolomite Limonite	60 25 10 5
4	Lowry AFB Clayey Sand	54.5	175	6.4	Positive	Illite Montmorillonite Magnesite Quartz	65 25 5 5
5	Limestone Sandy Gravel	7.9	25	1.3	Positive	Kaolinite Illite Limonite Magnesite	40 20 5 5
6	Dow AFB Till	13.0	42	2.3	Negative	Illite Quartz Gibbsite Limonite	45 40 5 5
7	Dow AFB Clay	11.4	37	1.5	Negative	Quartz Illite Gibbsite Limonite Feldspar and Mica	45 40 5 5
8	Boston Blue Clay	10.9	35	1.6	Negative	Illite Quartz Limonite Feldspar and Mica	40 15 5
9	East Boston Till	7.2	23	1.0	Negative	Quartz Illite Kaolinite Feldspar, Mica & Limonite	30 20 20
10	Limestone Glacial Till	8.0	26	0.9	Negative	Quartz Kaolinite Illite Mica	30 30 15
11	Peabody Sandy Gravel	7.4	24	1.2	Negative	Quartz Garnet, Topaz, Amphibole	40
12	New Hampshire Silt	4.4	14	1.2	Negative	Quartz Feldspar, Mica, Apatite	55
13	Ladd Field Silt	5.6	18	0.9	Negative	Quartz Amphibole, Feldspar	35

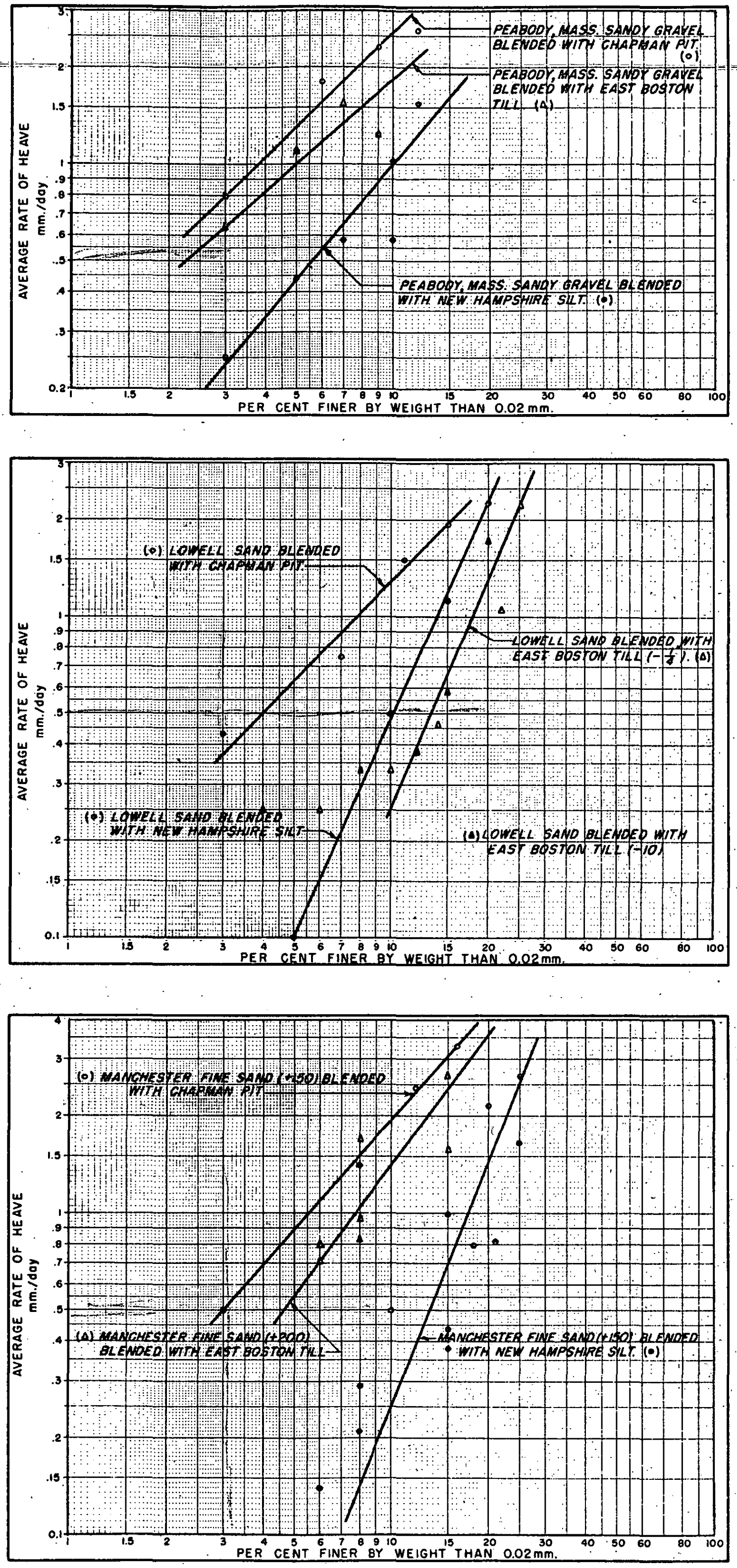
TABLE 2



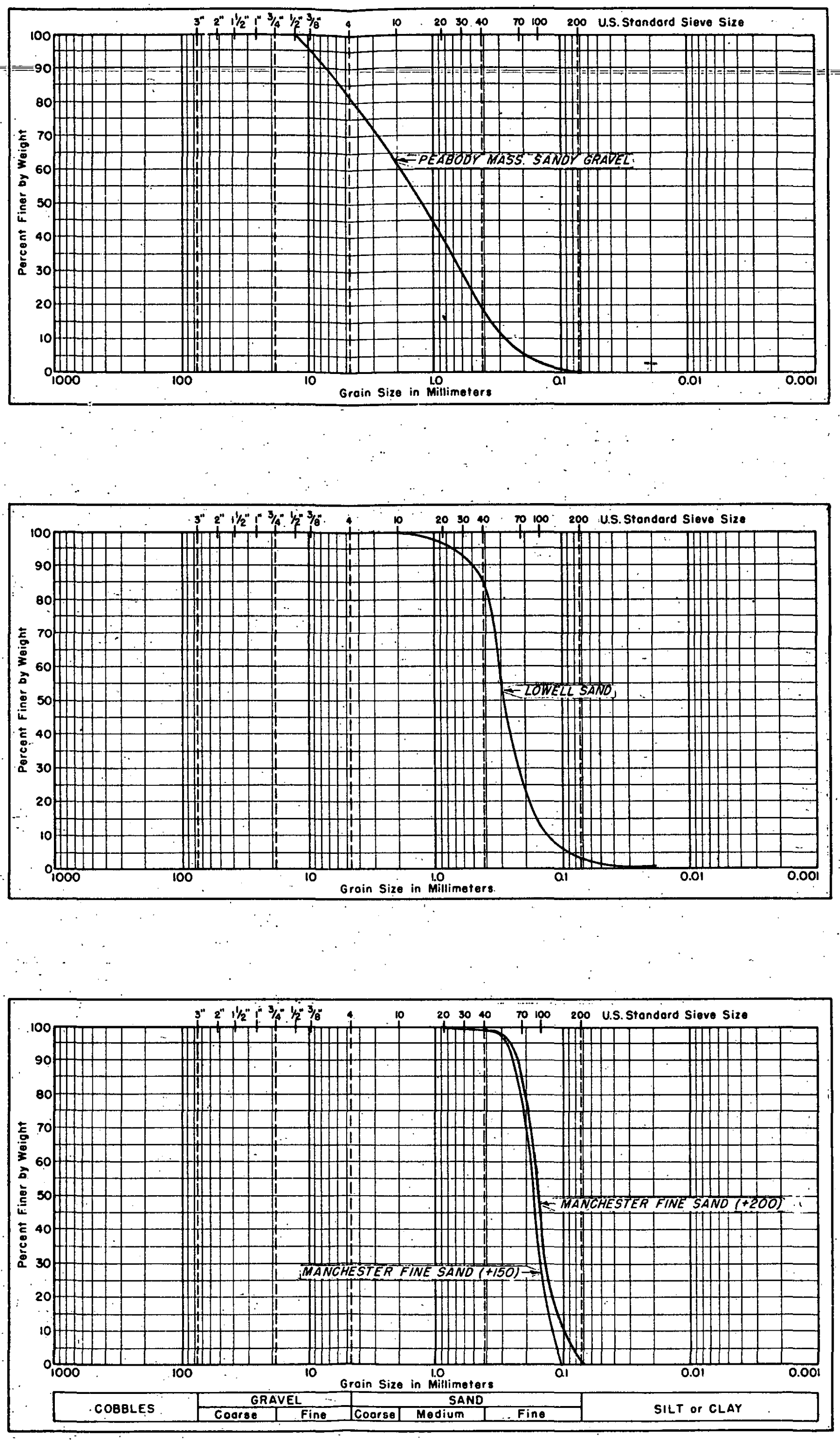
COLD ROOM STUDIES 1950 - 1951

GRADATIONS OF BASIC SOILS USED FOR TESTS

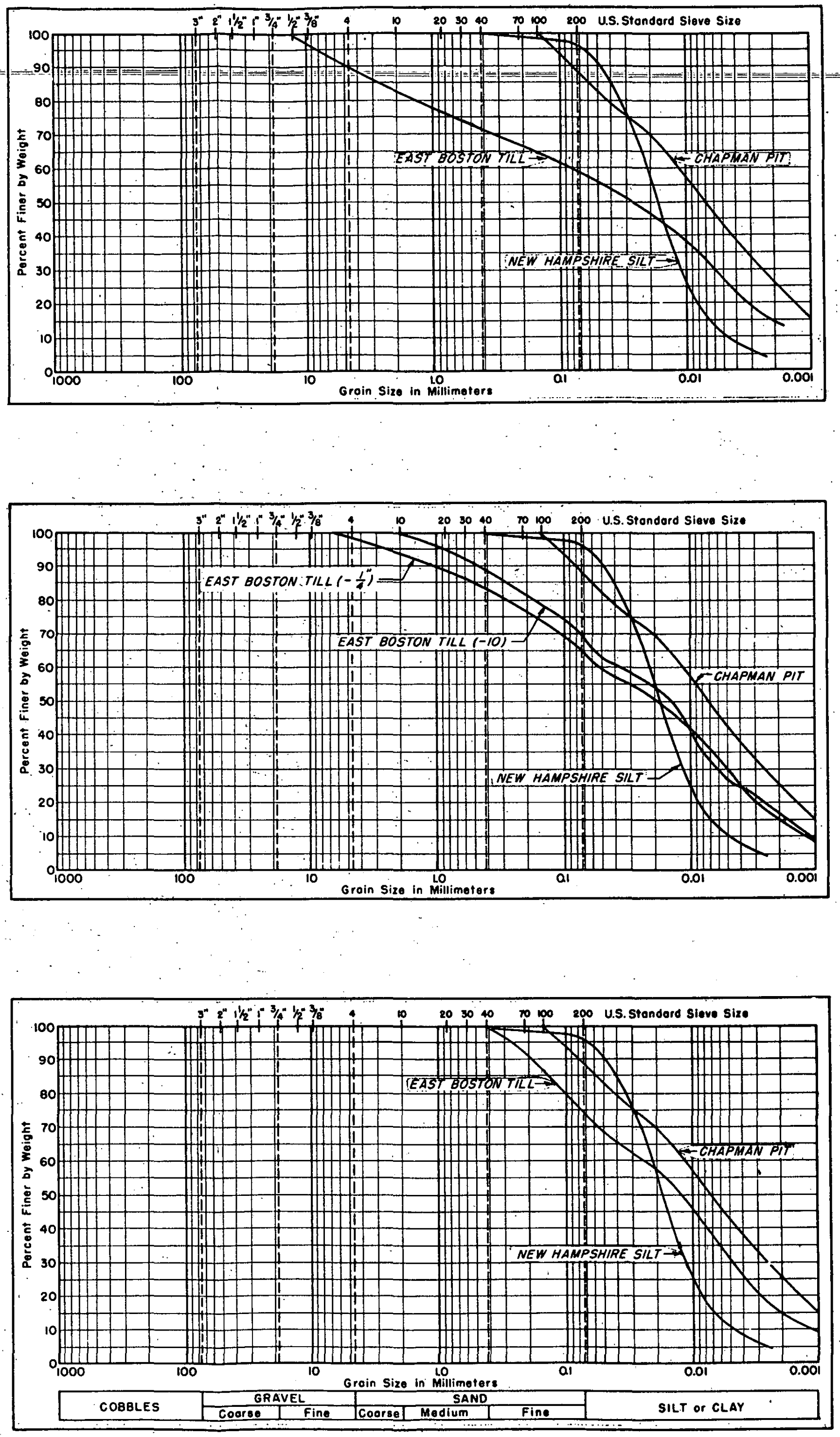
PLATE I



PLOTS FOR AVERAGE RATES OF HEAVE V.S.
PER CENT FINER BY WEIGHT THAN 0.02mm.



GRADATION CURVES FOR COARSE SOIL FRACTIONS



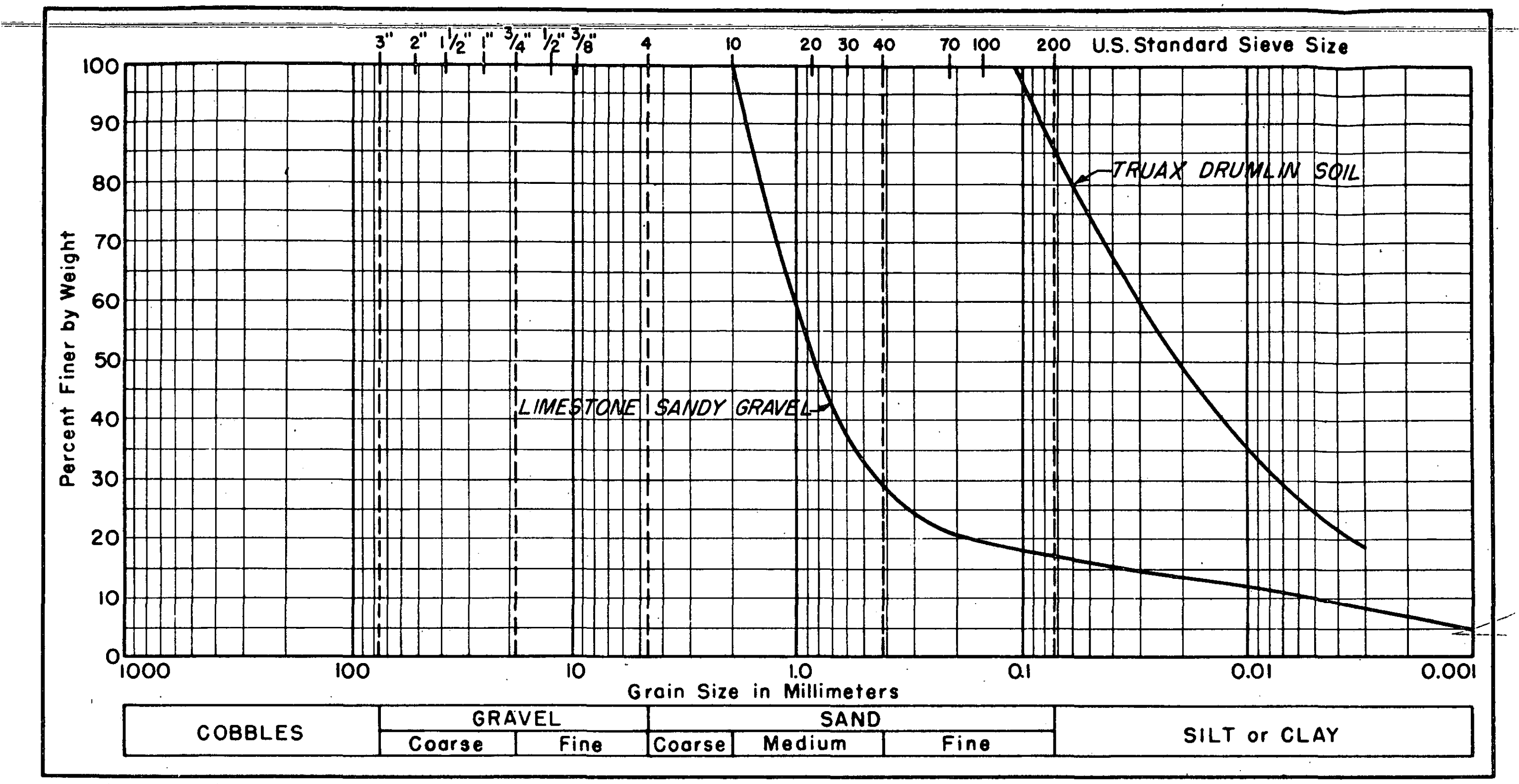
GRADATION CURVES FOR FINE SOIL FRACTIONS

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

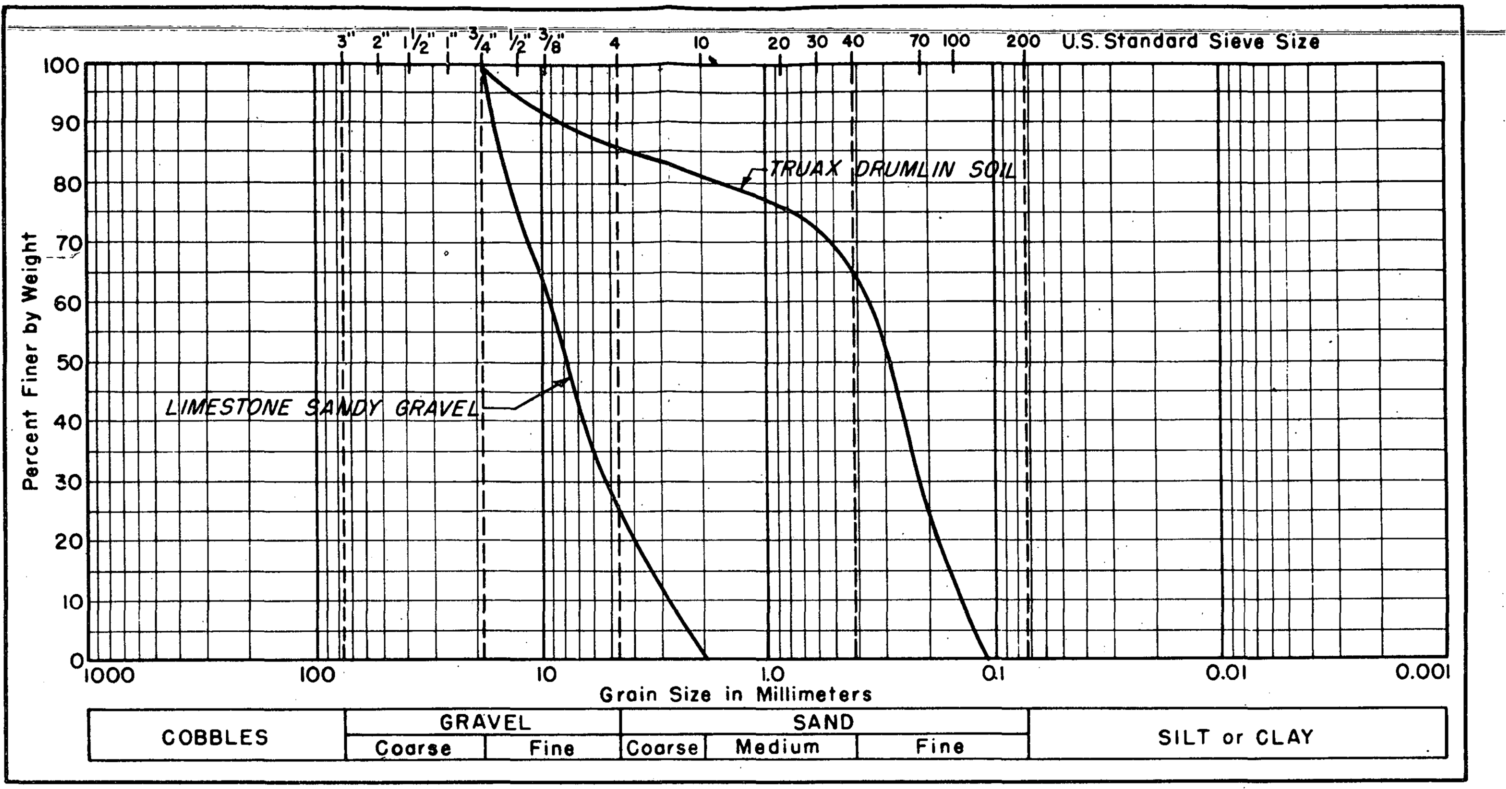
EFFECT OF
PER CENT FINER THAN 0.02mm.

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGINEERS
BOSTON, MASS.

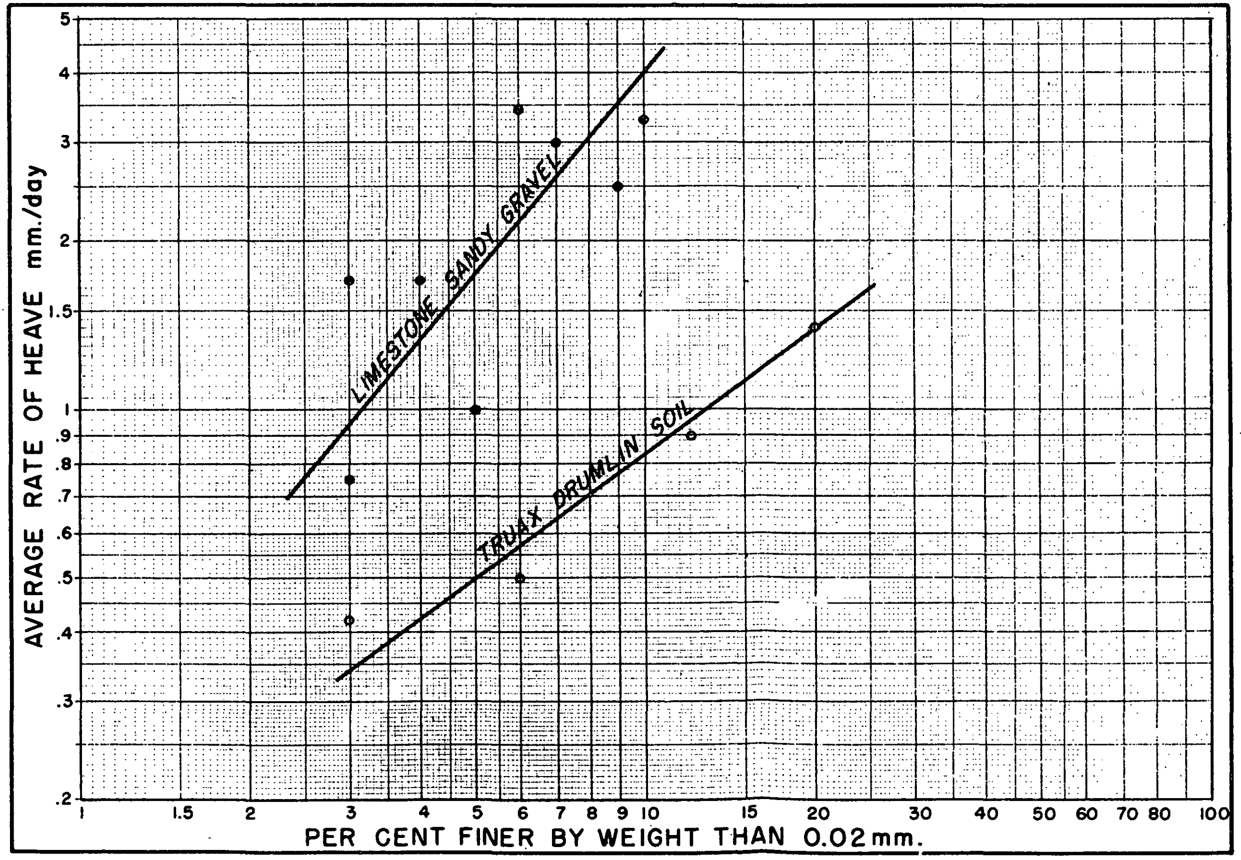
PLATE 2



GRADATION CURVES FOR FINE SOIL FRACTIONS



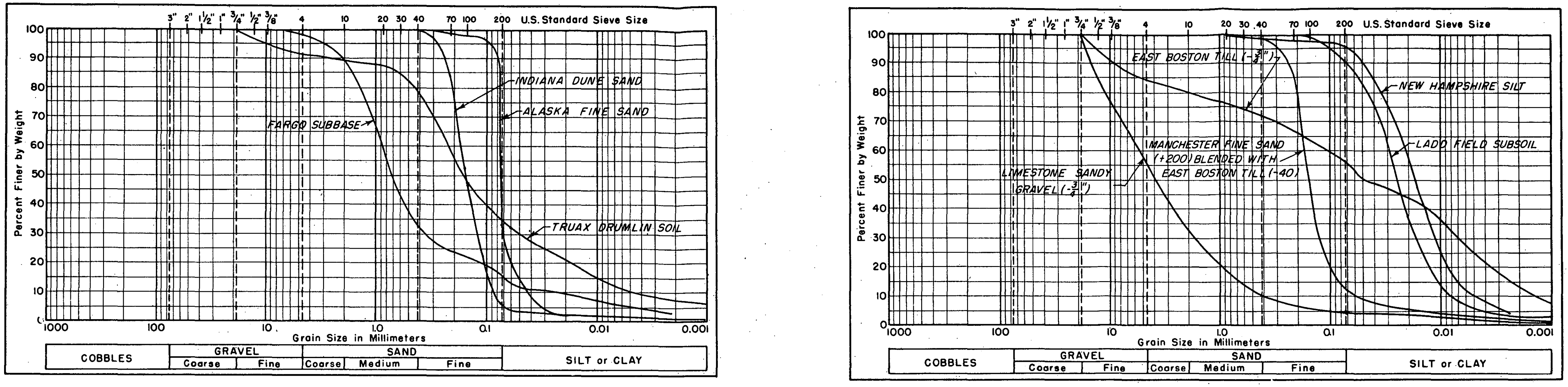
GRADATION CURVES FOR COARSE SOIL FRACTIONS



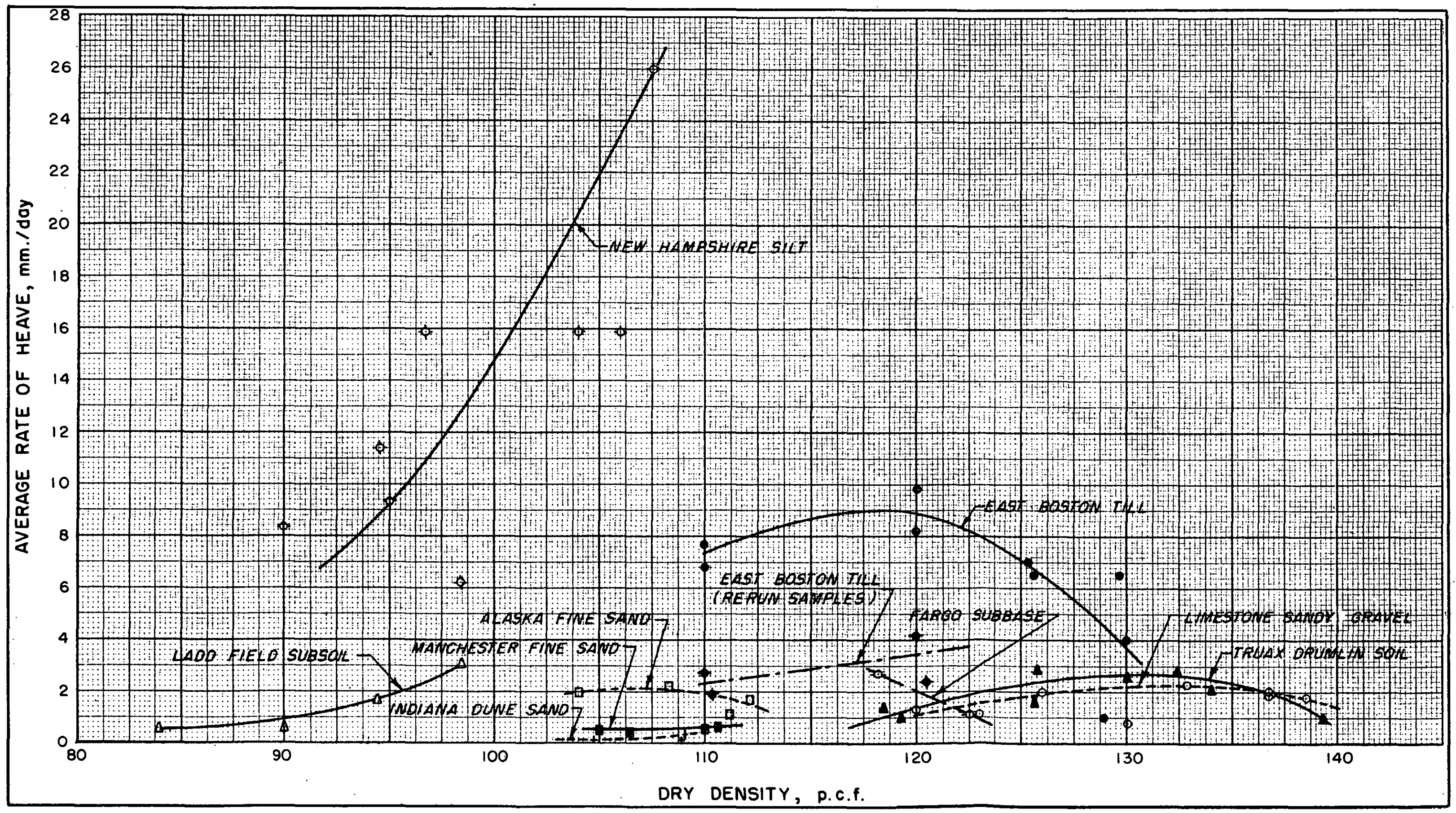
PLOTS FOR AVERAGE RATES OF HEAVE vs. PER CENT FINER BY WEIGHT THAN 0.02 mm.

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES
EFFECT OF
PER CENT FINER THAN 0.02 mm.

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGR.
BOSTON, MASS.



GRADATION CURVES



PLOTS OF AVERAGE RATE OF HEAVE vs DRY DENSITY

MATERIAL	MAXIMUM DRY DENSITY, p.c.f.
Alaska Fine Sand	107 (1)
East Boston Till	131 (2)
Fargo Subbase	127 (2)
Indiana Dune Sand	107 (1)
Ladd Field Subsoil	100 (3)
Limestone Sandy Gravel	139 (1)
Manchester Fine Sand	109 (1)
New Hampshire Silt	107 (2)
Truax Drumlin Soil	139 (2)

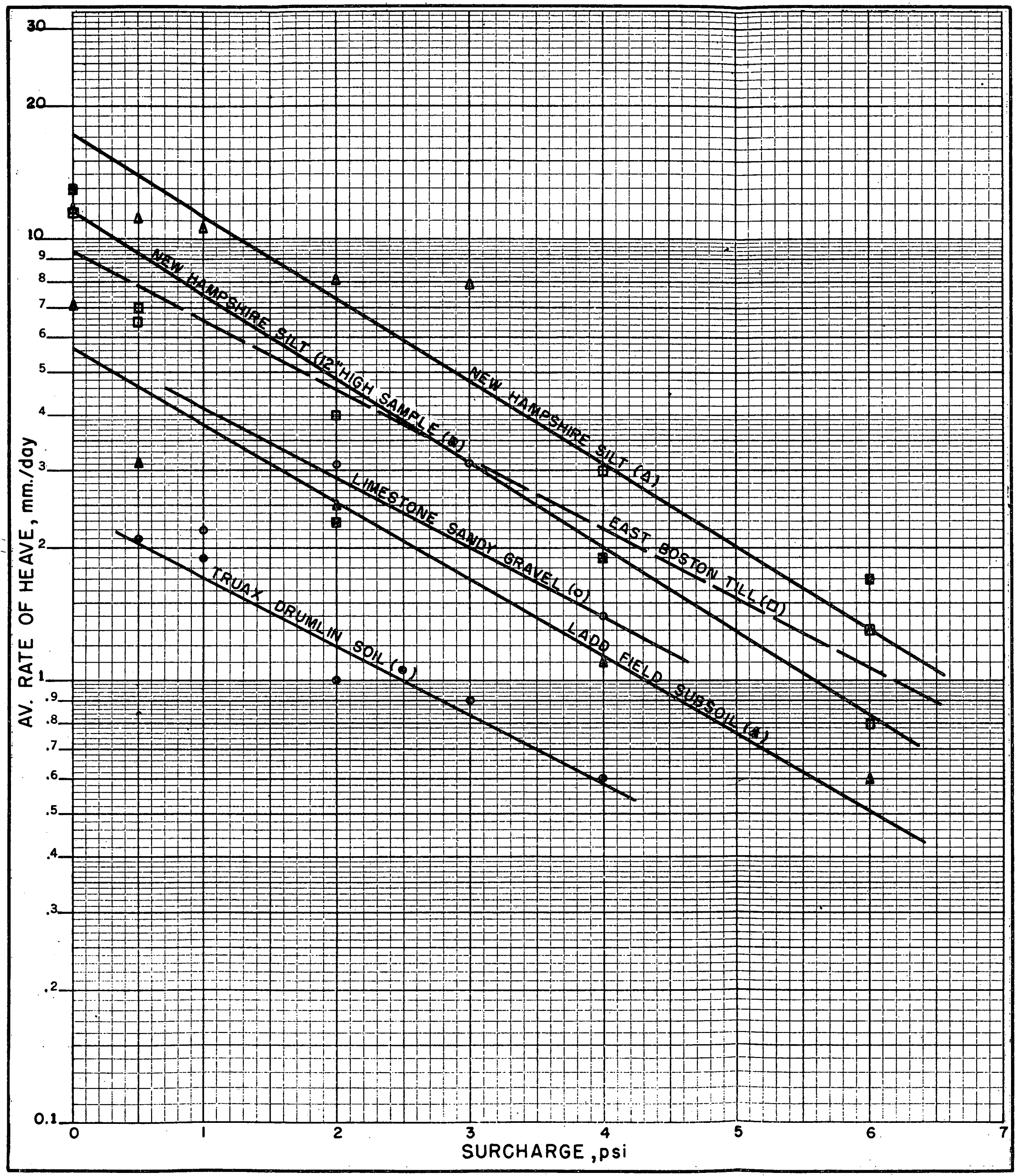
(1) Providence Vibrated Density
(2) Modified AASHO Method
(3) Standard Proctor Method

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

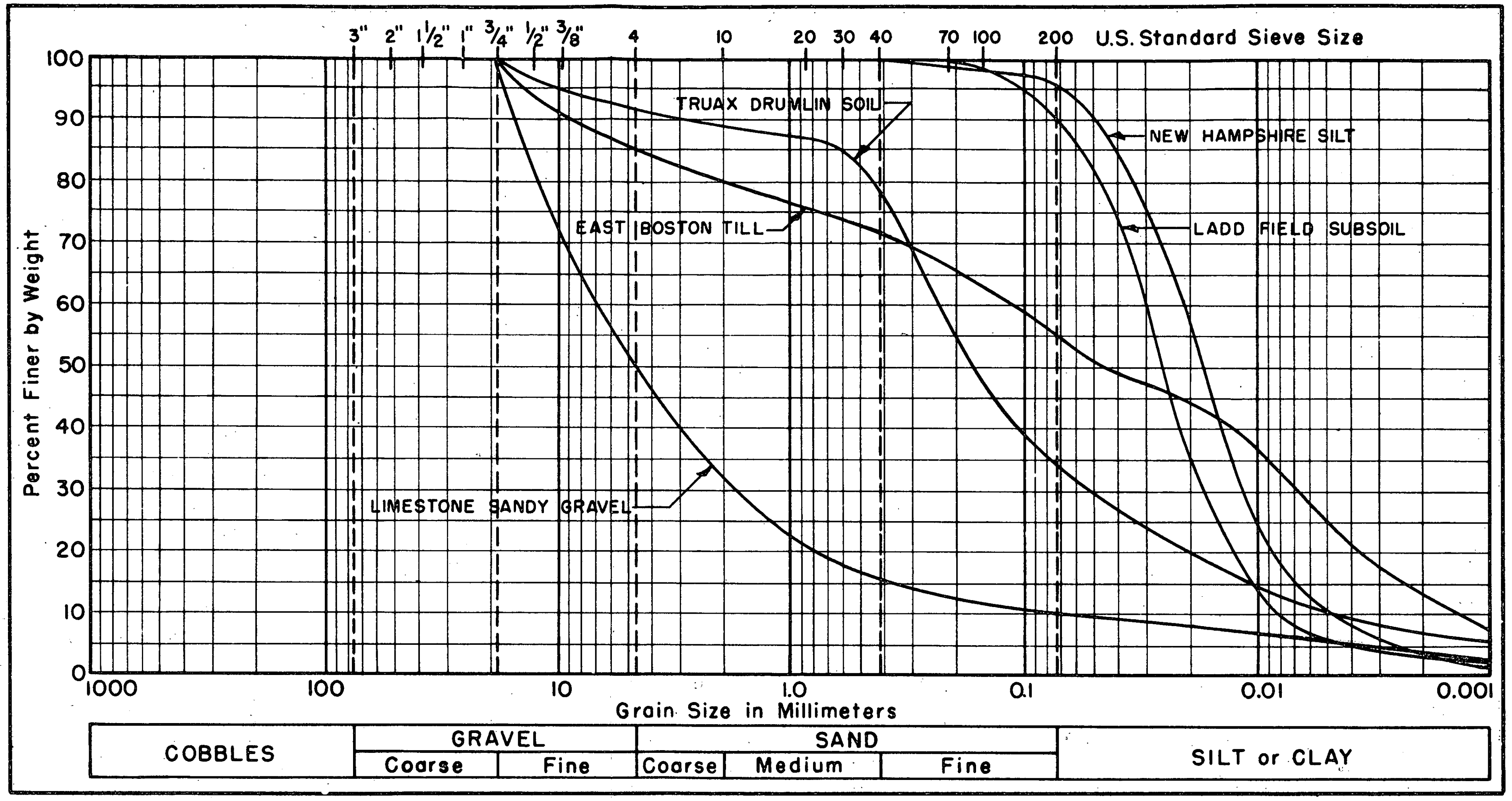
EFFECT OF
DEGREE OF COMPACTION

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGR.
BOSTON, MASS.

PLATE 4



PLOTS OF AVERAGE RATE OF HEAVE vs SURCHARGE



GRADATION CURVES

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

EFFECT OF
SURCHARGE

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGR.
BOSTON, MASS.

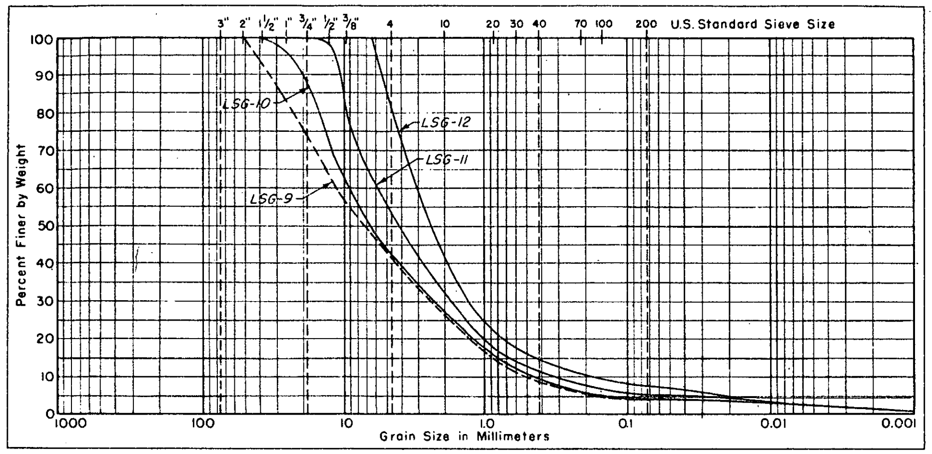


Figure 1
LIMESTONE SANDY GRAVEL

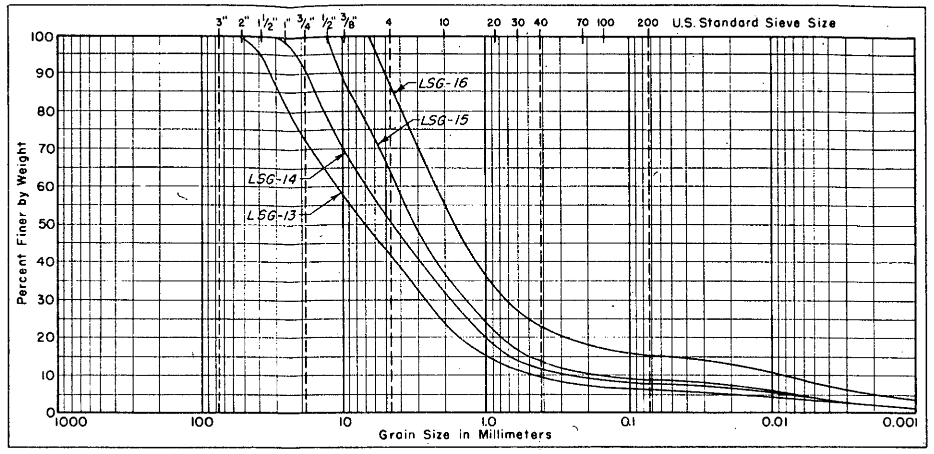


Figure 2
LIMESTONE SANDY GRAVEL
(NATURAL PIT RUN MATERIAL)

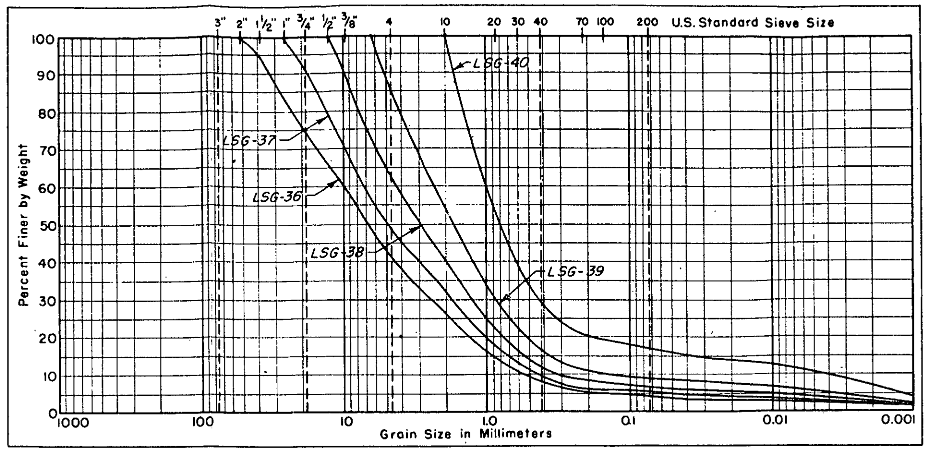


Figure 3
LIMESTONE SANDY GRAVEL

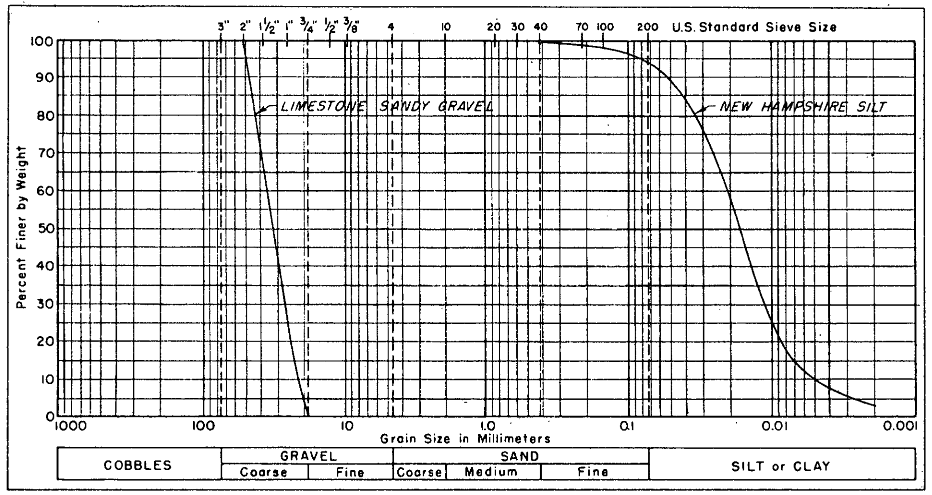


Figure 4
NEW HAMPSHIRE SILT BLENDED WITH LIMESTONE SANDY GRAVEL
(SAMPLES NHS-1 TO NHS-7 INCL.)

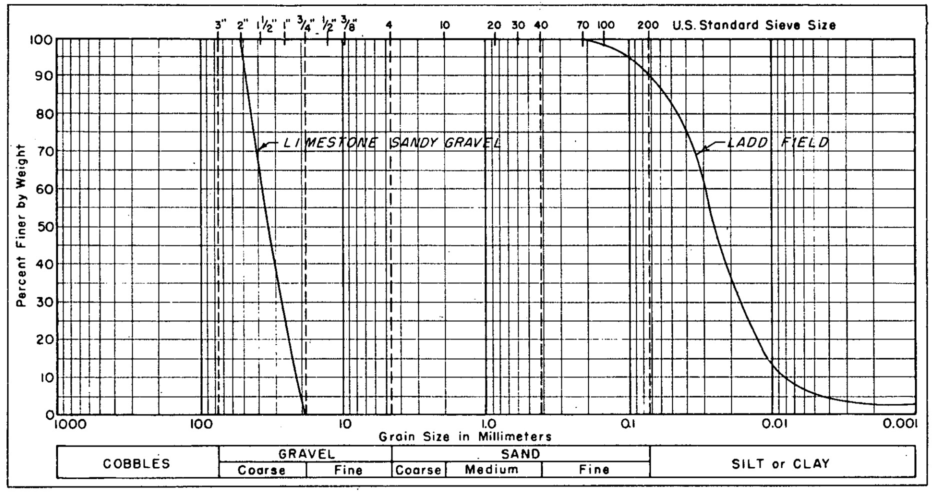


Figure 5
LADD FIELD SILT SUBSOIL BLENDED WITH LIMESTONE SANDY GRAVEL
(SAMPLES LF-6 TO LF-9 INCL.)

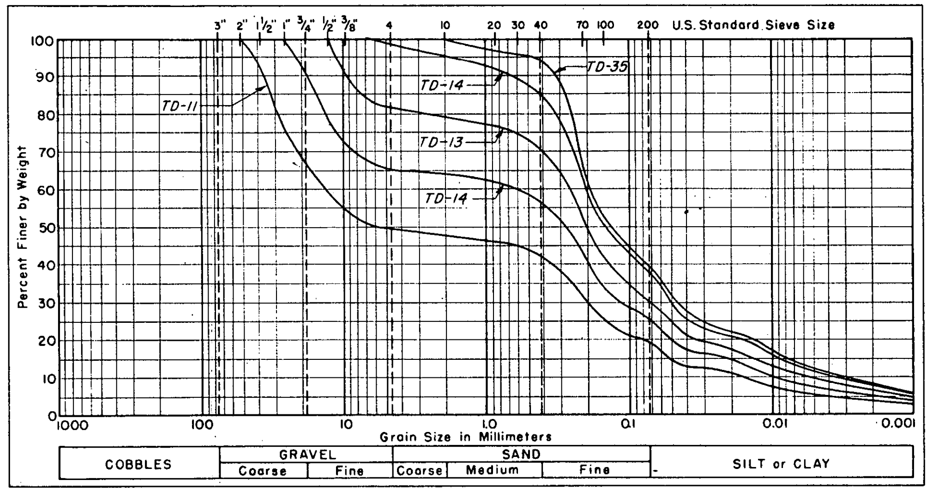
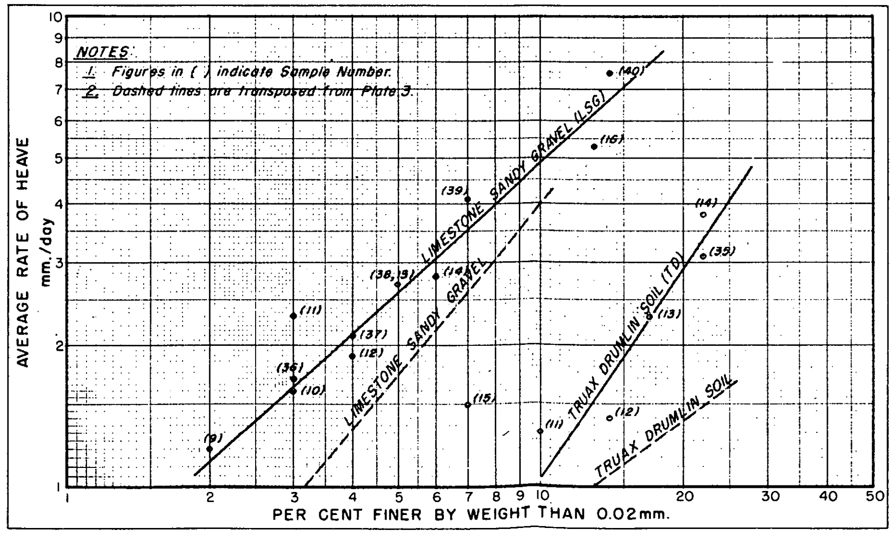


Figure 6
TRUAX DRUMLIN SOIL



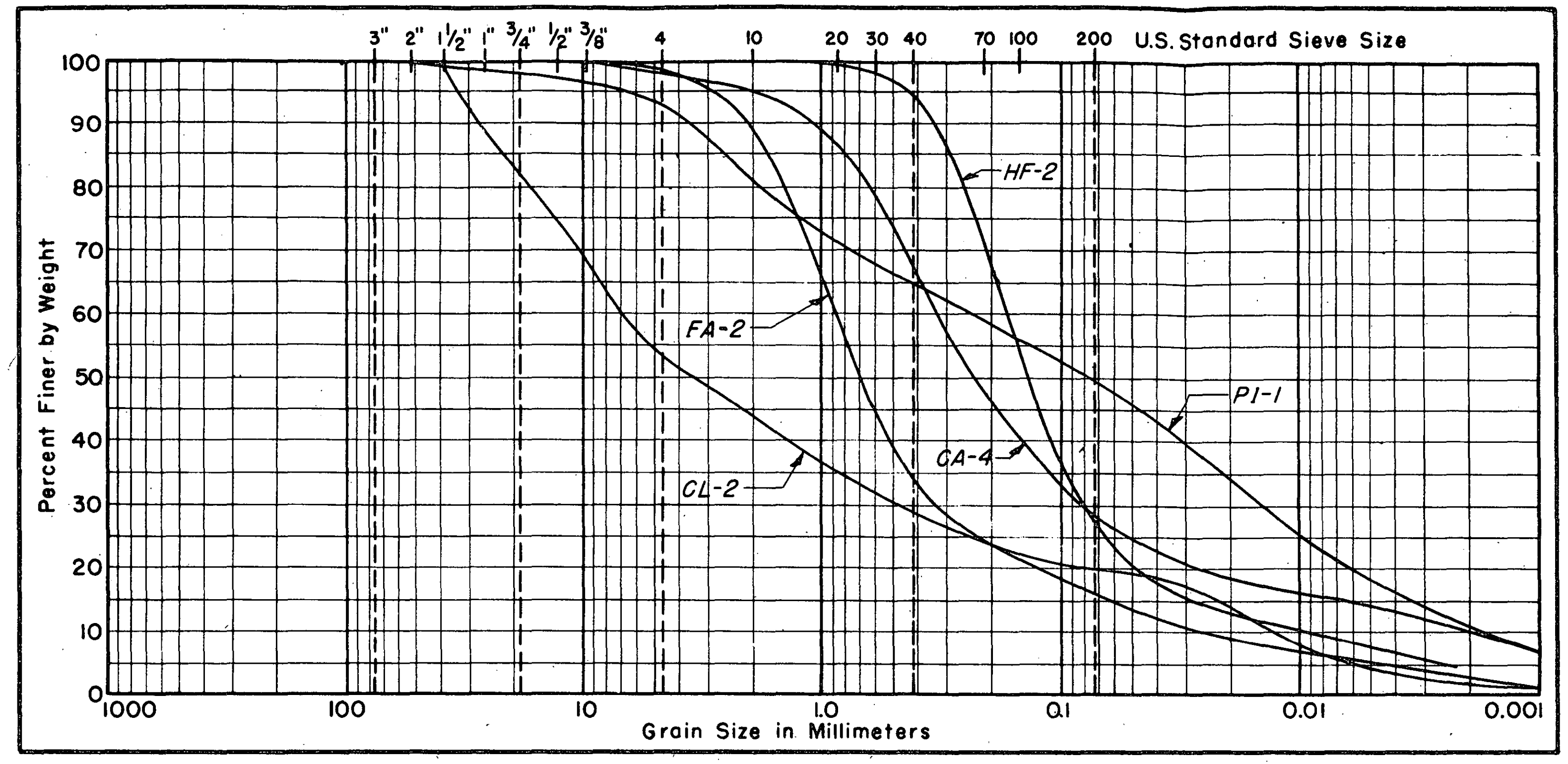
NOTES:
1. Figures in ( ) indicate Sample Number.
2. Dashed lines are transposed from Plate 3.

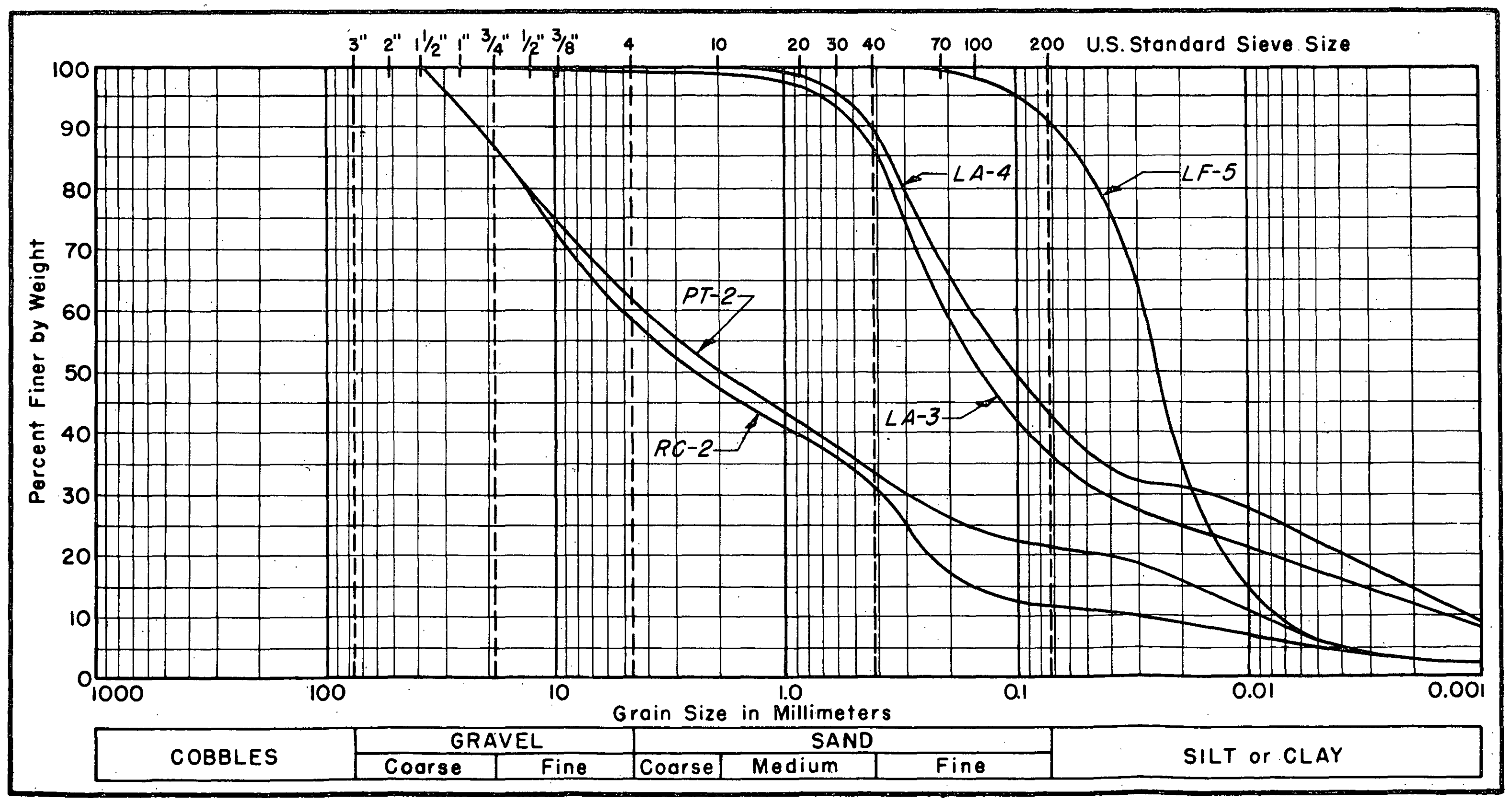
Figure 7
PLOT FOR AVERAGE RATE OF HEAVE VS. PER CENT FINER BY WEIGHT THAN 0.02mm.

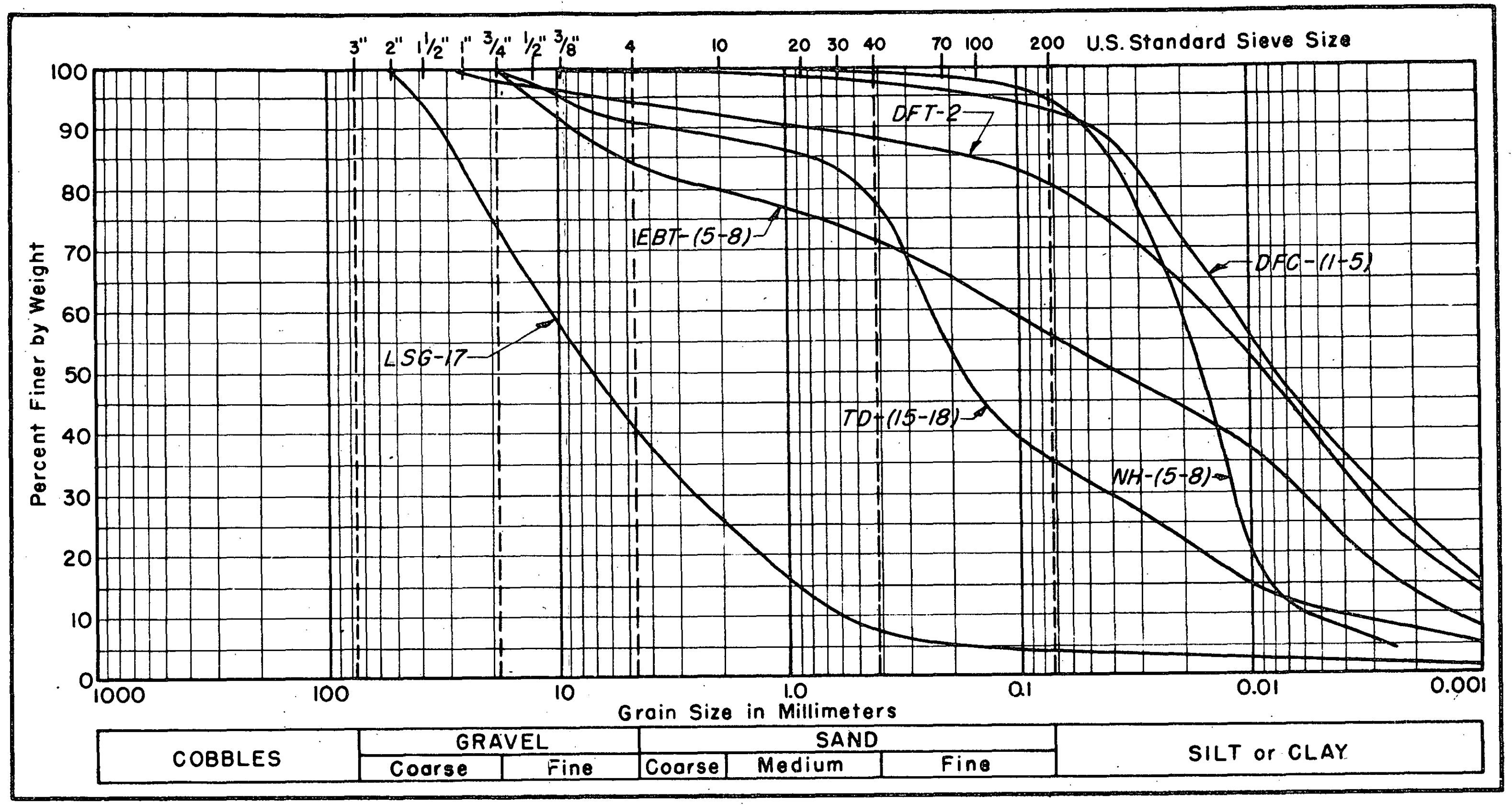
FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

GRADATION CURVES FOR EFFECT OF PER CENT AND SIZE OF COARSE AGGREGATE

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGINEERS
BOSTON, MASS.







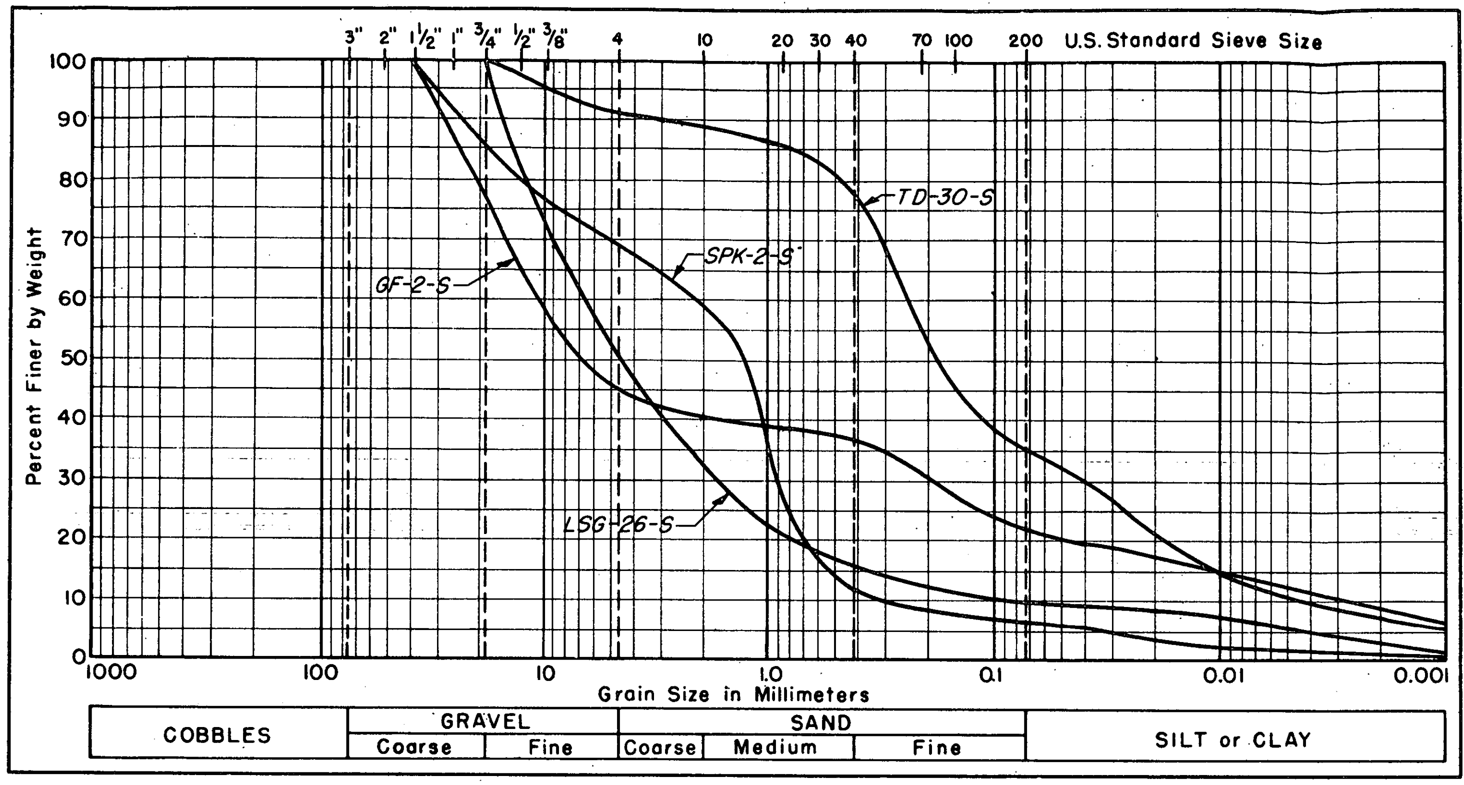
LEGEND:

LSG - Limestone AFB Sandy Gravel Base.
PI - Presque Isle AFB Silty Sandy Gravel Subgrade.
RC - Rapid City AFB Silty Sandy Gravel Base.
CL - Clinton County AFB Clayey Sandy Gravel Base.
PT - Patterson AFB Clayey Sandy Gravel Base.
TD - Truax AFB Drumlin Soil, Silty Gravelly Sand Base.
CA - Casper AFB Silty Sand Subgrade.
HF - Hill AFB Silty Sand Subgrade.
LA - Lowry AFB Clayey Sand Subgrade.
FA - Fargo Airfield Clayey Sand Subbase.
NH - New Hampshire Silt.
LF - Ladd Field Silt Subsoil.
DFC - Dow AFB Clay Subgrade.
DFT - Dow AFB Sandy Clay Subgrade.
EBT - East Boston Till.

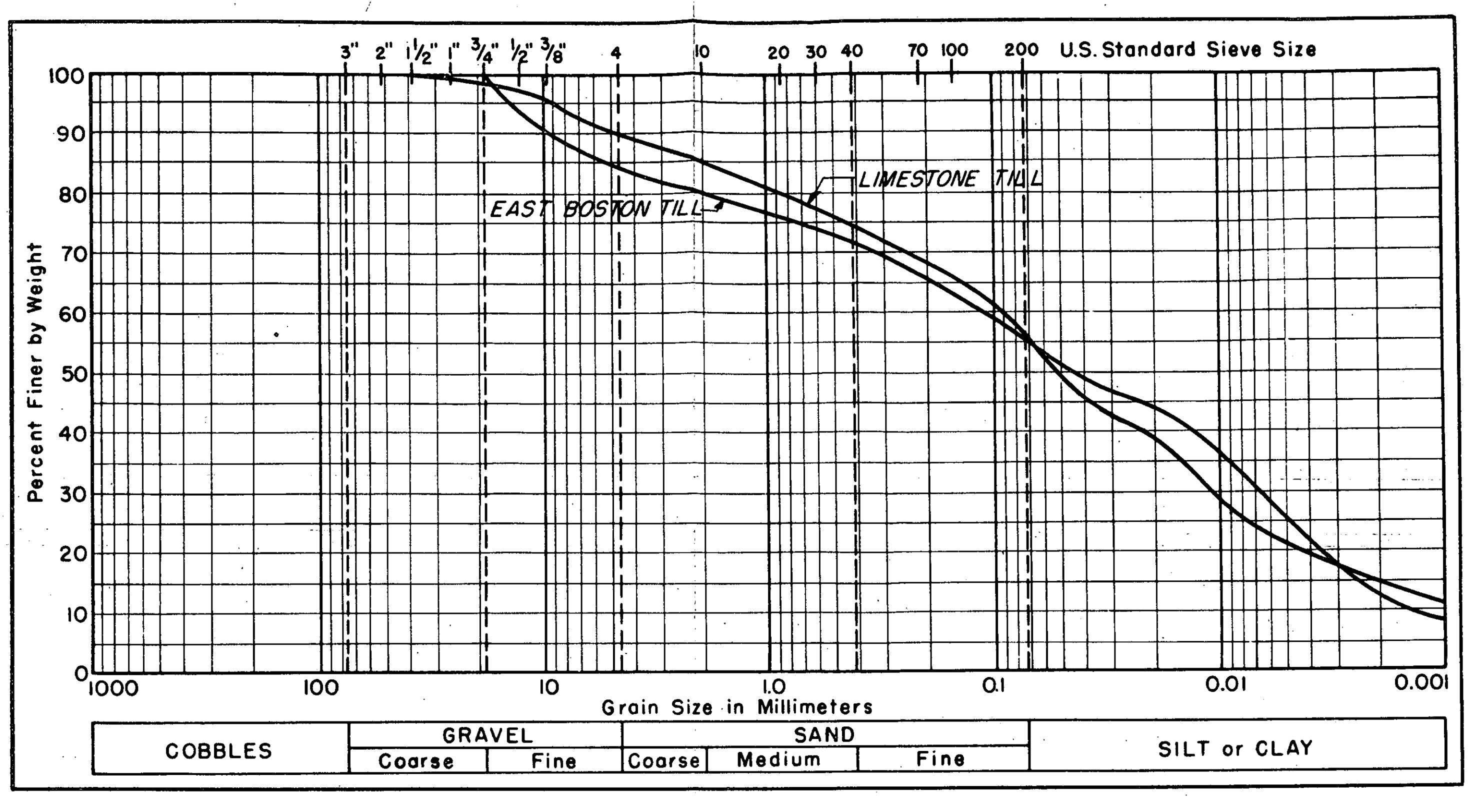
FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

GRADATION CURVES FOR
EFFECT OF
INITIAL DEGREE OF SATURATION

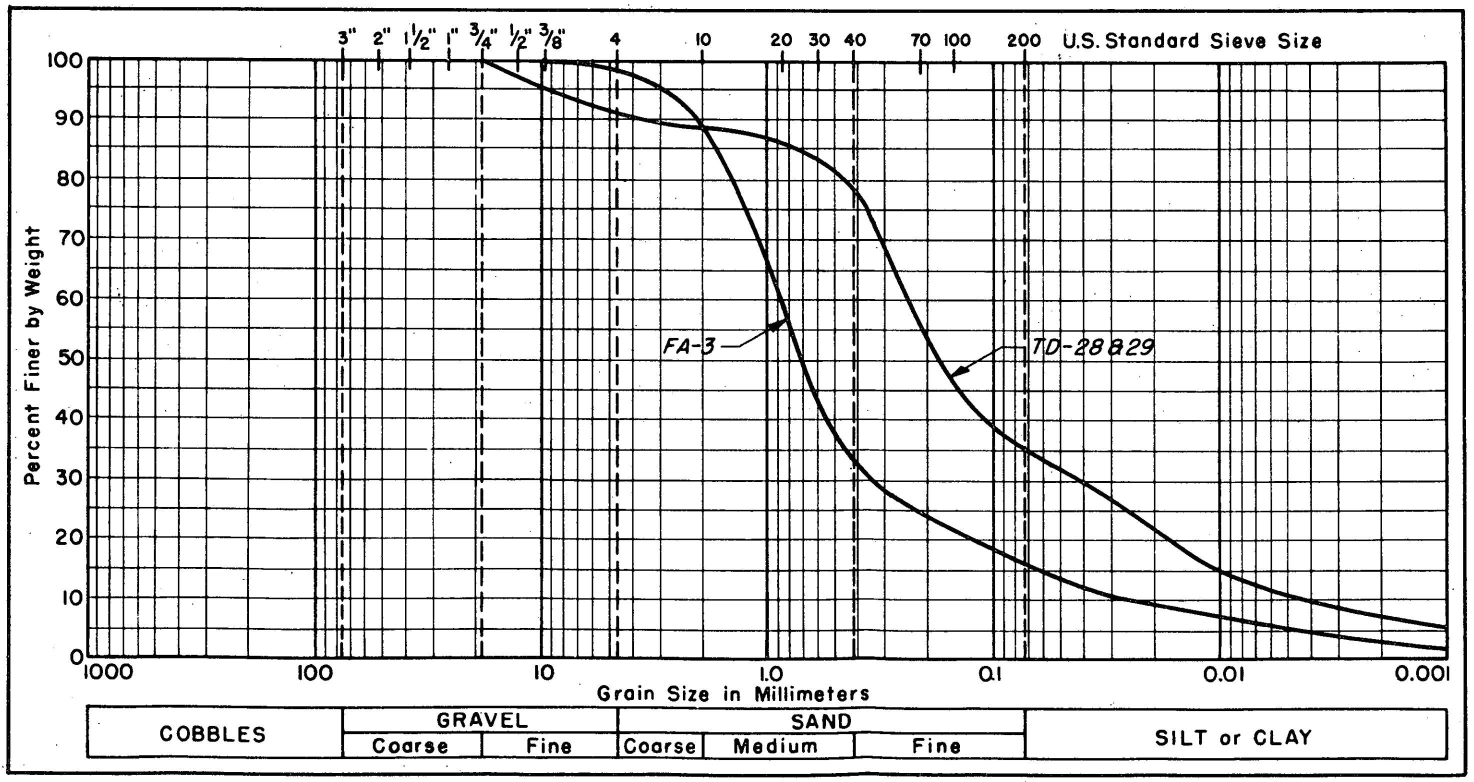
FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION, CORPS OF ENGR.
BOSTON, MASS.



GRADATION CURVES OF BASE MATERIALS



GRADATION CURVES OF SUBGRADE MATERIALS

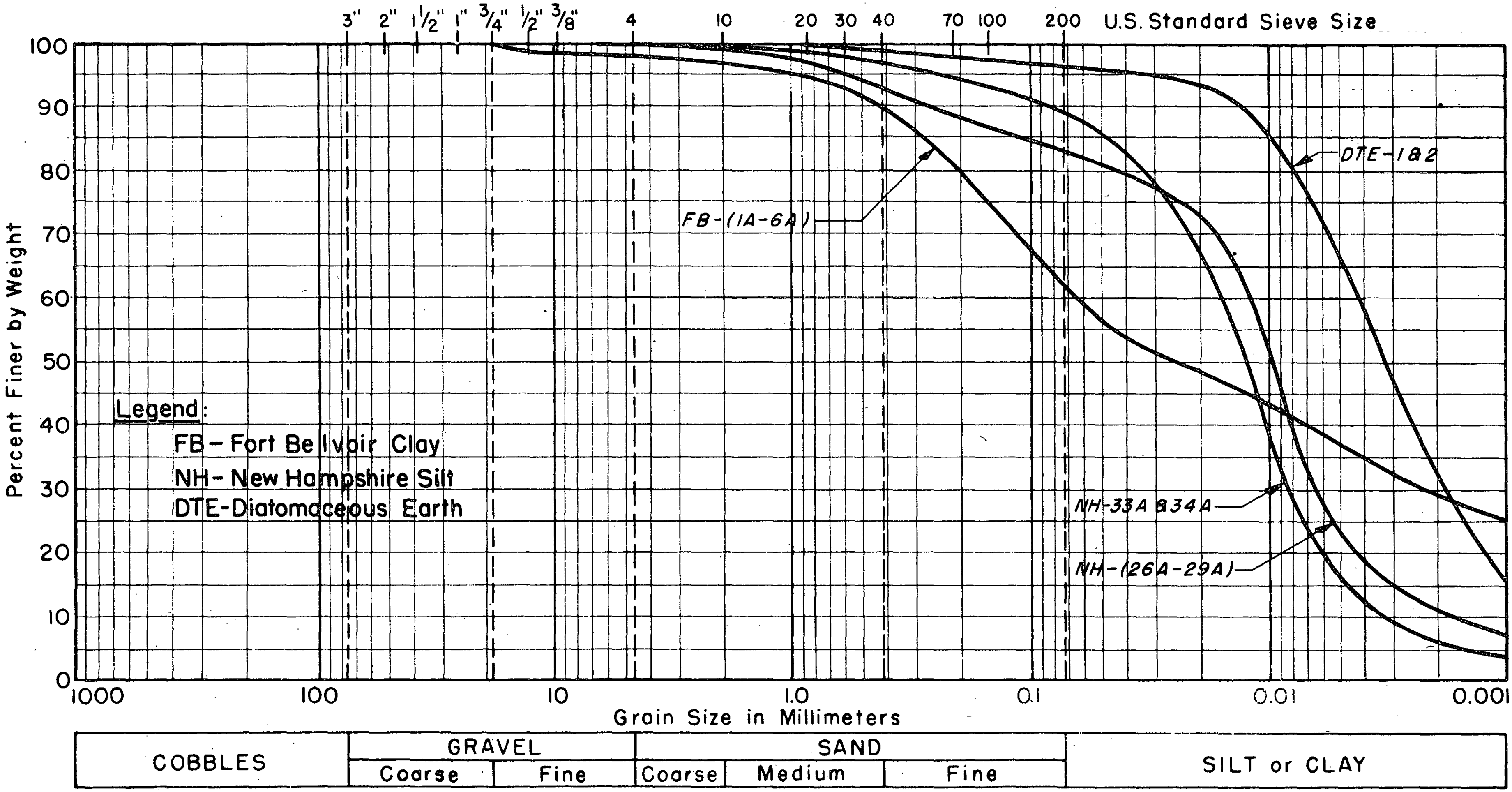


GRADATION CURVES OF TRUAX DRUMLIN SOIL AND FARGO MUNICIPAL AIRFIELD

FROST INVESTIGATION 1950–1951
COLD ROOM STUDIES

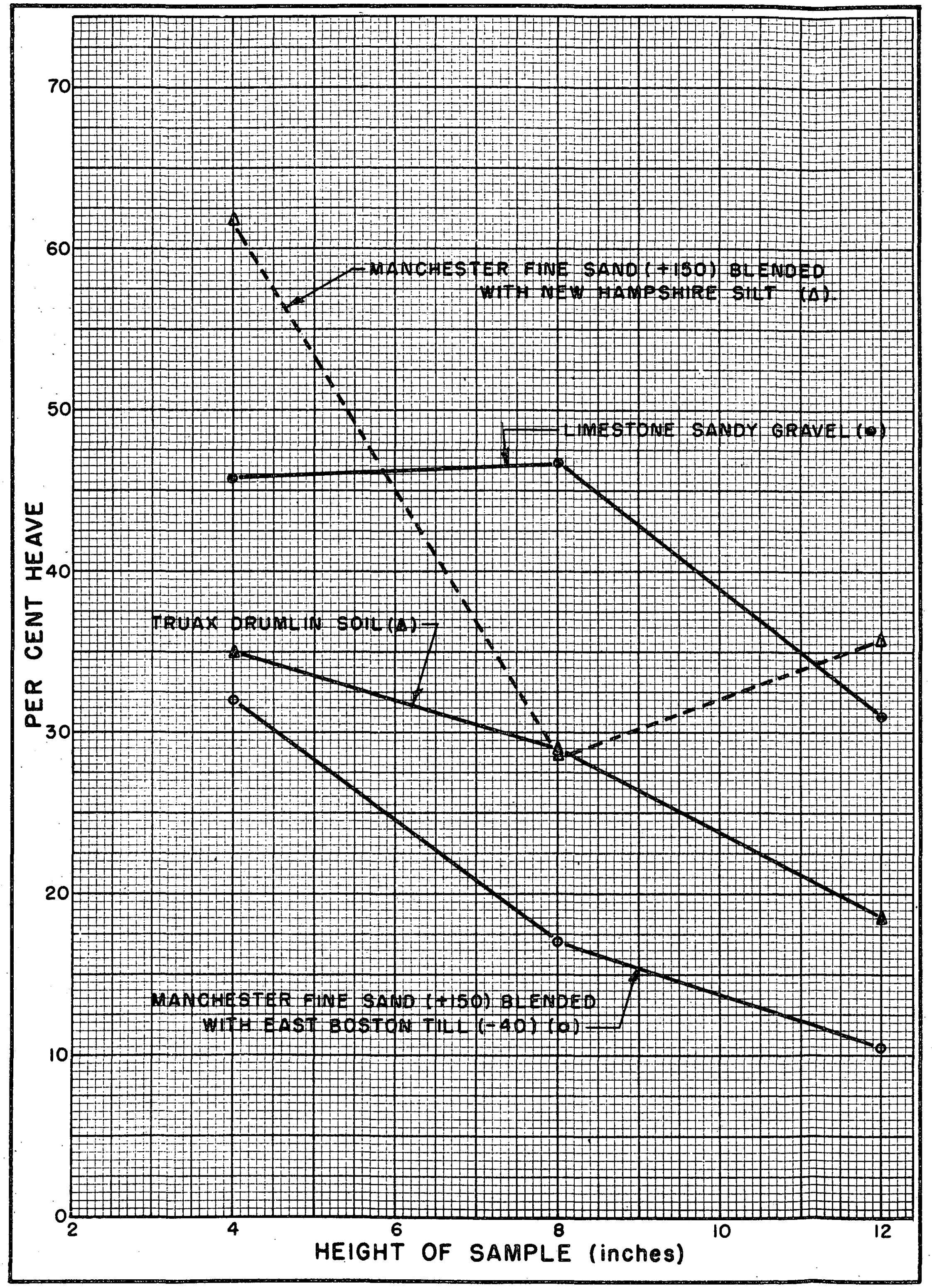
GRADATION CURVES FOR EFFECT OF ALTERNATE CYCLES OF FREEZE THAW

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGR.
BOSTON, MASS.

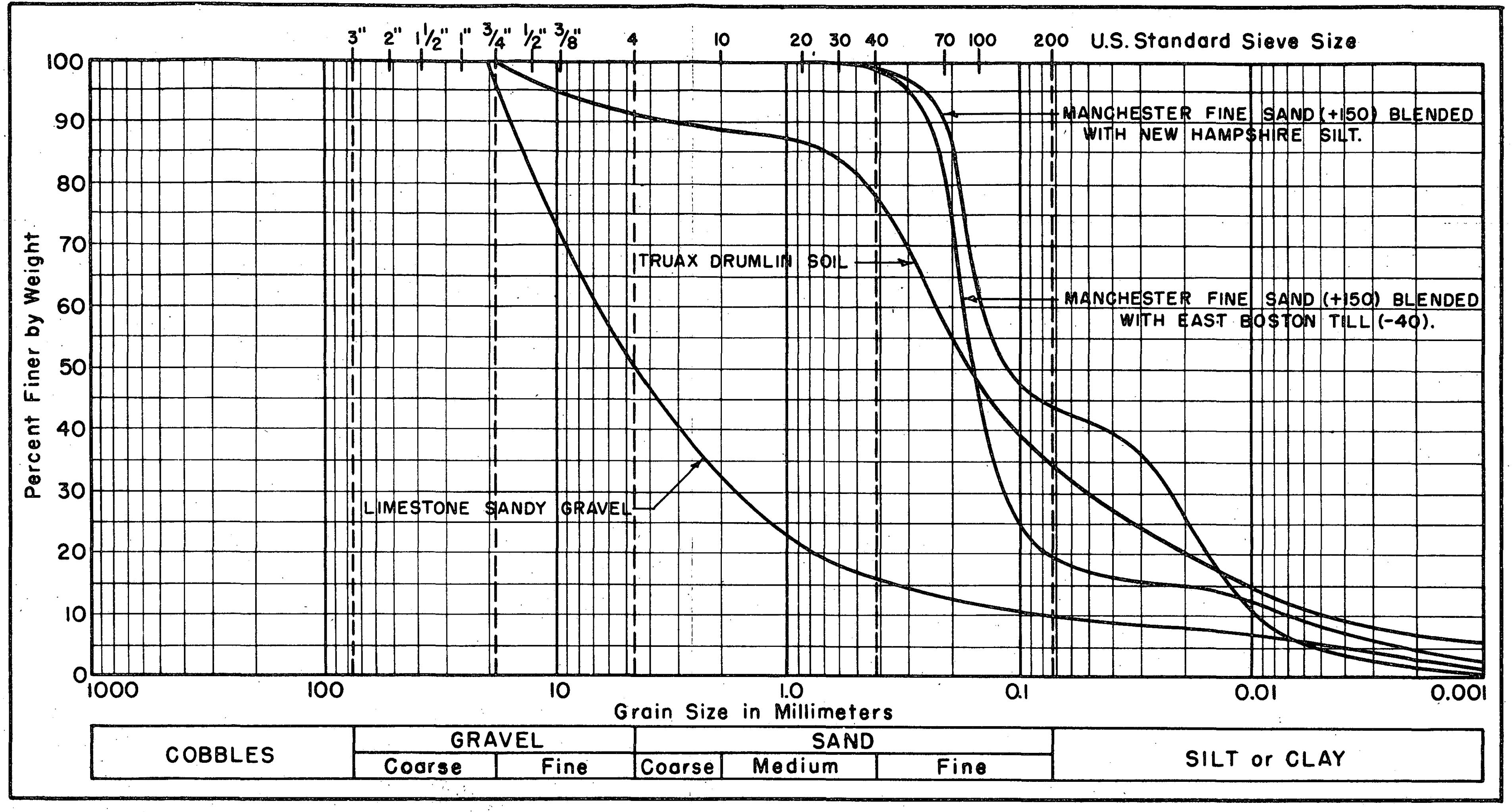


GRADATION CURVES FOR EFFECT OF ADMIXTURES

PLATE 9



PLOTS OF PER CENT HEAVE vs HEIGHT OF SAMPLE



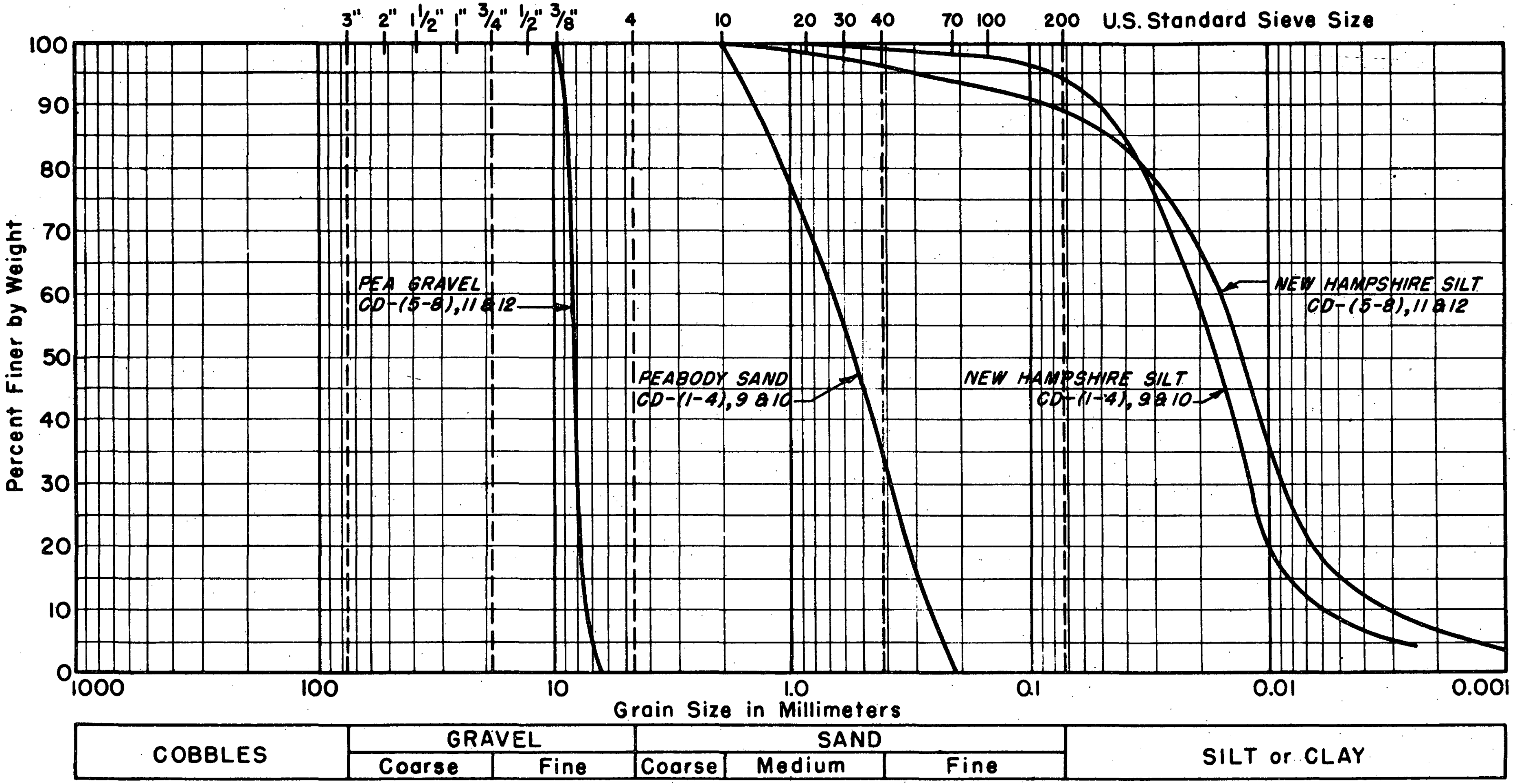
GRADATION CURVES

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

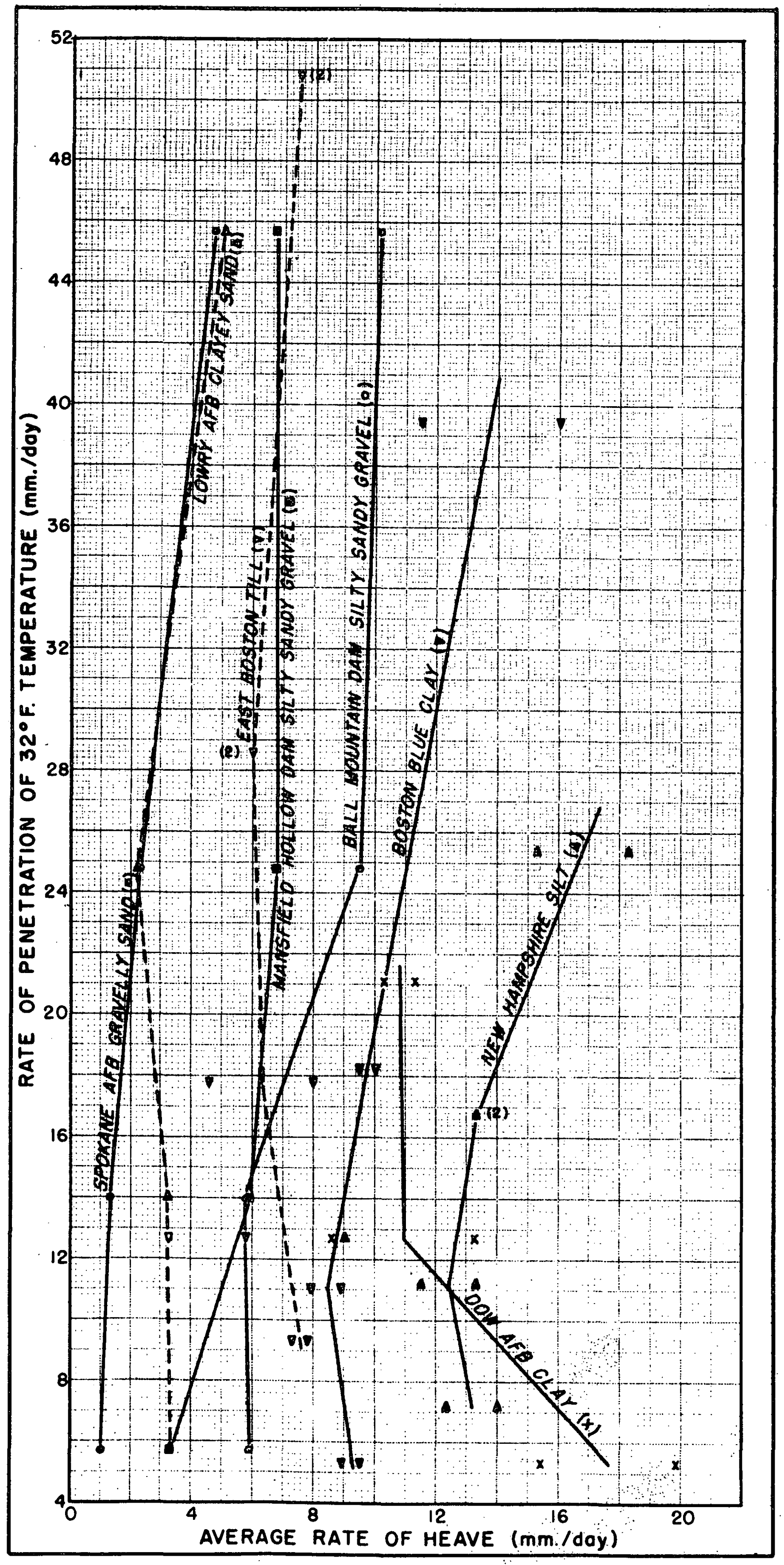
EFFECT OF
HEIGHT OF SAMPLE

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGR.
BOSTON, MASS.

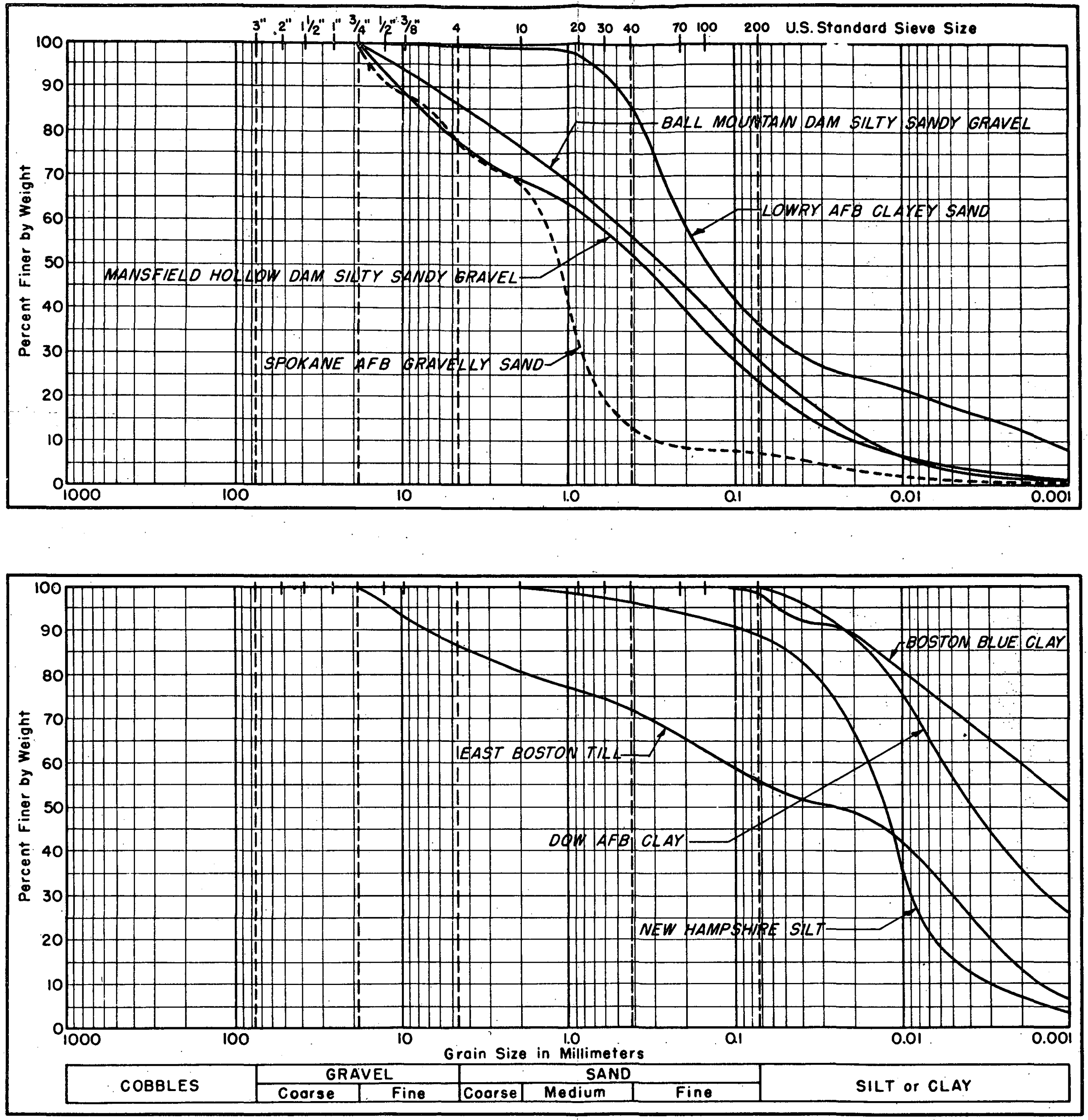
PLATE II



GRADATION CURVES FOR EFFECT OF CAPILLARITY AND CONDENSATION



PLOTS OF RATES OF PENETRATION vs AV. RATES OF HEAVE

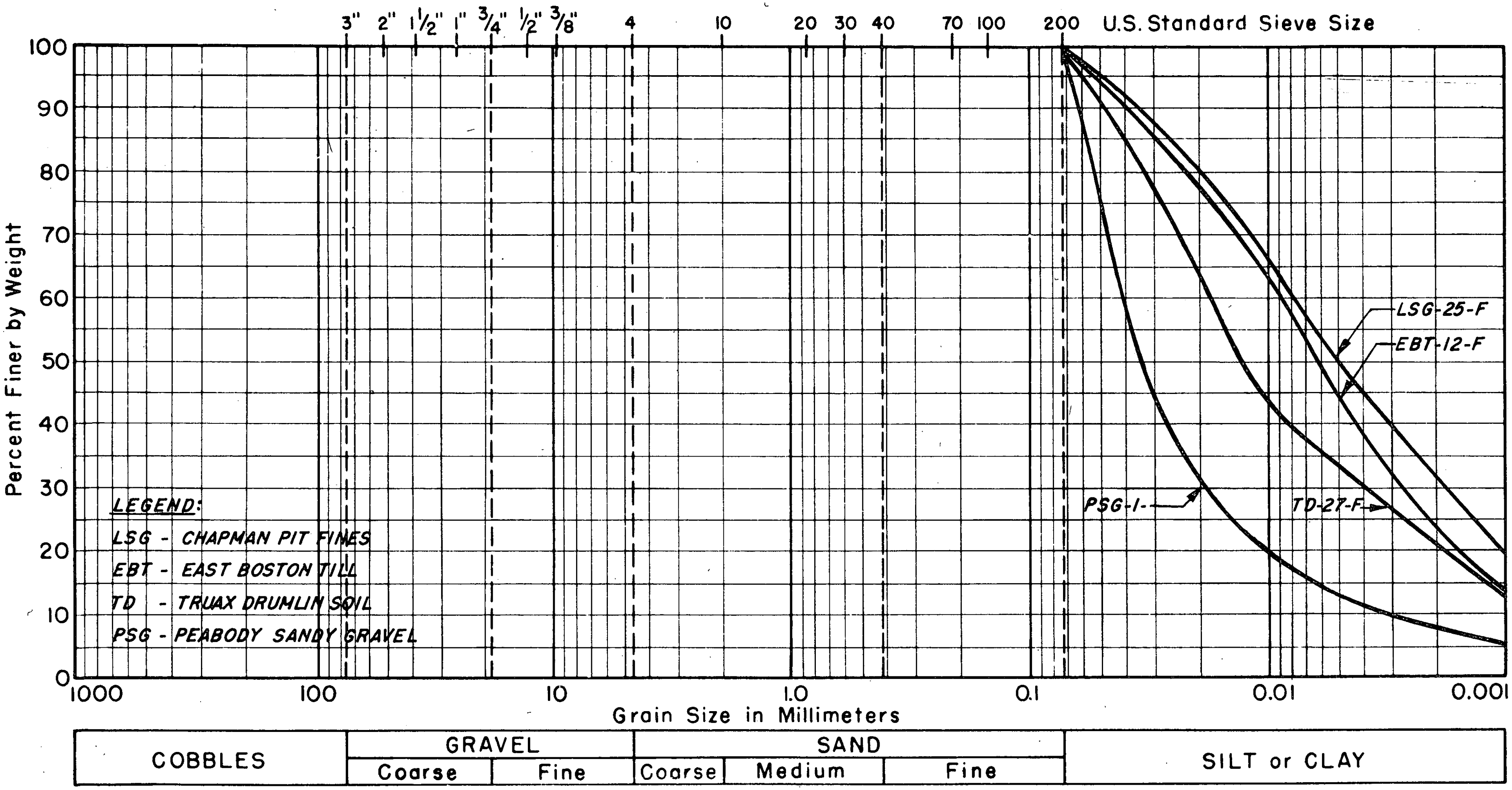


GRADATION CURVES

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

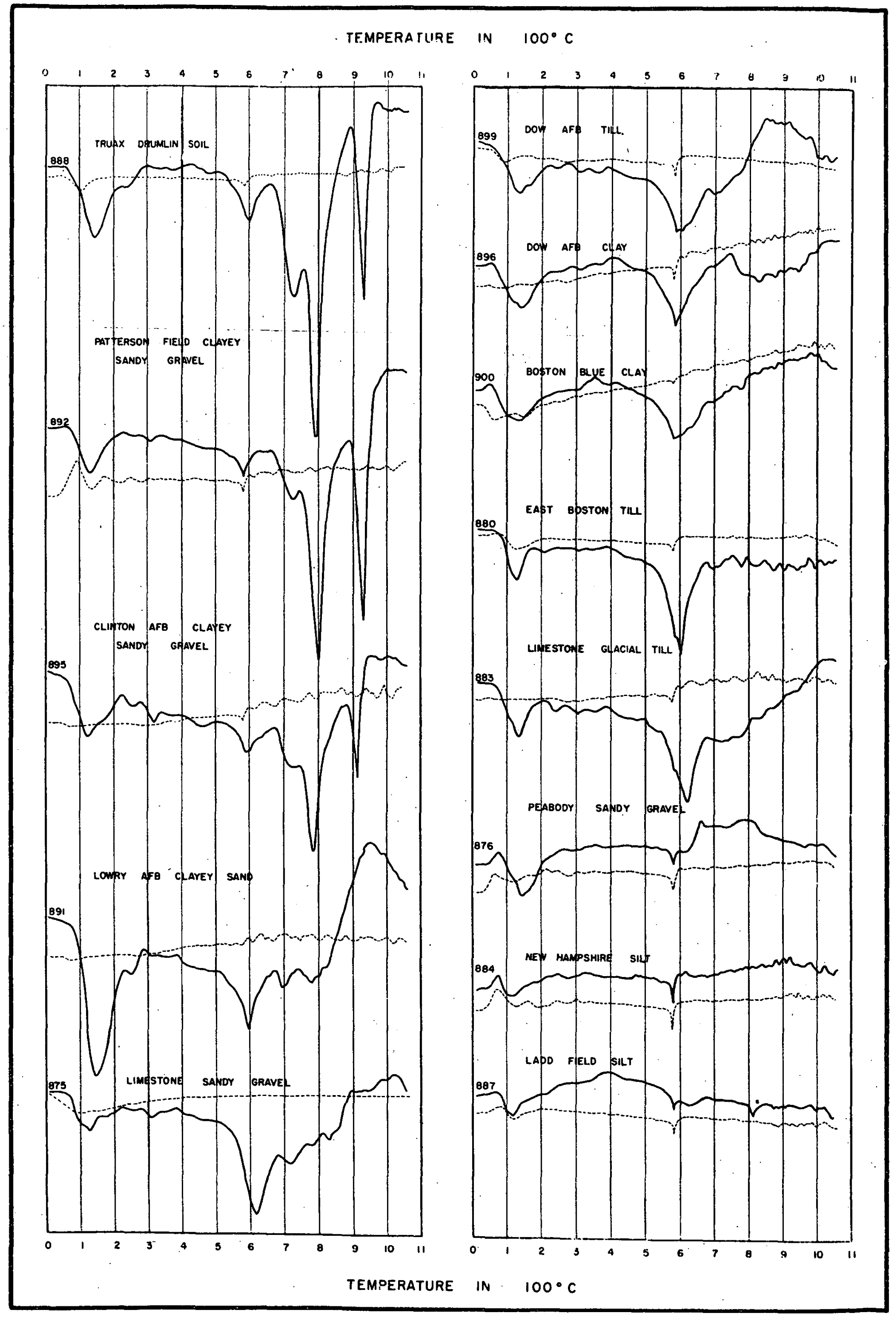
EFFECT OF
RATE OF PENETRATION

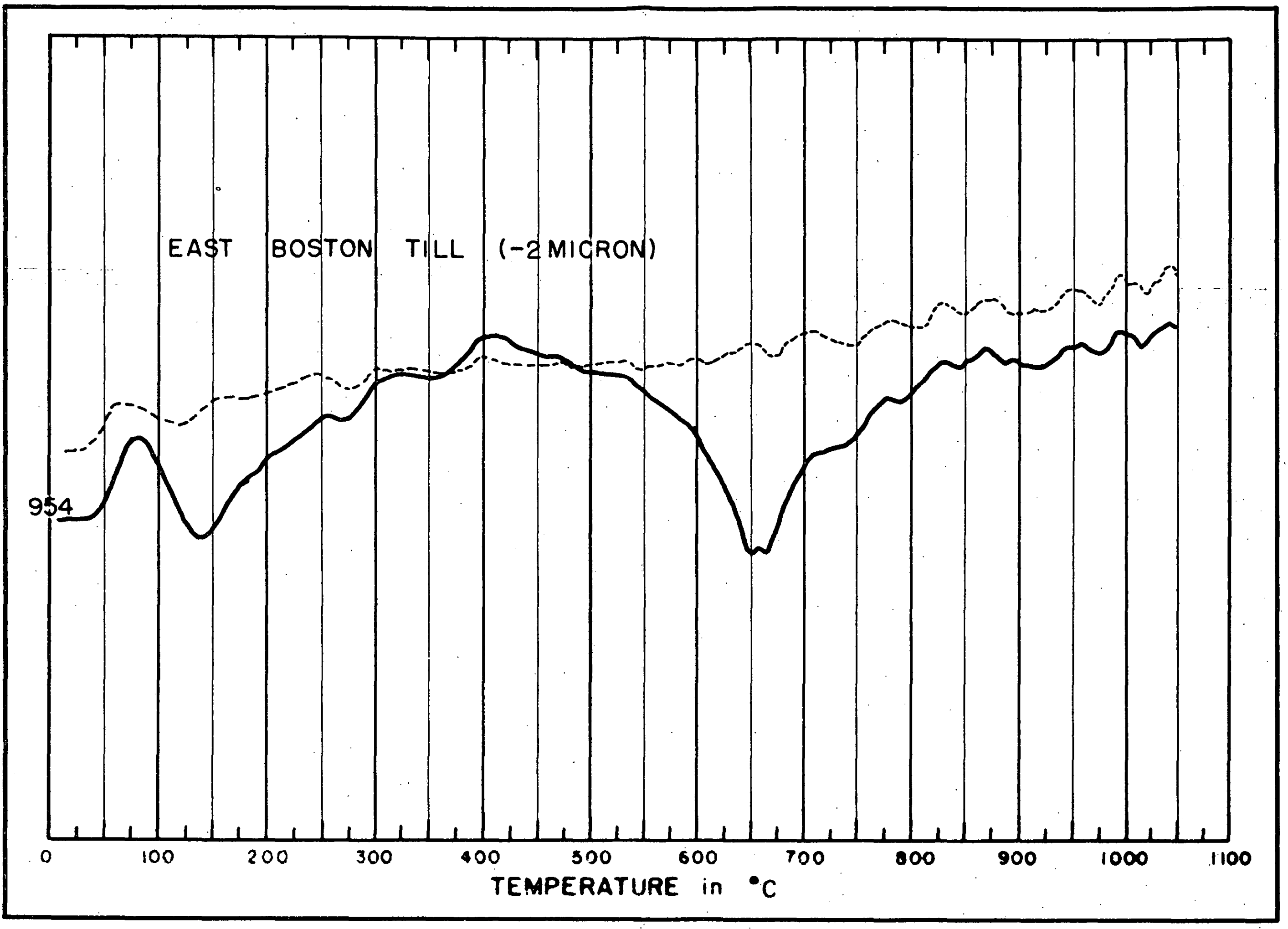
FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGR.
BOSTON, MASS.



GRADATION CURVES OF MINUS 200 MESH FRACTION SOILS

PLATE 12A





LEGEND

——— Initial Run.

------ Rerun.

NOTES:-

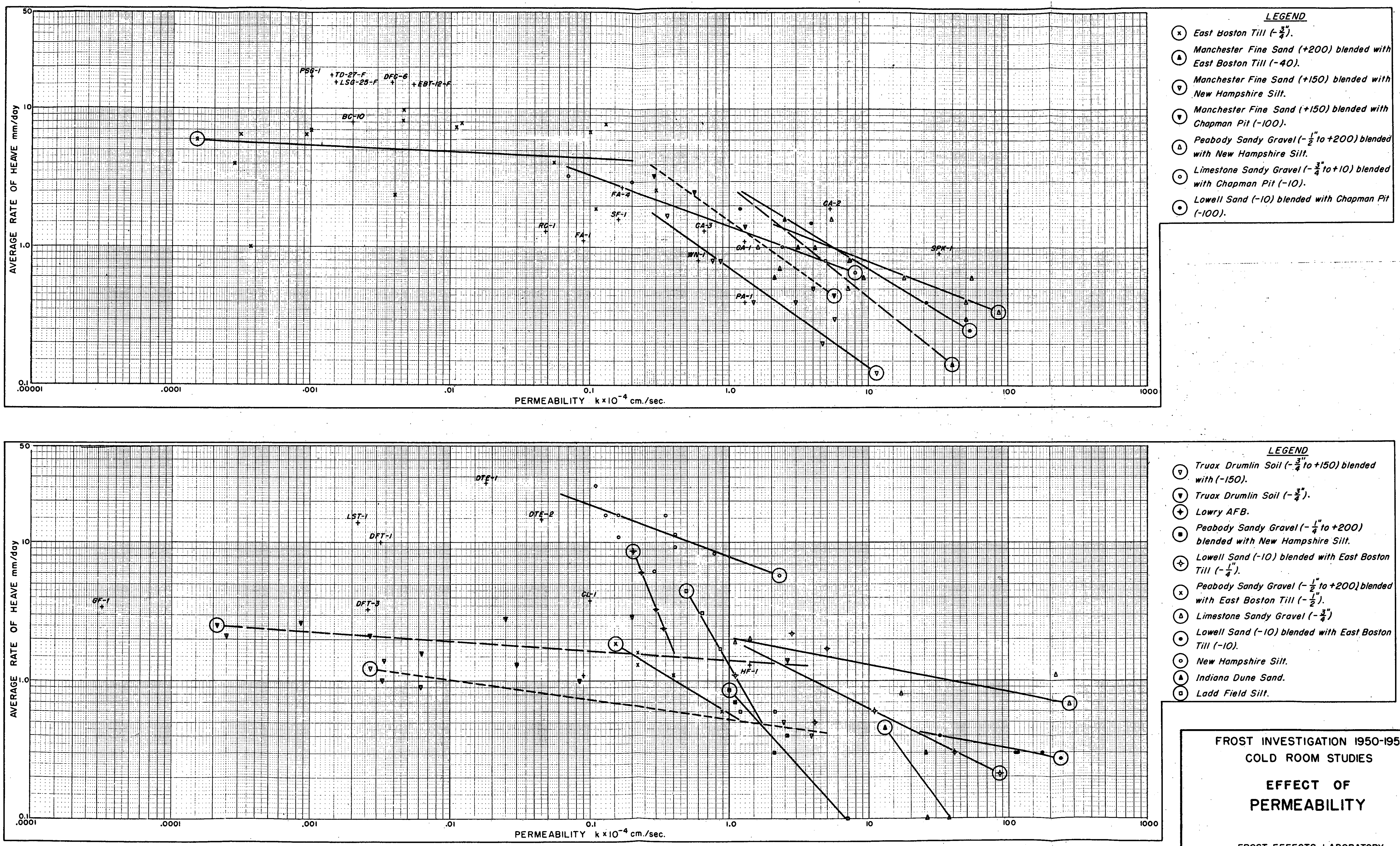
The number at the left of each initial thermogram is the test number.

Tests performed by Dr. T. William Lambe, Massachusetts Institute of Technology, Cambridge, Mass.

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

THERMOGRAMS OF
MINUS No. 200 MESH FRACTION SOILS

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGR.
BOSTON, MASS.



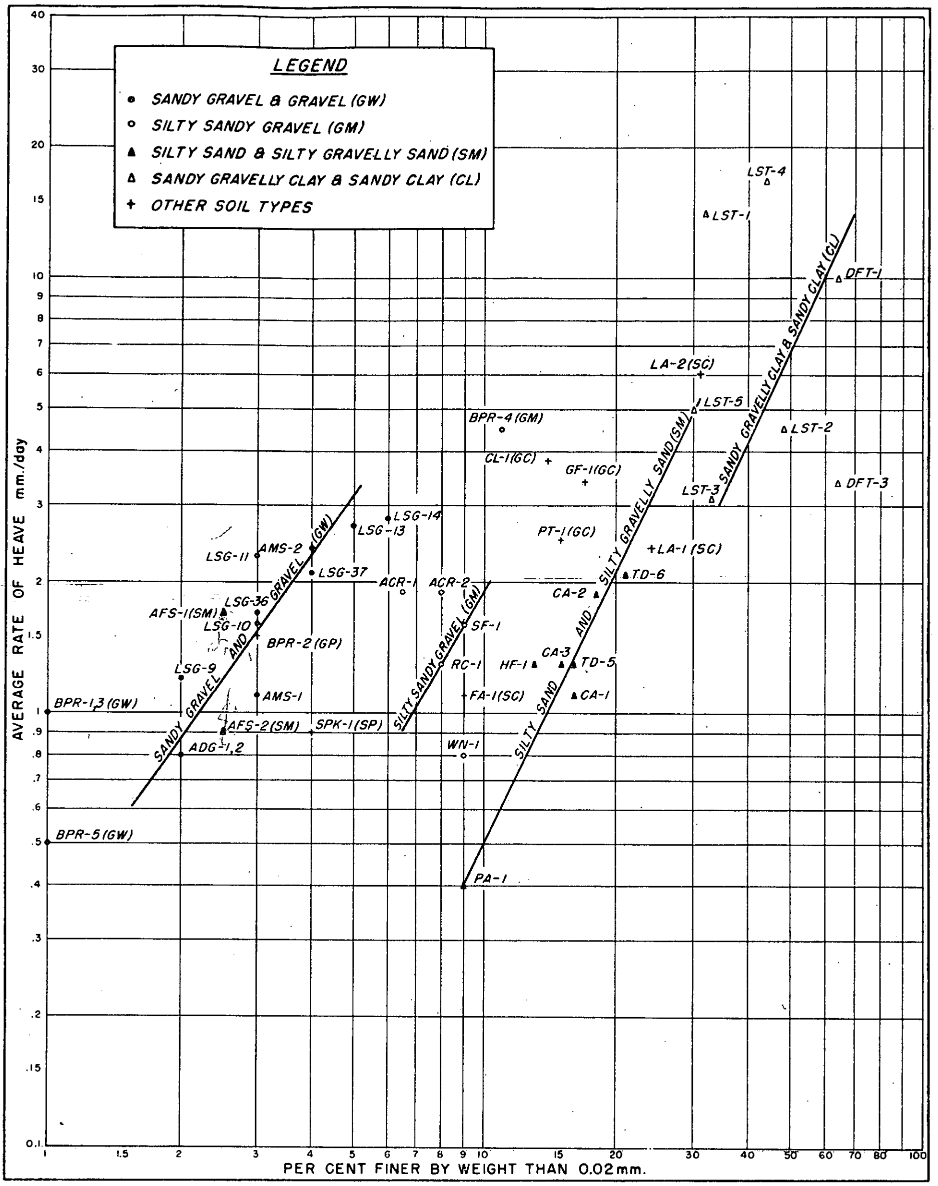
PLOTS OF AVERAGE RATE OF HEAVE vs PERMEABILITY

FROST INVESTIGATION 1950-1951
COLD ROOM STUDIES

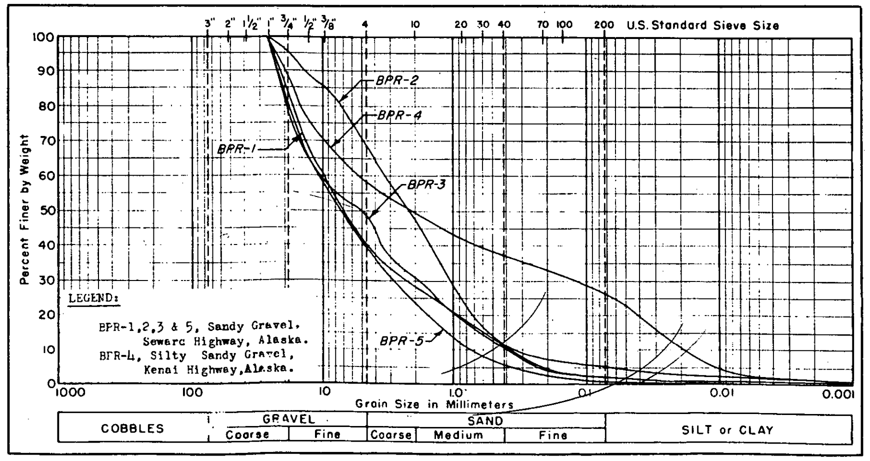
EFFECT OF
PERMEABILITY

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGINEERS
BOSTON, MASS.

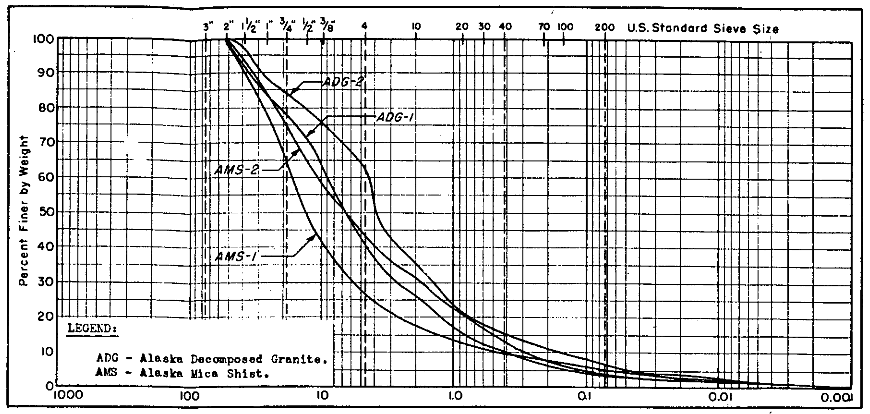
PLATE 14



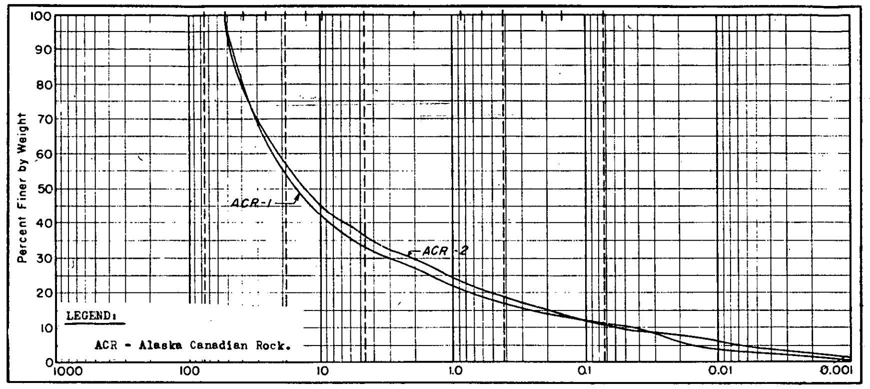
PLOTS FOR AVERAGE RATES OF HEAVE
VS
PER CENT FINER BY WEIGHT THAN 0.02 mm.



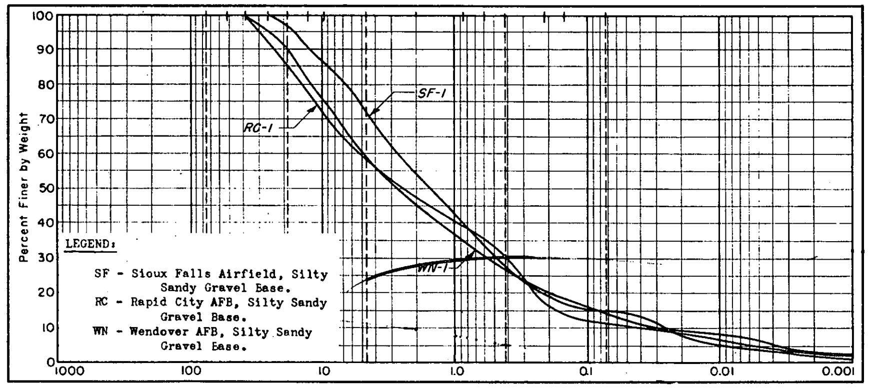
GRADATION CURVES FOR SANDY GRAVEL (GW AND GP), SEWARD HIGHWAY, ALASKA AND SILTY SANDY GRAVEL (GM), KENAI HIGHWAY, ALASKA



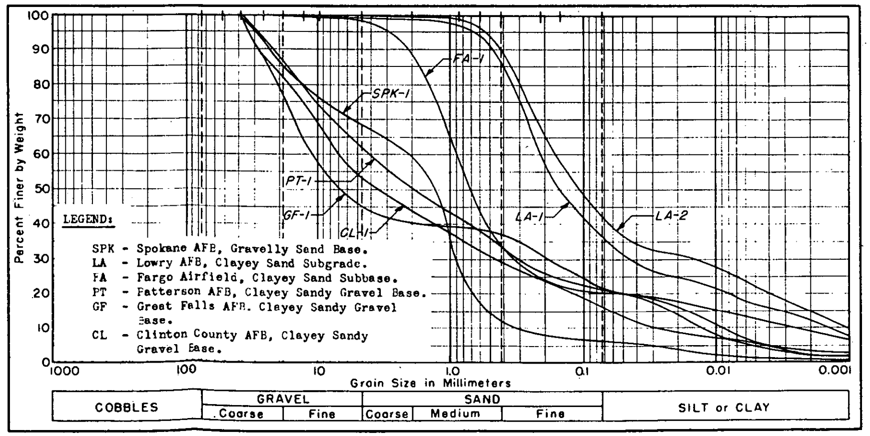
GRADATION CURVES FOR SANDY GRAVEL AND GRAVEL (GW)



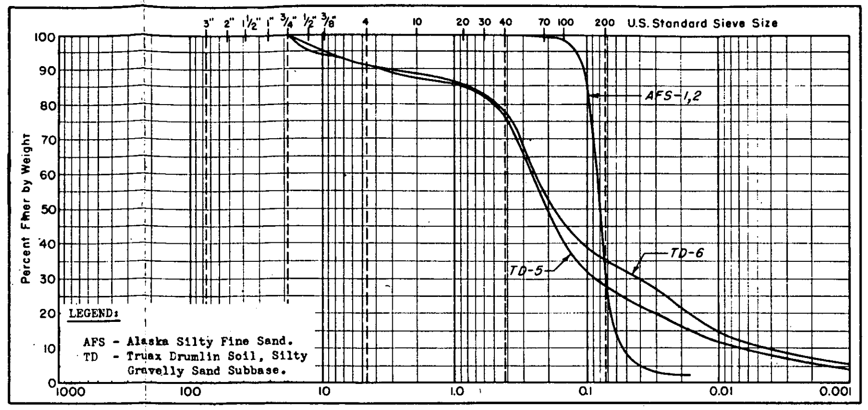
GRADATION CURVES FOR SILTY SANDY GRAVEL (GM)



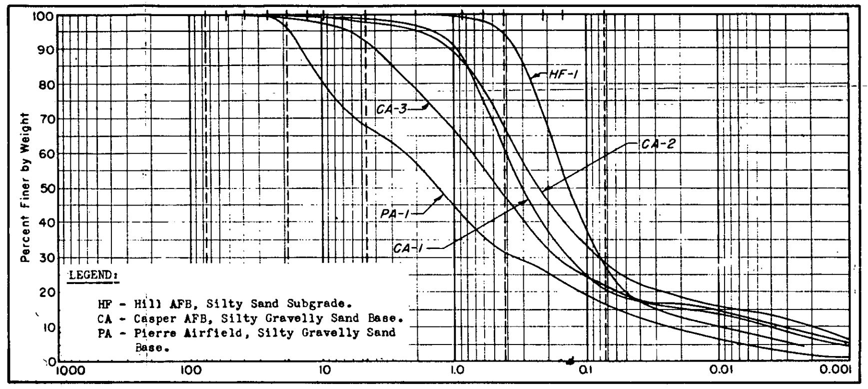
GRADATION CURVES FOR SILTY SANDY GRAVEL (GM)



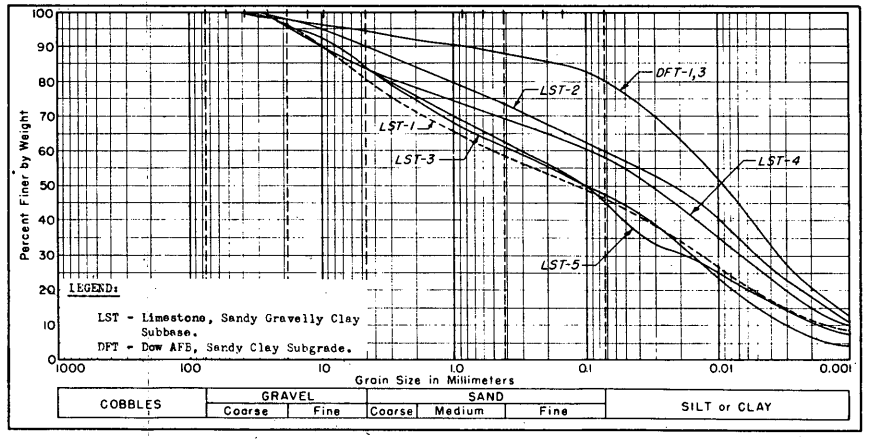
GRADATION CURVES FOR GRAVELLY SAND (SP), CLAYEY SAND (SC) AND CLAYEY SANDY GRAVEL (GC)



GRADATION CURVES FOR SILTY SAND AND SILTY GRAVELLY SAND (SM)



GRADATION CURVES FOR SILTY SAND AND SILTY GRAVELLY SAND (SM)



GRADATION CURVES FOR SANDY GRAVELLY CLAY AND SANDY CLAY (CL)

NOTES:

The subgrade and base soils were obtained from various airfields in the Northern United States and from Alaskan highways.

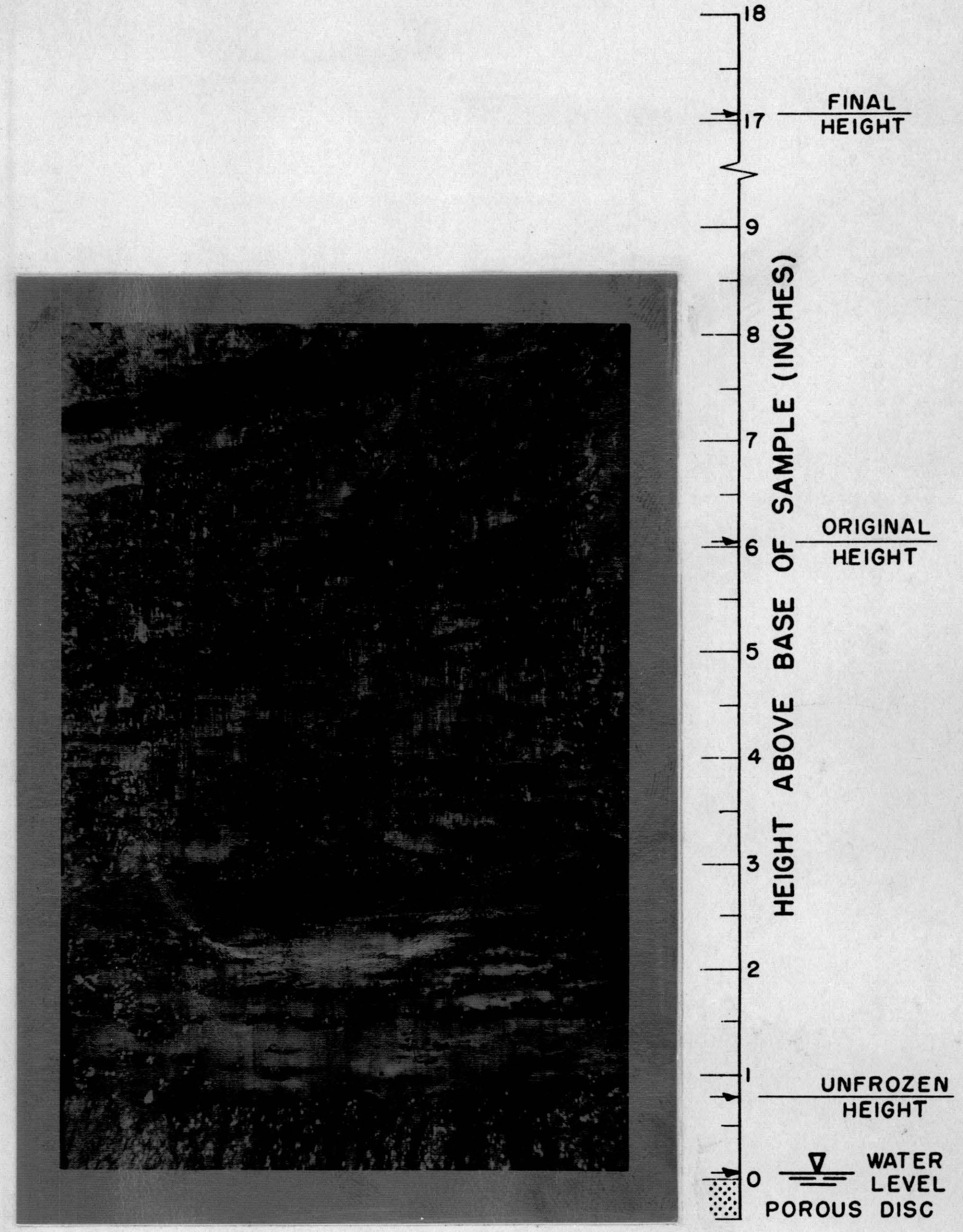
Gradation curves for Samples LSG-9,10,11,13,14, 36 and 37 are shown on Plate

FROST INVESTIGATION 1950–1951
COLD ROOM STUDIES

SUMMARY OF DATA

FROST SUSCEPTIBILITY OF BASE AND SUBGRADE SOILS

FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION CORPS OF ENGINEERS
BOSTON, MASS.



PHOTOGRAPH OF ICE SEGREGATION
IN MINUS No. 200 MESH FRACTION
OF LIMESTONE SANDY GRAVEL
SAMPLE No. LSG-25-F
(OPEN SYSTEM)

FIG. 1. LIMESTONE SANDY GRAVEL (-3/4")
TEST FOR EFFECT OF RATE OF PENETRATION
OF 32° F TEMPERATURE.

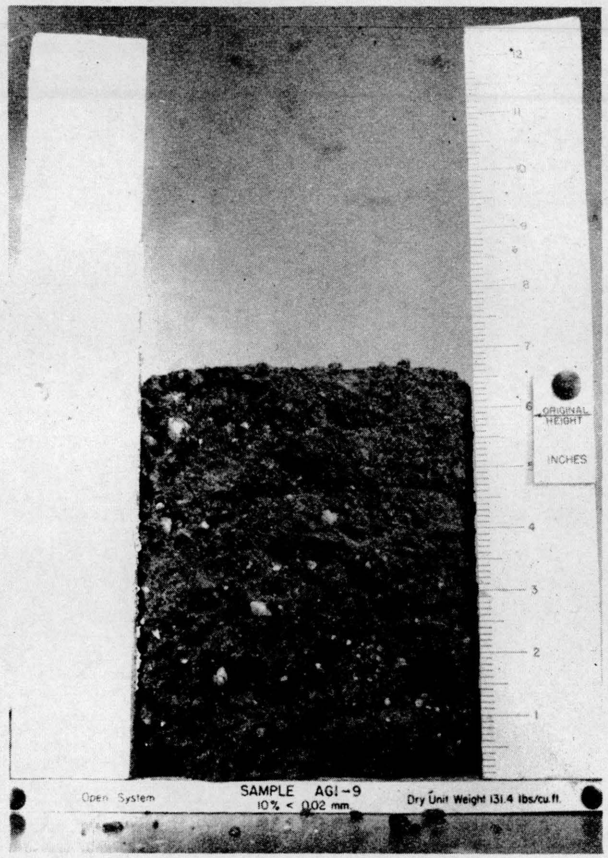


FIG. 2. PEABODY SANDY GRAVEL (-1/2"
TO ∠ #200) BLENDED WITH EAST BOSTON
TILL (-1/2")
TEST FOR EFFECT OF PER CENT FINER
THAN 0.02 MM.

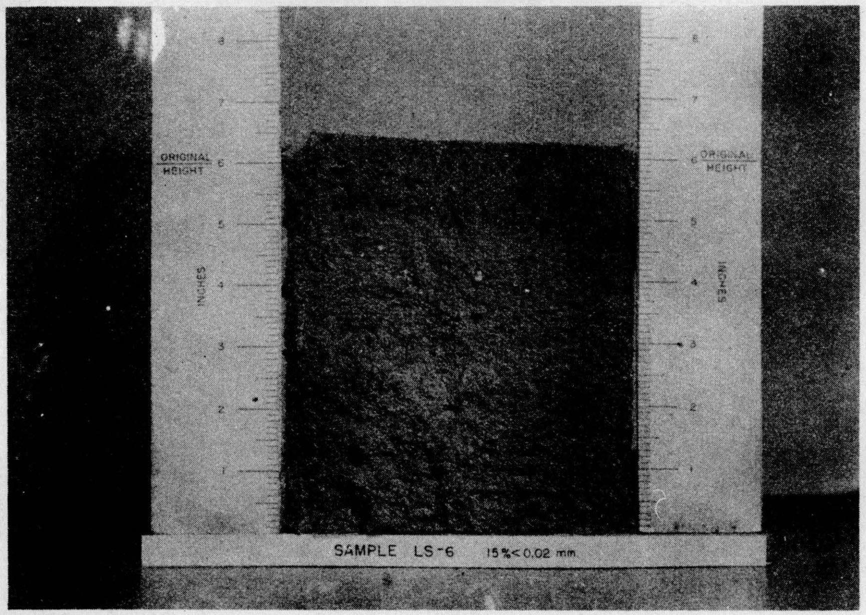


FIG. 1. LOWELL SAND (-#10) BLENDED WITH EAST BOSTON TILL (-#10)
TEST FOR EFFECT OF PER CENT FINER THAN 0.02 MM.

FIG. 2. MANCHESTER FINE SAND (+ #150) BLENDED WITH NEW HAMPSHIRE SILT.
TEST FOR EFFECT OF PER CENT FINER THAN 0.02 MM.

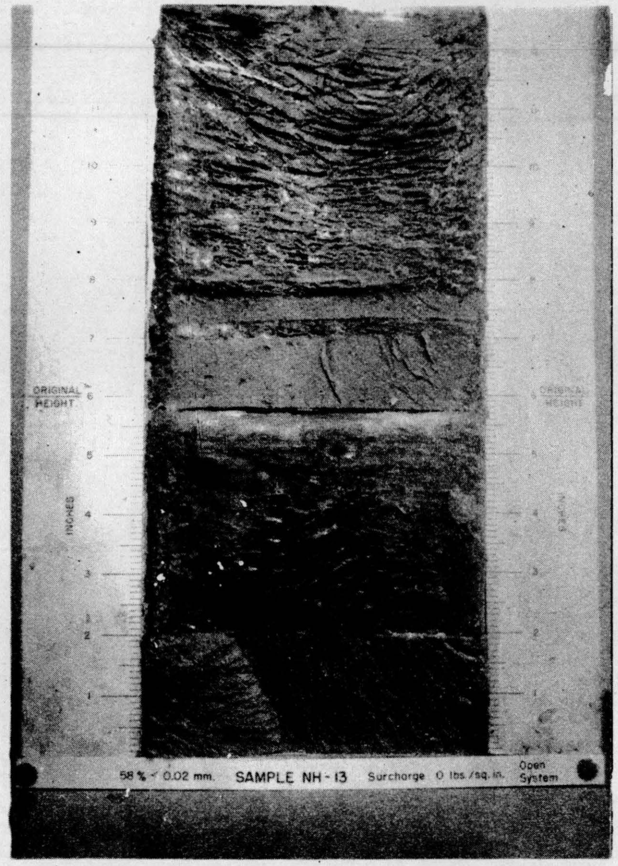


FIG. 1. NEW HAMPSHIRE SILT.
TEST FOR EFFECT OF SURCHARGE.

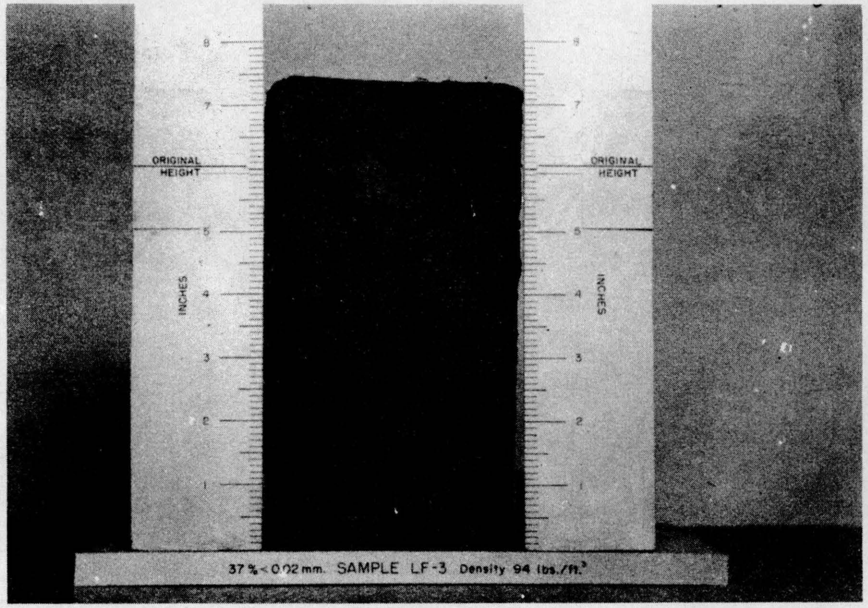


FIG. 2. LADD FIELD SILT SUBSOIL.
TEST FOR EFFECT OF DEGREE OF COMPACTION.

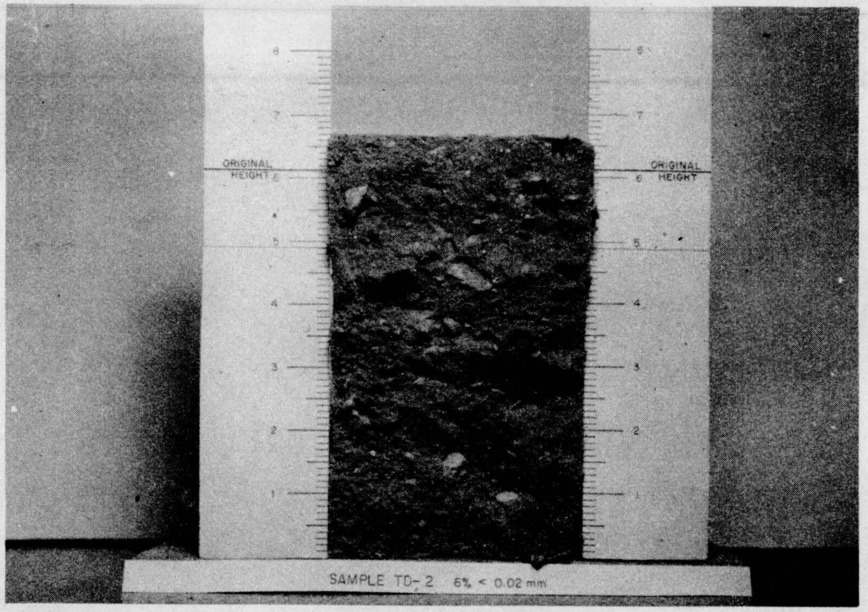


FIG. 1. TRUAX DRUMLIN SOIL, SILTY GRAVELLY SAND (-3/4")
TEST FOR EFFECT OF DEGREE OF COMPACTION.

FIG. 2. EAST BOSTON TILL, GRAVELLY
SANDY CLAY (-3/4")
TEST FOR EFFECT OF DEGREE OF COMPACTION.

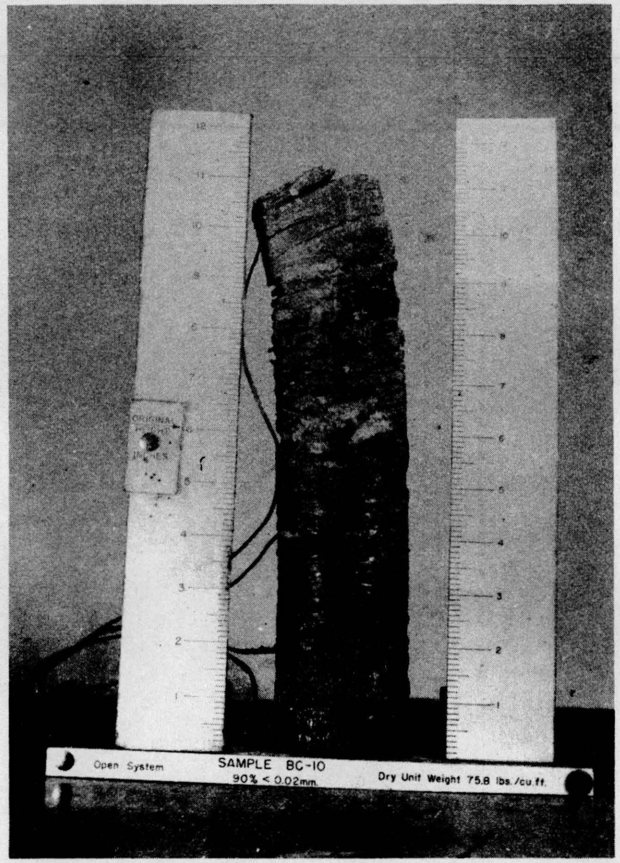


FIG. 1. BOSTON BLUE CLAY (UNDISTURBED). TEST FOR EFFECT OF RATE OF PENETRATION OF 32° F TEMPERATURE.

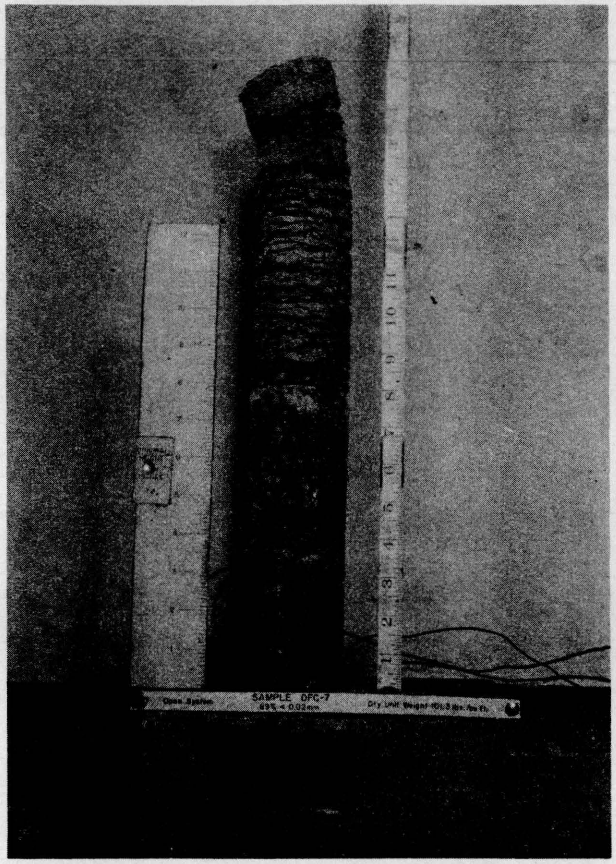


FIG. 2. DOW A.F.B. CLAY (UNDISTURBED). TEST FOR EFFECT OF RATE OF PENETRATION OF 32° F TEMPERATURE.

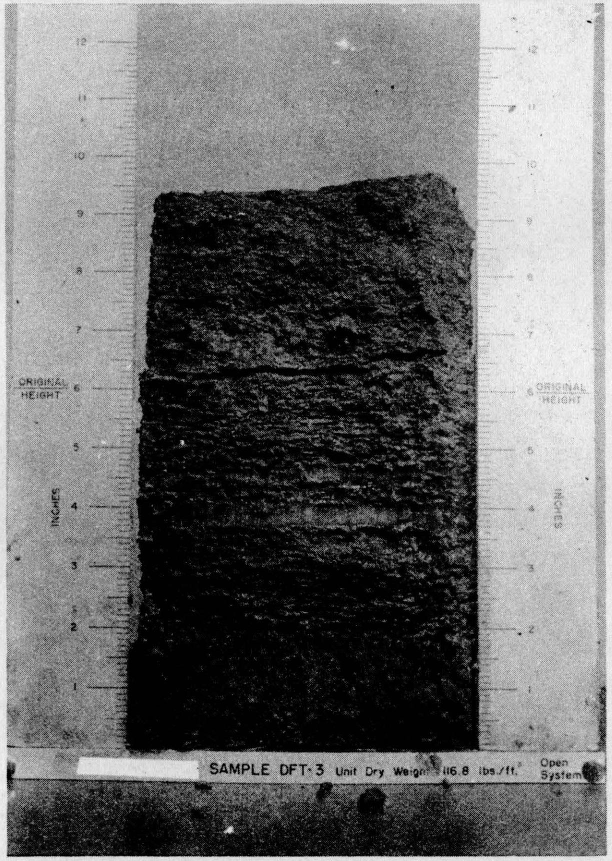


FIG. I. DOW A.F.B. SANDY CLAY SUBGRADE 64% < 0.02 MM.
TEST FOR FROST SUSCEPTIBILITY OF SUBGRADE AND BASE SOILS FROM VARIOUS AIRFIELDS.

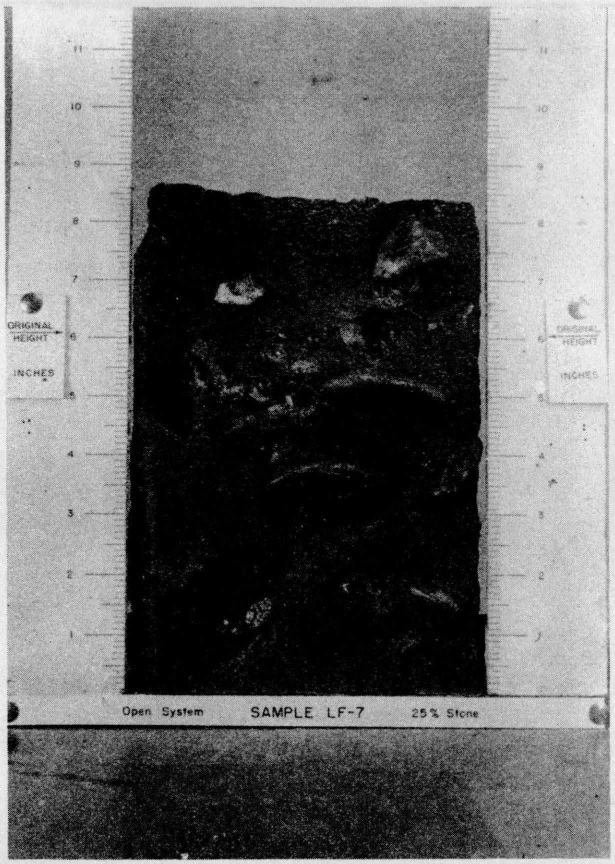


FIG. 2. LADD FIELD SILT BLENDED WITH LIMESTONE SANDY GRAVEL (-2" TO + 3/4")
TEST FOR EFFECT OF PER CENT AND SIZE OF AGGREGATE GREATER THAN 2.0 MM. IN SOIL GRADATIONS. NOTE ICE LAYER AT UNDERSIDE OF STONE.