CORPS OF ENGINEERS, U. S. ARMY

FROST INVESTIGATIONS

COLD ROOM STUDIES

THIRD INTERIM REPORT
OF
INVESTIGATIONS

WITH APPENDIXES A and B

TECHNICAL REPORT NO. 43

PREPARED BY

ARCTIC CONSTRUCTION AND FROST EFFECTS LABORATORY
NEW ENGLAND DIVISION
WALTHAM, MASSACHUSETTS

FOR

OFFICE OF THE CHIEF OF ENGINEERS
AIRFIELDS BRANCH
ENGINEERING DIVISION
MILITARY CONSTRUCTION

IN TWO VOLUMES   Revised October 1958   VOLUME ONE

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PREFACE

This report is the third in a series of reports, presenting the results of cold room studies of frost action in soils conducted during Fiscal Years 1952 and 1953 at the Arctic Construction and Frost Effects Laboratory (ACFEL), U. S. Army Engineer Division, New England. The studies are being conducted for the Office, Chief of Engineers, Department of the Army, Airfields Branch, Engineering Division, Military Construction, as part of a continuing program of frost investigations for the purpose of establishing and improving engineering design and evaluation criteria for roads, highways, and airfield pavements constructed on frost-susceptible soils which are subjected to seasonal freezing and thawing. The two previous reports in the series are:

> "Interim Report of Cold Room Studies", dated July 1950, covering initial studies.
>
> "Cold Room Studies, Second Interim Report of Investigation", dated June 1951, covering studies conducted from the initiation of the program in February 1950 through Fiscal Year 1951.

This interim report is presented in two volumes. Volume I contains the results of studies performed by Corps of Engineers personnel at ACFEL. Also included in Volume I are Appendix A, Equipment and Test Procedures, which presents detailed description of cold room, freezing cabinets, standard specimen preparation and test procedures; and Appendix B, Investigational Data, which contains tabulations of basic test data and results, plots of freeze and heave data, and water content distribution in all specimens after freezing. Volume II contains appendixes C and D. Appendix C, Mineralogical and Chemical Studies is a report submitted by Dr. T. William Lambe of the Massachusetts Institute of Technology, Cambridge, Massachusetts, who was engaged as a consultant on studies to determine the effect of frost action on mineral composition of soil fines, and on admixture studies for the modification of frost action in soils. Dr. Lambe provided the admixtures used in the tests, while the Corps of Engineers was responsible for the preparation and freezing of the test specimens. Appendix D contains all ACFEL investigational data for the mineral and chemical studies reported on in Appendix C.

This interim report was prepared to summarize the test results and conclusions for review by the Board of Consultants and to aid in formulating the direction and scope of future studies.

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SYNOPSIS

The effects of several individual factors which influence the formation and growth of ice lenses in different types of soils are shown. Test results are presented showing the effect of variations in the initial dry unit weight of sandy, silty and clayey soils. For sandy gravelly soils there appears to be an optimum initial dry unit weight at which ice segregation is a maximum, for silts heaving increases continuously with increasing density. Limited tests on clayey soils indicate that ice segregation is diminished with increase in initial dry unit weight. Overburden pressure or surcharge on a frost-susceptible soil is shown to reduce the rate of heaving, the effect being more pronounced in the silts and glacial tills than in the clay type soils.

Tests performed in the closed system (no free water available at bottom) show that ice lenses may form in the upper portion of the soil by transfer of soil moisture from the lower portion. Results of freezing tests, wherein the depth to water table was varied from 6 to 42 inches in glacial till, indicated that heaving was greatly reduced when the source of water was more than 18 inches below the freezing plane.

Other data are presented showing the effect of disturbance of soil structure and of variations in natural soil gradations. It is concluded that the gradation of a soil still offers the most expedient means of recognizing a potentially frost-susceptible soil.

PART I - INTRODUCTION

1-01. Purpose. The object of the investigation described herein is to determine by comparative laboratory tests, the effects of the variables which significantly influence frost action in soils, with the ultimate purpose of formulating improved engineering design criteria for situations where frost is a problem.

1-02. Scope of Studies Presented in This Report. This report presents the results of cold room studies for Fiscal Years 1952 and 1953. The investigations described herein include the following items, listed in order of presentation in this report:

a. The relationship between initial dry unit weight and intensity of ice segregation.

b. The relationship between surcharge pressure during freezing and intensity of ice segregation.

c. The effects produced when soil is frozen in a closed system.

d. The effect of disturbance of natural soil structure by remolding on intensity of ice segregation.

e. The relationship between depth to water table from plane of freezing and intensity of ice segregation.

f. The relationship between natural soil gradations and intensity of ice segregation.

g. The freezing point of soil moisture.

h. Mineralogical and chemical studies.

i. The crystallography of segregated ice lenses in frozen soil.

A complete listing of the items contemplated for study in the overall program has been given in the second interim report.[11*]

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*Raised numbers refer to references listed at end of report.

1-03. Authorization. Frost investigations during Fiscal Year 1952 were allocated by Job Number, New England Division-52-ESA-ES, Directive 1, dated 29 December 1951, file ENGMG, from the Chief of Engineers to the Division Engineer, New England Division. Instructions and Outlines for Cold Room Studies were transmitted as Inclosure with OCE 2nd Indorsement, dated 22 August 1951, to basic letter dated 23 April 1951, from the Chief of Engineers to the Division Engineer, New England Division, Subject: "Frost Investigation, Fiscal Year Ending 30 June 1952."

Frost investigations during Fiscal Year 1953 were authorized and funds allocated by Job Number, New England Division-53-ESA-ENG, Directive 1, dated 16 October 1952, file ENGEC, from the Chief of Engineers to the Division Engineer, New England Division. Instructions and Outlines for Cold Room Studies were transmitted as Inclosure with letter dated 30 January 1953 from the Chief of Engineers to the Division Engineer, New England Division, Subject: "Transmittal of Instructions and Outlines."

1-04. Definitions. Descriptions of tests and analyses of results involve specialized use of certain terms and words. Definitions of these words and terms as employed in this report are as follows:

Average daily temperature - The average of the maximum and minimum temperatures for one day or the average of several temperature readings taken at equal time intervals during one day, generally hourly.

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

Degree-days - Each degree in any one day that the average daily air temperature varies from 32^{o}F. The difference between the average daily air temperature and 32^{o}F. equals the degree-days for that day. The degree-days are minus when the average daily temperature is below 32^{o}F. and plus when above.

Degree-hour - A variation of one Fahrenheit degree from 32^{o}F. for a period of one hour. The degree-hour is negative if below 32^{o}F. and positive if above 32^{o}F.

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

Frost action - A general term for freezing and thawing of moisture in materials and the resultant effects on these materials and on structures of which they are a part or with which they are in contact.

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

Frost penetration - The maximum depth from the surface to the bottom of the frozen zone.

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

Frozen zone - The range of depth within which the soil is frozen. The frozen zone may be bounded both top and bottom by unfrozen soil.

Heterogeneously frozen soil - A soil in which a part of the water is frozen in the form of macroscopic ice occupying a space in excess of the original voids in the soil.

Homogeneously frozen soil - A soil in which water is frozen within the material voids without macroscopic segregation of ice.

Ice lenses - Ice formations in soil occurring essentially parallel to each other, generally normally to the direction of heat loss, and commonly in repeated layers.

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

Non-frost-susceptible materials - Cohesionless materials such as crushed rock, gravel, sand, slag and cinders in which ice segregation does not occur under normal freezing conditions.

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

Percent heave - The ratio, expressed as a percentage of the amount of heave to the original height of the frozen soil.

Rate of heave - The average rate of heave in millimeters a day, determined from a representative portion of the plot of heave versus time, in which the slope is relatively constant and during which the penetration of the 32^{o}F. isotherm is relatively linear and between 1/4-inch and 3/4-inch per day. Rate of heave is averaged over as much of the heave vs. time plot as practicable, but the minimum number of consecutive days used for a determination is five. This measure of frost susceptibility is used in open system tests only.

Standard Proctor density - The maximum dry unit weight obtained by compacting soil in a 1/30-cu ft cylinder using 3 layers, 25 blows per layer of a 5.5 lb tamper, 12-in. drop, as described in ASTM Standard Designation D698-42T.

Modified AASHO density - The maximum dry unit weight obtained by standard Method of Test for the Compaction and Density of Soils, AASHO Designagion T99-49 using 1/30-cu ft cylinder, but substituting 5 layers, 25 blows per layer of a 10-lb tamper, 18-in. drop for 3 layers, 25 blows per layer of a 5.5-lb tamper, 12-in. drop.

Corps of Engineers' (C of E) airfield density - The maximum dry unit weight obtained by compacting soil in a 1/10 cu ft cylinder using 5 layers, 55 blows per layer of 10-lb tamper, 18-in. drop as described in paragraph 3 b of Appendix B to Chapter 2, Part XII of Engineering Manual for Military Construction entitled "Airfield Pavement Design, Flexible Pavements."

Providence vibrated density - The maximum dry unit weight obtained by compacting a soil sample in a 7-in. inside diameter steel cylinder under the combined action of a 1000 pound static load and vibration produced by blows of 2-1/2 pound hammer over the exterior walls of the cylinder. (See Kenneth S. Lane, "Providence Vibrated Density Test," Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering. Rotterdam, Vol. IV, pp. 243-247-1948).

1-05. Acknowledgments. The frost investigations, of which these cold room studies are a part, are being conducted by the Arctic Construction and 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. Thomas B. Pringle, Chief, Airfields Branch, and by Mr. Frank Hennion, Assistant Chief.

Brigadier General Alden K. Sibley is the Division Engineer, U.S. Army Engineer Division, New England, and Mr. John Wm. Leslie is the Chief of the Engineering Division, NED. Mr. Kenneth A. Linell is Chief of the Arctic Construction and Frost Effects Laboratory and is directly responsible for the program of frost investigations. The studies were under the direct supervision of Mr. James F. Haley, formerly Deputy Chief, Arctic Construction and Frost Effects Laboratory.

Dr. Arthur Casagrande of Harvard University; Dr. P.C. Rutledge of Moran, Proctor, Meuser and Rutledge, Consulting Engineers; and Professor K.B. Woods of Purdue University are the investigational consultants.

Dr. T. William Lambe of the Massachusetts Institute of Technology is consultant on studies to determine the effect of mineral composition of soil fines and investigations of admixtures to prevent or minimize frost action in soils.

PART II - SOILS, TEST PROCEDURES AND FROST CLASSIFICATION

2-01. Soils Selected for Tests. - The sources and classifications of the soils which have been subjected to testing in the Fiscal Years 1952 and 1953 are summarized in Table 1. As shown there, the soils ranged from well-graded silty sandy GRAVEL (GW-GM) to a highly plastic CLAY (CH). Classifications are based on The Unified Soil Classification System.[12] Included in Table 1 are a considerable number of subgrade soils and proposed base course materials of questionable frost susceptibility from airfield and highway projects located in the northern United States, Alaska, Canada, Iceland and Greenland; these soils were forwarded to the Arctic Construction and Frost Effects Laboratory during Fiscal Years 1952 and 1953 for laboratory freezing tests to measure their relative frost susceptibility. The gradation curves of the soils used in the investigations are shown on Plate 1.

2-02. Standard Laboratory Freezing Test Procedure. In these studies, soil specimens were generally prepared for freezing in a 5.91-in. inside diameter steel molding cylinder to an approximate height of 6-in. and to a predetermined density by means of a static load and/or vibration. Cohesionless soils were molded at a low moisture content to improve the apparent cohesion and to aid specimen handling after molding. All other materials were molded at optimum moisture content as determined by the modified AASHO density test procedure. Some undisturbed specimens of cohesive soils were trimmed to the proper size.

The specimens ejected from the molding cylinder, or trimmed to size, were placed in 6-in. diameter heavy cardboard containers. In the earlier tests, the interiors of these containers were lubricated with petrolatum to prevent friction between the specimens and the container walls during heaving. In the most recent tests, a liner consisting of sheet cellulose acetate or 1-in. high cellulose acetate strips lapped in a telescopic manner, was placed within the cardboard container. The acetate liner was coated on both sides with silicone*.

The specimens were then evacuated from the top and bottom and saturated from the bottom using deaired water. All specimens were allowed to temper for a minimum of 24 hours at 35°F. before the freezing tests. Thermocouples were inserted at intervals along the

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*Silicone used is a non-melting, translucent material that retains the consistency of petroleum jelly at temperatures ranging from -40°F. to over +400°F. It is heat stable, oxidation resistant, inert to metals, plastics and most organic materials and has other useful characteristics, i. e., waterproof and water repellent.

height of at least one specimen in each freezing cabinet; this was done to measure temperature changes. The specimens 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 in. above a porous stone at the bottom of each specimen tested in the open system. A surcharge weight of 0.5 psi was placed on top of each specimen, simulating a minimum height of 6 inches of pavement.

The specimens were frozen from the top by gradually decreasing the temperature above the specimens in the freezing cabinet, while the bottoms of the specimens were exposed to the cold room temperature maintained between 35^{O}F. and 38^{O}F. The temperature in the test cabinet was lowered to obtain approximately 1/4 in. penetration per day of the 32^{O}F. temperature into the specimens. Heave measurements were taken daily. At the completion of the test, usually after 24 days, the specimens were removed from the freezing cabinet, measured, split longitudinally, photographed, examined for ice segregation, and finally broken up to determine the water content distribution.

A more detailed description of the standard laboratory specimen preparation and freezing procedures is presented in "Appendix A: Equipment and Test Procedures." The heave data, the penetration of the 32^{O}F. temperature, the cumulative degree-hours below 32^{O}F., and the test cabinet temperatures all have been plotted versus time. These plots are in "Appendix B: Investigational Data." The water content distribution in each specimen, before and after testing for each test series, is also presented in "Appendix B: Investigational Data." Appendixes A and B are found at the end of this report.

2-03. Evaluation of Frost Susceptibility. The cold room tests performed in the series of studies reported herein have been designed to subject the soil to a very severe combination of the conditions conducive to frost action. The soils have been generally compacted to densities in the range of average field densities, and the rate of penetration of the freezing temperature into the specimens has averaged 1/4 inch per day, which is considered to be representative of field freezing conditions during the latter half of the freezing period when penetration is slower and heaving is greatest. However, in the majority of the tests performed in this investigation, an unlimited supply of water has been provided at the base of the specimens. In the field, this would correspond to an extremely pervious aquifer only a short distance below the plane of freezing. This is a severe condition, and it results in virtually the maximum rate of ice segregation and heave which the soil can exhibit under natural field conditions. The results are, therefore, not usually quantitatively representative of actual heave to be expected in the field. The cold room test procedures are considered satisfactory, however, for determining the relative degree of frost susceptibility of various soils, with the possible exception of unweathered clays which may show unduly low heave for at least the first cycle of freezing. In clays, which are unfissured and have not previously been frozen, the rate of heaving may be low initially, but as the clay is repeatedly thawed and refrozen and becomes fissured, the rate of heaving may become much greater.

Rate of heave (see definition, p. 4) has been found to be relatively independent of rate of freezing, over the range of freezing rates employed in the investigation. Therefore, average rate of heave has been utilized as the basis for expression, comparison, and evaluation of test results. The following tentative scales of average rate of heave have been adopted for rates of freezing between 1/4 in. and 3/4 in. 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
Greater than 8.0	Very high

The evaluation given by the standard freezing test should be considered empirical in nature. Average rate of heave does not represent a simple and fundamental physical value, since such factors as surcharge and moisture availability vary continuously during the test. The progressive decrease in thickness of soil through which water is drawn to the freezing plane tends to make moisture progressively more readily available at the plane of freezing and thus to permit a progressive increase in rate of heave, during the test. At the same time, increasing surcharge on the freezing plane tends to decrease the rate of heave, the estimated possible decrease due to surcharge effect being up to as much as 15 to 20% between the start and end of a test on a specimen of 6-inch initial height. Since the changes in moisture availability and surcharge produce opposite effects, the net effect is to tend to produce a more uniform rate of heave than might otherwise be expected.

Inspection of specimen heave records such as those shown on Plates B1 through B31 of Appendix B shows that the rate of heaving is quite frequently non-uniform. This may be due to factors such as those discussed above, but also to such other influences as erratic temperature control in the freezing cabinet or a disturbance to the free supply of water to the specimen. A slight rise in the cabinet temperature or presence of an air bubble in the water supply line is quickly reflected in the heave rate. For these reasons, the average rate of heave is computed from a representative portion of the heave vs time plot as described on p. 4 rather than from the whole curve.

It will be found that the values of average rate of heave and percent heave shown in the tabulations in this report frequently fail to correlate with each other. This is due to the different data and methods used in the computation of each. While average rate of heave is determined from a portion of the heave vs time plot, the percent heave is determined from direct scale measurements of:

(a) the total height of each specimen before and after freezing, and

(b) of the height of the portion of the specimen actually frozen at end of test.

The summation of the daily heave readings is not used for the percent heave determination because it does not always agree with the measurements taken of the specimen at end of test. The difference is usually caused by the formation of an ice lens, up to 0.1 inch in thickness, which frequently forms during the initial stages of freezing, beneath the steel surcharge plate on all standard size specimens, or by the errors in the daily heave readings caused by either slight or moderate tipping of some of the more highly frost-susceptible specimens during heaving. In making direct scale measurements of the height of the frozen specimens, any ice lens directly beneath the surcharge plate is disregarded; this thickness thus is not included in percent heave value. The growth of this ice lens will have been reflected however, in the accumulated daily heave readings. For specimens which have been deformed, an average height is determined for computation of percent heave.

PART III - COLD ROOM INVESTIGATIONS

3-01. Effect of Variations in Dry Unit Weight (Degree of Compaction). During Fiscal Year 1951, a series of tests had been performed on various soil types to study the relationship between intensity of ice segregation and such physical soil properties as void ratio and dry unit weight. The test results, as presented in the Second Interim Report of Investigations, dated June 1951, showed the following:

a. In well-graded frost-susceptible soils, the intensity of ice segregation increased moderately with increase in dry unit weight until a peak value was reached; further increase in initial dry unit weight then resulted in a slight decrease of ice segregation.

b. In uniformly graded frost-susceptible sands, the initial dry unit weight had negligible influence on the intensity of ice segregation.

c. In inorganic silt soils, the intensity of ice segregation increased with initial dry unit weight up to the maximum dry unit weights which could be attained with these soils.

In Fiscal Years 1952 and 1953, freezing tests related to this phase of the cold room studies were continued using the following three soils.

a. Silt subgrade material from the Field Research Area, Fairbanks, Alaska.

b. Clayey sand from Fargo, North Dakota.

c. Clay subgrade soil from the Western Association of State Highway Officals (WASHO) Road Test Section, Malad, Idaho.

The gradation curves of the test materials are shown on Plate 1. The test data for all the 1952 to 1953 test specimens are tabulated in Table B1 of Appendix B.

On Plate 2 of this report, the relationship between the dry unit weight and the average rate of heave for these test specimens has been plotted for comparison with results obtained in Fiscal Year 1951. Included on Plate 2 are also the results of tests on soil types from Project Blue Jay reported in paragraph 3-06, Tests of Natural Soil Specimens Used for Frost Susceptibility Tests, and listed in Table B7 of Appendix B.

Latter materials were tested for relative frost susceptibility at approximately 95% and 100% of maximum dry unit weight. Gradations of the Blue Jay soils are shown on Plate 1.

Results of all tests in this series are summarized in Figure 8 of Plate 2.

(1) Fargo Clayey Sand. The test results on the remolded Fargo clayey sand subgrade specimens (FA-5 and FA-6) indicate a decrease on heave rate with an increase in dry unit weight. This is shown in Figure 4 of Plate 2. Additional freezing tests at lower dry unit weights, using this material, are to be performed to further develop the indicated curve.

(2) Fairbanks Silt. The data for the undisturbed silt specimen (LFT-10) and the remolded silt specimens (LFT-13 and LFT-14) from the subgrade of the Fairbanks Permafrost Research Area, Fairbanks, Alaska, fit approximately an extension of the Ladd Field silt curve plotted in Figure 5 of Plate 2. The gradation of the silt from the Fairbanks Permafrost Research Area (Fairbanks Silt) is almost the same as for the silt from Ladd Field and is similar to New Hampshire Silt-A, although coarser.

The test data indicates that the silt from the Fairbanks Research Area follows the same pattern of behavior as New Hampshire Silt-A, in that for both soils, the rate of heave is greatly increased with increase in dry unit weight. However, as indicated in Figure 5, the Fairbanks Silt is apparently a considerably less frost-susceptible material than the New Hampshire Silt. The lower magnitude of rate of heave of Fairbanks Silt may be attributed, as an hypothesis, to (1) the presence of undecomposed organic matter, (2) the smaller percentage of quartz mineral fines in the minus 200 mesh fraction of this soil, as compared to New Hampshire Silt, and (3) the size and shape of the voids in the soil specimen, which are dependent upon the size and shape of the soil particles. Freezing tests* by ACFEL have shown that fibrous, partially decomposed peat with an organic content of 82% from Fairbanks, Alaska, heaved only between 0 and 8% after twelve days of freezing. The Fairbanks Silt contained an average of 4.5 percent organic matter (determined by the H_2So_4 - $K_2Cr_2O_7$ digestion method adapted from Peech[9]), with slightly more than half being non-colloidal.

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*An exploratory test series to determine description, classification and strength properties of frozen soils performed by this office for the U.S. Army Snow, Ice and Permafrost Research Establishment, Wilmette, Illinois. Results of these tests are reported in Volume 1 of the Draft Report of Investigations for Fiscal Year 1952, entitled "Investigation of the Strength Properties of Frozen Soils", June 1953.

According to Dücker[6], the frost sensitive properties of soils are chiefly due to the quartz flour which has little or no swelling properties. Clays with high swelling characteristics such as montmorillonite (mineral of bentonite) are substantially impervious and should exhibit little or no ice segregation upon freezing, depending upon the exchangeable cation[7]. New Hampshire Silt contains 40 to 55 percent of quartz fines while the quartz content of the Fairbanks Silt fines varies between 20 and 35 percent. Furthermore, Fairbanks Silt was found to contain approximately 10 to 15 percent montomorillonoids and 10 percent chlorite, neither of which were found present in the New Hampshire Silt. Therefore, it does not appear unreasonable to expect that the frost susceptibility of Fairbanks Silt would be less than that of New Hampshire Silt.

(3) WASHO Test Section Clay. As shown in Figure 7 of Plate 2, the test results for the remolded clay specimens from the subgrade of the WASHO Road Test Section, Malad, Idaho, indicate a slight decrease in the rate of heave with increase in dry unit weight for the density range investigated.

(4) Project Blue Jay Soils. As shown in Figures 1, 2 and 4 of Plate 2, the tests on the Project Blue Jay soils generally confirm the relationship between rate of heave and dry unit weight established in previous test series on gravelly soils. It is demonstrated that increasing the degree of compaction in such soils from approximately 95% to 100% of the maximum density results in a slight to moderate decrease in intensity of ice segregation. As has been brought out previously, however, the advantage of obtaining a high degree of compaction in these soils is questionable because, even if the soils could be made almost non-frost-susceptible by compaction, one would expect a loosening of the soils after one or more freezing cycles. This may be less true when the soils are well-drained than when they are at relatively high degrees of saturation.

(5) Discussion of Effect of Dry Unit Weight. The fact that materials of diverse mineral characteristics and origins follow similar trends when grouped according to gradation characteristics, as shown in the individaul Figures 1 through 7 on Plate 2, indicates that whether a material will show increasing or decreasing rate of heave with increase in dry unit weight, or whether it will show an "optimum" is dependent largely on the sizes and distributions of grains. This is not to say that the degree or level of frost suceptibility is thus largely controlled; this hypothesis relates only to upward or downward trend with change in tightness of packing. While it seems obvious that the rate of heave in a given soil should be governed in some degree by the size and shape of the voids, as controlled by the grain size distribution and degree of densification, it is not necessarily obvious whether an increase in degree

of compaction in a given soil should result in an increase, or in a decrease, in the rate of frost heave in absence of experimental test results such as shown on Plate 2, or that soils of similar gradation characteristics will show similar trends of rate of heave vs. dry unit weight. A basic study of the frost action phenomenon in soils could probably interrelate quantitatively the effects of such variables as void ratio, void size, and permeability, so as to provide a fuller explanation of the observed trends.

Since frost penetration was kept advancing into the specimens, rate of heave was not limited by rate of removal of heat, but by rate at which water was made available at the freezing plane. In turn, the rate at which water could be made available must have depended on (1) the pressure differential which could be generated within the soil water to draw moisture to the plane of freezing, (2) the effective permeability (and compressibility) of the soil mass <u>below</u> the plane of freezing, and (3)* the facility with which water could be made available to the ice through moisture films <u>at</u> the soil-ice-plane. Since the applied surcharge pressure was not varied in these tests, the vertical pressures on the plane of freezing were comparable in all specimens, and the effect of this factor on flow in water films at the soil-ice boundary can be disregarded in a comparison of results.

In considering the performance of the silt specimens, it is obvious that the effect of lower permeability at the higher unit weights is greatly outweighed in these materials by other influences acting to produce an opposite trend. One of the factors thus acting might be an increase in the force of moisture attraction to the growing ice lenses with increase in density. Such an increase might be the result of more effective supercooling in the soil immediately below the plane of freezing, which in turn might result, in part, from the reduced cross-sections of the moisture threads filling the voids, and, in part, from the greater effective thermal conductivity of the soil phase at the higher densities. In addition, it is possible that closer packing of the soil grains provides better continuity of the adsorbed moisture films, more soil-ice contacts of individual grains per unit area at the freezing plane, (and consequently less unit surcharge pressure on the moisture film surrounding each grain) with the result that greater volume of moisture can flow to the freezing surface, in spite of a lowering of permeability of the densified soil.

In the clay soils and in the well-graded soils, it is presumed that permeability reduction probably outweighs the other factors, resulting in a reduction of rate of

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*According to Beskow's concept.

heave with increasing density. Thought should be given to simple experiments to measure and evaluate the individual factors discussed above.

Thought should also be given in practical pavement design to the possibility that initial high densities in frost-susceptible soils may be lost after the first winter as a result of loosening by frost action. The most obvious solution for guaranteeing the built-in stability of high density base courses and subgrades in modern highways and pavements is to use only free-draining non-frost-susceptible materials within the zone subject to frost action. Possibly, this may be aided in the future by use of chemical additives to modify materials which would otherwise be unsuitable.

3-02. Effect of Surcharge. In Fiscal Year 1951, it was brought out that heave rate decreased as the surcharge increased. This same trend has been observed by other investigators (Beskow[1], Taber[10]) in laboratory tests. It is evident that if variations in overburden pressure do cause variations in frost heave of soil under field conditions, this relationship can be taken into account in formulating engineering design criteria for construction on frost-susceptible soils.

However, a possible weakness in the test methods was visualized. In particular, it was questioned whether side friction on the soil specimens during laboratory freeze tests was influencing or producing the observed trend. For example, is there more lateral expansion or crystal growth during freezing under the heavier surcharge load? Could the total volumetric expansion be the same under heavier surcharge, but be unobserved because it occurred laterally instead of vertically? Could the increase in side friction resulting from possible lateral expansion be the cause of the change in heave, rather than the surcharge pressure itself? To explore these considerations, additional studies and laboratory tests were performed in Fiscal Years 1952 and 1953.

a. Lateral Expansion. Studies of the structure of frozen soil show that under one-dimensional heat flow, growing ice layers orient themselves, generally perpendicular to the direction of heave or heat transfer, and that substantial lateral expansive force due to growth of the crystals does not occur. The latter factor has been demonstrated indirectly by Beskow in his experimental tests to devise apparatus for reducing the sliding resistance between the soil mass and the container walls in laboratory specimens. Beskow utilized a container consisting of a series of short glass rings, placed on top of each other to form one cylindrical container. These glass rings would have broken during freezing of the specimens under any substantial expansive force; however, such phenomena was not reported during the tests. Further, in routine tests by this laboratory, specimens frozen in cardboard cylindrical containers lubricated with petrolatum or in lucite containers with a liner composed of sheet acetate and silicone, have shown no change in circumference or have decreased in circumference (lateral shrinkage of the unfrozen zone in closed system tests), as compared to the dimensions before the freezing test.

b. Experiments to Evaluate Side Friction. Exploratory tests were performed in Fiscal Years 1952 and 1953 to evaluate the magnitude of frictional restraint upon heaving offered by various specimen containers and of various methods used to minimize the frictional forces. Gravelly sand (the minus 3/4-in. fraction) from Peabody, Massachusetts, and Silt-B from New Hampshire were used for these tests. The grain size distribution of these soils are shown on Plate 1, and the pertinent data for this test series are given in Table 32 of Appendix B. Individual soil specimens were prepared for quick freezing (1-3/4-in. per day) in 6-inch I.D. micarta containers and/or tapered lucite cylinders, 5.5-in. I.D. The specimens were packed to a six-inch height and various liner types were used. The relative effectiveness of each of these liners and the magnitude of frictional restraint were evaluated by determining the force required to eject the frozen soil specimens from the containers. The results of this test series are listed below :

Soil	Container	Liner Type and Lubricant	Frictional Side Restraint psi	Equivalent heaving pressure, psi, which would just balance frictional restraint after specimen frozen 6 in.
Peabody Gravelly Sand	Micarta	Petrolatum sheet	6.6	26.4
	"	Acetate w/Silicone	5.8	23.2
"	"	1" Acetate strips (lapped) w/Silicone	3.1	12.4
"	"	1" Acetate squares (lapped) w/Silicone	1.2	4.8
"	"	1" Acetate strips (lapped) w/Liqui-Moly	0.9	3.6
"	"	Dental dam (lapped) w/Liqui-Moly	0.3	1.2
"	Tapered Lucite	Silicone	1.4	6.1*
New Hampshire Silt-B	"	Liqui-Moly	23.8	104.0*
	"	Sheet acetate and Liqui-Moly	1.8	7.9

*Containers assumed 5.5 inches avg. I.D. and 6.0 inches high for computations.

The Micarta containers were 6 inches I.D. The lucite containers were 6 inches in height and were tapered from 5.65 inches I.D. at the top to 5.40 inches I.D. at the bottom.

The high value of frictional side restraint and corresponding equivalent heaving pressure obtained for New Hampshire Silt-B in the tapered lucite cylinder lubricated with liqui-moly is attributed to the non-affinity of this lubricant to lucite. This was evidenced by the fact that, upon ejection of the frozen silt specimens, the interior surface area of the lucite cylinder was very clean, whereas liqui-moly adhered to the contact surface of the frozen specimens. According to information available, lubrication with this material is achieved by the molecular structure of the form of molybdenum used in liqui-moly. According to this theory, each molecule orients itself so that it is firmly attached by molecular attraction to each face of mating bearing surfaces, leaving two molybdenum-coated friction surfaces bearing against each other instead of the original bearing materials. In this particular test, only one surface - the soil surface - was coated with molybdenum, which presumably resulted in the high frictional side restraint.

c. 12-inch Diameter Specimen. In the side friction tests reported in the preceding paragraph, side friction on the laboratory specimen is equivalent to an intensity of surcharge acting over the cross section of the specimen, varying from 0 at start of freezing to 4 times the maximum surcharge applied in the tests when freezing reaches a depth of 6 inches. Consideration of the relationship between the surface area on which friction may act along the perimeter of the specimen and the cross sectional area of the specimen suggests that by increasing the diameter of the specimen without increasing its height, the relative effect of the side friction should be reduced since the side frictional area increases only as the diameter, whereas the cross sectional area on which surcharge and heave pressures act increases as the square of the diameter. To examine this relation, a sample of Truax Drumlin Soil (TD-36) was molded in a 12-inch diameter transite container. The specimen was reduced to a 6-inch height with a compactive effort equivalent to that of the modified AASHO density test, and it was then subjected to an open system freezing test. Prior to placing the soil into the container, the inside walls of the transite were first lubricated with a thin coating of silicone and lined with 1-inch wide by 0.007 inch thick cellulose acetate strips in a telescopic fashion. The surfaces of the acetate were lubricated with silicone.

The 12-inch diameter size necessitate substitution of a 1/2 inch thick filter built up from Ottawa Sand, 18 x 14 mesh bronze screen cloth, and 64 x 64 weave muslin (against base of specimen), in lieu of the customary 3/8 inch thick porous disc and filter paper utilized in preparation of 6-inch diameter test specimens. Except for the aforementioned differences, the testing procedures for this specimen were similar to those described in paragraph 2-02, Part II, Soils, Test Procedures and Frost Classification.

As indicated in Figure 2 of Plate 2, the test result for this 12-inch diameter specimen plots directly upon the curve established in Fiscal Year 1951 for the 6-inch diameter specimens. The 1951 six-inch diameter specimens were prepared with only use of petrolatum on the walls of the cardboard container to reduce friction. Therefore, the test on the 12-inch diameter specimen should have been under reduced relative side frictional resistance, as compared with the 1951 tests, as may be deduced by examination of the tests summarized in the table in paragraph 3-02 a, above. This factor and the doubling of the diameter height ratio of the specimen, would be expected to show a marked change in the heave rate if the side friction is a significant factor in these tests. The close agreement of the data from this test with the previous results, as shown in Figure 2 of Plate 2, indicates that the factor of side friction does not significantly affect the test results. However, it is recognized that this represents only a single test and that a larger number of tests are required for conclusive proof.

d. <u>Additional Surcharge Tests in Fiscal Years 1952 and 1953.</u> The following soils were used in further surcharge tests:

(1) Undisturbed Silt from the subgrade of the Fairbanks Permafrost Research Area, Fairbanks, Alaska (Fairbanks Silt).

(2) Remolded silt from Valparaiso, Indiana (Indiana Silt).

(3) Remolded clay subgrade soil from the WASHO Road Test Section, Malad, Idaho, (WASHO Clay).

The pertinent data from these tests are listed in Table B3 of Appendix B. The average heave rates are plotted against intensity of surcharge on Plate 3. The data shown thereon includes all the 1951, 1952, and 1953 test results. The grain size distributions of the soils tested in the three fiscal years are included also on Plate 3.

In general, all the test results show the tendency for decrease in rate of heave with increase in surcharge which was originally shown in the Fiscal Year 1951 report. The two specimens containing an appreciable clay content, namely, the East Boston Till and the WASHO Clay show a tendency toward a less decrease in rate of heave with surcharge than the other soils, which produce more or less parallel curves. This result appears to be in agreement with Beskow's observations; he found, similarly, that the finer-grained soils were less affected by surcharge. Following Beskow's reasoning, in the clay soils, the film of water at the critical plane between the already-formed ice lens and an underlying soil particle is apparently less readily cut off by a surcharge load than it is in the coarser-grained soils such as silts. This may be not only because of relatively thicker and presumably stronger films on the clay particles, but also because of the vastly greater number of particle contact points at the freezing surface in the clay, as compared with the silt, with consequent lesser unit surcharge stress on the intervening films of the clay particles.

Some difficulty was experienced during these tests in establishing accurate daily heave measurements for the silt specimens under heavy surcharge loads. The specimens had a tendency to deform and tip laterally during the freezing process and this resulted in erratic average heave rates, thus accounting for some of the scattering shown on Plate 3.

e. Discussion of Effect of Surcharge.

(1) There seems at this time to be no doubt that surcharge does reduce frost heave as indicated by the tests. However, in evaluating the tests in terms of field conditions, it must be remembered that the condition which we have attempted to approximate in the laboratory is that of the freezing of a surface which extends infinitely in a horizontal plane and over which heave is at all points uniform, so that there is no shear or bending action in the frozen layer. Actually, however, if heave is restrained by a surcharge pressure locally, as under a road embankment, the resulting shear and bending developed in the layer of frozen material at the edges of the embankement results in mobilizing lifting force over an area which extends well outside the immediate area over which surcharge is actually applied. Again, however, the latter condition is for one of assumed uniform frost penetration, both under and beyond the roadway pavement. The comparison becomes somewhat complicated if we consider the fact that snow cover will normally reduce the extent of frost penetration beyond the edges of a pavement, thus tending to balance the reduction in heave under the pavement due to surcharge against a reduction in heave at the edges because of less severe freezing.

It is believed that the relationship between surcharge and heave which has been shown in these tests, can be taken advantage of in actual cases if a reasonable assumption of the effective area over which heave forces are to be assumed can be made. In order to obtain field data on this point and to confirm the validity of the laboratory tests, it is believed that a test area should be constructed on which 3 to 5 different surcharge intensities can be applied to full-scale foundation areas. These areas should be selected and prepared well before the time that the actual surcharges are applied, and the heaves of the test areas should be determined for full seasons both before and after surcharge application. Preferably each of the measurement periods should cover several seasons in order to permit averaging-out of water contents and other variables. Snow should be kept cleared from the test areas and for a reasonable distance around in order to obtain uniform frost penetration and results which are conservative. The method of surcharge application should be carefully considered in order that the effect of surcharge will not be obscured by variations in freezing conditions or other factors. For example, use of gravel layers of different thicknesses to apply surcharge will result in differences in frost penetration. However, prior to the construction of any test section, it is recommended that an attempt be made to correlate field data from the Fairbanks Permafrost Research Area and other locations where information on pavement and base course thicknesses and heave observations are available.

(2) The experiments to evaluate side friction, reported in paragraph 3-02b, above, indicate that in a rigid container the frictional side restraint can reach rather high values, particularly in relation to the surcharge intensities used. Thus, the standard laboratory freezing tests might show considerably higher rates of heave if side frictional restraint could be entirely removed. Also, the effect of the surcharge loadings might be considerably greater in a relative sense. On the other hand, the results of the single large-diameter test reported in paragraph 3-02c, above, appear to indicate that side friction is not a significant factor. It is believed that this may be because the comparison tests in cardboard containers also had low side friction due to the ability of the containers to stretch and distort moderately. It is, therefore, planned to run additional laboratory tests to measure the friction in the 6-inch diameter cardboard containers used in the standard laboratory test. Further, a series of heave tests should be run in which the only variable is the side friction, using the various friction-reducing methods reported in paragraph 3-02b, and a plot of side-friction vs heave, or rate of heave, should be obtained.

3-03. Closed System Tests.

a. Test Program. In Fiscal Year 1951, 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. The test data indicated that the water content of the upper frozen portion of each test specimen was increased considerably above its original value, and that the water content thus reached bore a direct relation to the initial degree of saturation. On the other hand, the water content in the lower portion of the test specimen decreased to a relative low value which appeared to be independent of the initial degree of saturation and was relatively constant for a given soil. Since the previous report, additional tests have been undertaken to further examine these indicated water content relationships.

The materials subjected to testing in the new studies were:

(1) Glacial clays from North Cambridge, Massachusetts; Searsport, Maine; and Fargo, North Dakota.

(2) Well-graded Silt-A from Goff's Falls, New Hampshire, and silt subgrade soil from Fairbanks, Alaska.

(3) Sandy clayey gravel from Revere, Massachusetts, (locally referred to as East Boston Till), and silty gravelly sand (glacial till) from Portsmouth, New Hampshire.

The gradation curves for these soils are shown on Plate 1.

Specimens of these soil types were prepared at degrees of saturation between 90% and 100% in the new test series, except the Portsmouth glacial till specimens, which were prepared at approximately 70%, 80%, 90%, and 100% saturation. All specimens were tested in the closed system (see Definitions). The brass nipple of the base receptacle was capped to prevent loss of moisture by downward drainage. No special provision was made to insure maintenance of atmospheric pressure at the base of specimen. Pertinent data from this test series are summarized in Table 2. Pertinent data from Fiscal Year 1951 tests are also included on Table 2 and are indicated by an asterisk thereon. Complete data on Fiscal Years 1952 and 1953 tests are given in Table B4.

A summary plot of the closed system freezing tests to date is shown on Plate 4. The water content distributions after freezing for the specimens in the new series reported herein are shown on Plates B37, B38, B39, B40, B43, B53, B61 and B62.

b. Moisture Reductions at Bottoms of Specimens. The data in Table 2 and on Plate 4 show that for most soils the water content in the unfrozen zone at the bottom of specimen, or the bottom frozen inch of the specimen, had decreased by the end of the test to a value which appears to be relatively constant for a given soil and in some cases completely independent of the initial degree of saturation. In the unfrozen zone of the undisturbed and remolded specimens of the three lean clays, the water content decreased considerably, as water moved to the zone of freezing where ice lenses were being formed. Reference to Table 2 and Plates B61 and B62 shows that there was no consistent and definite migration of moisture in the highly plastic clay from Fargo, North Dakota, either when tested undisturbed or when tested in the remolded condition. The very bottoms of the two undisturbed specimens of Fargo clay do show slightly lower water contents, but the evidence is insufficient to establish that freezing is the cause.

In the remolded and undisturbed silt and remolded glacial till specimens, the water content of the unfrozen zone decreased below the initial moisture content. The greatest decrease was observed in the New Hampshire silt. The plastic limit and/or the shrinkage limit (determined according to ASTM standards, 1952), are indicated for each soil on Plate 4.

c. Moisture Between Ice Lenses. The water content of the soil between segregated ice lenses in the frozen zone was also determined in several of the test specimens as shown on Table 2. It may be noted that the most impervious specimen of the group tested for moisture contents between the ice lenses, the remolded Boston Blue Clay (BC-21), showed a reduction of moisture content to the shrinkage limit, whereas the coarsest material, the New Hampshire Silt (NH-48 and NH-49) actually showed considerable increase over the initial moisture content. Other materials showed intermediate results. Evidently, ice segregation occurred even within the soil between the ice lenses, in the silt, and moisture was readily withdrawn from the underlying soil from some distance, so long as it remained available within the specimen. On the other hand, it was apparently very difficult in the remolded clay to replace extracted moisture by movement from below. The undisturbed Boston Blue Clay (BC-22) either was able to do this somewhat more readily, or else moisture extraction was cut off before achieving full effect by formation of an ice lens at a lower level, since the results show moisture content between ice lenses about 10% higher than in the remolded Boston Blue Clay. This may be due to the flocculent structure and lower compressibility of the natural clay (Casagrande[3]).

d. Moisture Gain at Tops of Specimen. The water content increase in the top inch of the specimens is also shown on Table 2 and Plate 4, and inspection of the latter plate confirms the previous conslusion that the moisture content of the upper frozen portion of the specimen bears a direct relation to the initial degree of saturation. However, no tests were performed with the Fargo Clay at reduced degree of saturation, and it may be that clays as fat as the Fargo soil will not follow this trend.

e. Discussion of Closed System Tests. In the earlier cold room tests, many specimens experienced temperature "kick-backs" due to sudden, spontaneous freezing after supercooling. This resulted in quick freezing in at least the upper part of these specimens, with resultant probable lower water gain there. Review of the test records indicates that the following specimens probably suffered temperature kick-backs to some degree:

Dow AFB specimens	DFC-1 through 5
East Boston Till specimens	EBT-5 through 8
Portsmouth AFB specimens (slight in 10 through 12)	PAFB-9 through 12
Truax AFB specimens	TD-17 and 18

As a result, water content in the top inch of these specimens, as plotted on Plate 4, should tend to be somewhat lower than if kick-backs had not occurred.

Some of the scatter of the test results is probably caused by variations in initial dry densities. Variations in ice segregation would be expected with differences in density.

Any migration of moisture in the Fargo Clay must have been over very short distances less than about an inch, which was the order of thickness of the water content slices (see Plates B61 and B62). On the other hand, migration was most pronounced in the two silt specimens. It is believed that this difference in performance is controlled by such factors as differences in effective permeability (in the soil mass and at the soil ice lens interface), differences in amount of mobile moisture which is present in the soil, and differences in pressure gradient, toward the freezing plane, capable of being developed in soil moisture. From a practical point of view, one way in which the problem is of interest is in helping to evaluate the extent to which partial desiccation can be produced in a mass of unfrozen soil by frost action in an adjoining mass of soil with which it is in contact. For example, to what extent can drying and consolidation be produced under the foundation of a heated building by frost penetration down past the walls of the building? The tests presented herein indicate that it is very unlikely that such drying could occur in a fat clay, but that it would not be unlikely in a coarse, relatively pervious silt. However, much needs to be learned before such a problem can be analyzed quantitatively for any given soil condition. Test information is needed which will relate temperature gradient or rate of removal of heat to pore pressure gradients in the soil underlying the frozen layer in such a way that rates and patterns of moisture flow can be computed for any given set of conditions.

The evidence to date indicates that a reduction of percent saturation to the order of 70% does not eliminate ice segregation and heave but does reduce it substantially, as well as reducing moisture gain in the top inch of the specimen. This conclusion is applicable only for the first cycle of freezing.

3-04. Effect of Sample Remolding. A series of tests was carried out to determine the effect of remolding on ice segregation.

a. Tests Performed. The following soils were tested:

(1) Lean clays from Cambridge, Massachusetts and Searsport, Maine.

(2) Highly plastic clay from Fargo, North Dakota.

(3) Silt from Fairbanks, Alaska.

(4) Stratified clay, consisting of relatively thin bands of very fine sand, silt and clay, from Portsmouth, New Hampshire.

Undisturbed cubic-foot specimens of the lean clays and the stratified clay were obtained at depths sufficiently below the frost zone to exclude any effects of previous frost action. The silt was obtained as undisturbed cubic-foot specimens from the subgrade at Runway Test Section RN-4 in Area No. 2 of the Field Research Area, Fairbanks, Alaska, within the zone of permafrost degradation. The Fargo fat clay was obtained as undisturbed specimens, approximately 6-1/2 inches in diameter and 8 inches in height, from the subgrade adjacent to Taxiway 2B of Fargo Municipal Aiport between the depths of 2.2 to 3.8 ft below the ground surface. The gradation curves for these materials are shown on Plate 1.

Undisturbed and remolded companion* specimens of the lean clays and stratified clay were subjected to freezing both in the open system and closed system types of test. Available quantity of the Fairbanks silt permitted testing of undisturbed and remolded specimens in the open system only. Undisturbed and remolded specimens of Fargo clay were tested in the closed system and remolded specimens in the open system. The undisturbed Fairbanks silt and Fargo clay specimens in this series were not subjected to freezing in the same test chamber with their respective remolded specimens.

b. Test Results. The pertinent test data for the specimens are shown in Table B5. The percentage heaves for the materials investigated, based on the original height of the frozen portion and as determined in each type of freezing system, are summarized in the following table :

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*Companion signifies that the soil specimens were prepared to similar dry unit weights and degrees of saturation and were tested together in the same freezing cabinet.

		Undisturbed		Remolded	
Material	Type of System	Original Height of Frozen Portion in.	Heave %	Original Height of Frozen Portion in.	Heave %
Boston Blue Clay	Open	4.00	111.8	3.94	58.9
	Closed	5.12	10.7	5.43	11.0
Searsport Clay	Open	3.25	240.3	4.28	47.2
	Closed	6.00	7.3	6.00	9.7
	Open	3.75	155.2	5.36	38.6
	Closed	6.00	4.8	6.00	6.8
Fargo Clay	Open	-	-	5.80	18.4
		-	-	5.75	24.0
	Closed	6.00	2.0	5.60	8.6
		5.50	2.2	6.00	9.7
Fairbanks Silt	Open	4.42	124.0	4.80	81.8
	Open	-	-	5.30	102.1
Portsmouth	Open	2.99	95.3	3.07	114.9
Stratified Clay	Closed	5.00	6.8	5.00	5.0

The test results indicate that generally when these soils are remolded, the percentage heave is greatly reduced in an open system and slightly increased in a closed system, as compared to the corresponding percentage heave for undisturbed specimens. The Portsmouth stratified clay provides the sole exception.

c. Discussion of Effect of Specimen Remolding on Ice Segregation. This frost behavior change is attributed to the structure alteration produced by the rearrangement of the soil particles during remolding. Fine particles deposited in an alluvial medium in nature are likely to have a loose and random flocculated structure. Even though consolidated under overburden pressure, the original porous structure remains, exhibiting considerable strength.

Upon remolding, the particles are oriented into new positions. The permeability is decreased. For example, others have found that the permeability of remolded Boston Clay is 1/200th of that in the undisturbed state[8]. A decrease in permeability would affect the rate at which water could be supplied to a growing ice lens. The large decrease in heave observed in open system tests after remolding is attributed to this decrease in permeability.

In the closed system, water is made available for ice segregation only from within the soil specimen, and if all portions of the specimen were to remain saturated, the total increase in specimen volume would not exceed the volume increase of the portion of the water in the specimen which freezes. Actually, the increase tends to be larger because of the tendency for free water to be removed from the soil voids and be concentrated in the ice lenses, leaving the voids partially filled. Water is supplied for ice lens growth from the material directly below the plane of freezing, resulting in the consolidation of this material under the resultant pore water tension. If ice forms within the soil voids as well as in ice lenses, there may be some distention again as crystallization occurs. As the plane of freezing advances, the material next below becomes consolidated, and the process continues until no more mobile water is anywhere available. In the open system, the process is the same except that water is drawn up from the source at the bottom of the specimen, as well as from the soil voids.

Since soil in the remolded state is also more compressible than the same soil in the natural state[3], it is visualized that during the freezing process, a slightly greater volume of pore water is made available for ice lens growth in the remolded cohesive soil than in the undisturbed. The slightly greater heave shown by remolded specimens as compared with undisturbed specimens were tested in a closed system, may in part be attributed to the expansion of this additional amount of water in freezing. However, other effects of the changed structure brought about by remolding may also be involved.

Although the Fairbanks silt material exhibited the same trend as the clays, this frost behavior change cannot be totally attributed to a structure alteration similar to that effected by remolding clay soils. Vertical seepage fissures and paths developed by past freezing, and the presence of old root holes, undoubtedly resulted in a more ready source of moisture for ice segregation in the undisturbed Fairbanks silt specimen.

This series of freezing tests also indicated that the percentage heave of remolded Portsmouth stratified clay increased in an open system and slightly decreased in the closed system type of test, as compared to the natural material.

This reversal in frost behavior is attributed to the stratification in the natural material. Remolding probably in this case increased the overall vertical permeability and by producing a relatively well-graded mixture, probably also slightly increased the capacity of the thickness equivalent of the sand and silt layers to retain moisture against the suction created by the growing ice lenses.

This reasoning points up the fact that differences in frost action of varved clays are strongly dependent upon the permeability of the finest layers, when water is available only by flow in the vertical direction.

From the standpoint of decreasing the effects of frost action, however, the possible advantage of remolding the lean clays and silt has not been proved, since loosening and rearrangement of the structure of these soils could result after a few freezing cycles, which could possibly restore the avilability of pore water for ice segregation.

3-05. Effect of Proximity of Water Table. An exploratory series of tests was performed to determine the effect of the relative proximity of the water table on ice segregation in the minus 3/4-in. fraction of the highly frost-susceptible gravelly sandy clay (East Boston Till C) from Revere, Massachusetts.

The East Boston till specimens were prepared at about optimum moisture content with a compactive effort equal to that of the Corps of Engineers Airfield Density Test. The specimens were molded in 5.45 in. inside diameter lucite cylinders to approximate heights of 1.0 ft, 1.5 ft, 2.5 ft and 3.5 ft. The inside walls of the portions of the lucite cylinders which were to project into the freezing cabinet were lightly coated with petrolatum and lined with 0.007-in. thick cellulose acetate, the interior surface of which was also lubricated with petrolatum to minimize the side-wall friction in the specimens during heave. All specimens were saturated in the cold room to a temperature between 35°F. and 38°F., prior to freezing, by the procedure described in paragraph 2-02 of Part II, Standard Test Procedure, Appendix A. The average degree of saturation for each specimen was computed from weights of specimen and container before and after saturating; the dry unit weights were computed from the predetermined dry weights of soil and container volume.

Thermocouples were inserted along the longitudinal axis at 2-in. intervals in the upper 12-in. of one of the four till specimens. In addition, thermocouples were placed at the top, and 12-in. from the top, in another specimen. The four specimens were placed in the freezing cabinet so that the top 12-in. of the specimens were in the cabinet.

The remaining lengths of the specimens protruded below the cabinet and were exposed to the cold room temperature of 35 - 38^{O}F.

A supply of deaired water was connected to the receptacle at the base of each specimen and the constant water level device was adjusted to a height such that the water in the base receptacle would rise to about 1/4-in. above the porous stone and be in contact with the soil. The specimens were frozen at a rate of penetration of the 32^{O}F. temperature, approximately 1/4-in. per day under a surcharge intensity of 0.5 psi. Only the portions of the specimens which were within the cabinet were frozen. At the completion of freezing, the specimens were removed from the cabinet and weighed to determine the change in water content. Distribution of water contents for the unfrozen portion was obtained by removing the soil mass in about 1-inch increments with a metal spoon. The frozen portion was ejected from the lucite container, measured for amount of heave, weighed to determine the average change in water content of the frozen portion and then split in two longitudinally. Observations for the location, distribution and magnitude of ice lens formation were made on one-half of the specimen and the remaining half was used to determine the water content distribution for every inch of depth. The test data and moisture determinations after freezing for this series of tests are given on Table B6 and Plate B45 of Appendix B.

The individual moisture content determinations for the East Boston specimens, EBT-42, 43, 44 and 45, shown on Plate B45, together with the results of sample EBT-25, have been plotted on Plate 5 as average curves to yield a composite plot. The data for specimen EBT-25 were taken from the Second Interim Report of Investigations for Fiscal Year 1951 to add the effect of a water source 6 in. from the top of the specimen, lacking in this test series. Examination of this composite plot reveals (a) that unless an unlimited source of water is available within a depth of 4 to 6 in., ice segregation at the plane at which freezing is occurring is limited in this soil principally to what it can extract from the water already present in the soil below the level of freezing, and (b) that in the 42-in. specimen (EBT-45), water was extracted for ice segregation from a maximum depth of about 18 in. below the freezing plane. Substantial increase, or decrease, in the rate of frost penetration would change these results quantitatively. Plate B45 shows higher water contents than the original values in the lower 2 to 3 in. of specimens EBT-43 and 44, and also in the bottom fraction of an inch in EBT-42. This makes it appear that these specimens were able to expand and take on water in these regions; however, it probably represents density variations due to specimen preparation or handling.

The relationship between average rate of heave and depth to water table, measured from the top of specimens of East Boston Till, is presented on Plate 6. The rates of heave shown thereon are based on about 11 inches of frozen depth. It is seen that, on an arithmetic plot, the average rate of heave for East Boston Till decreases non-linearly with an increase in water table depth for the range explored, approximately 0.5 to 3.5 ft. The greatest decrease in average rate of heave occurred with decrease in water table to about 18 in. and additional increase in depth up to 3.5 ft had little effect.

In general, this exploratory series of tests measured the effects not so much of water table proximity as of depth to an aquifer, an unlimited source of water. In order to determine the effect of depth to water table within a homogeneous soil mass, it is recommended that test equipment be designed to give a practical equivalent of infinite depth of specimen, or, as a minimum alternate, the specimens should all be of the same length, with the water table controlled at different levels in the specimens. Provisions should also be made in the equipment to obtain the distribution of degree of saturation, as well as water content, with depth in situ, both prior to and after freezing, in order to establish more conclusively the moisture distribution pattern with variations in water table proximity. Finally, it is recommended that additional tests be conducted using densities for these materials which will give fairly high rates of heave, to accentuate the differences, as the current test densities were such that the rates of heave were almost negligible.

It may be noted that several cycles of alternate freeze-thaw might have altered the soil structure sufficiently to produce conditions favorable to increased ice segregation. Increase of frost action with time has been observed to occur in the field, particularly in cut sections, where exposure to the first winter following construction has produced relatively minor frost action, but considerable heaving has occurred during subsequent winters.

3-06. Frost Susceptibility Tests of Natural Soils Specimens. Tests were performed to determine the relative frost susceptibility of base course and subgrade soils from various airfields and highways in the northern United States, Canada, Alaska, Iceland and Greenland. Included in these soils were materials proposed for base course construction. The majority of the soils were submitted by various Division and District offices for laboratory freezing tests, in accordance with paragraph 4-07 (a), Chapter 4 of Part XII of the Engineering Manual. The materials were generally tested in the remolded condition at a density, between 90 and 100 percent of maximum density, as determined by applicable laboratory compaction procedures. However, subgrade silt (Specimen LFT-10) from the Fairbanks Permafrost Research Area, Fairbanks, Alaska, and clay specimens from Portsmouth (New Hampshire) AFB, Searsport, Maine, and Cambridge, Massachusetts, were subjected to laboratory freezing tests in the undisturbed state.

The data for the complete series of Fiscal Years 1952 and 1953 tests are presented in Table B7 of Appendix B. The grain size distribution of the test specimens and the relationship between the average rate of heave and percentage finer by weight than 0.02 mm are plotted on Sheets 1, 2 and 3 of Plate 2 in this report. Included on plots of rate of heave vs percentage finer than 0.02 mm are applicable test results from the Fiscal Year 1951 second interim report.[11] On Sheet 2 of Plate 2, envelopes have been drawn to encompass the points falling into specific groups outlined by the Unified Soil Classification System.[12] On Sheet 3 of Plate 2, lines have been drawn through the same data to show the average relationship of a soil group between its rate of heave and the percent finer than the 0.02 mm size.

Examination of the summary plots reveals that (a) the average rates of heave of similar soil types fall into definite envelopes, (b) a rather wide range of rates of heave may be obtained at any given percent finer than 0.02 mm and a given rate of heave may be obtained with a number of different soil types, and (c) there is a progressive increase in the percentage of minus 0.02 mm material at which a given rate of heave is obtained as soil type changes from coarse to fine. There is a considerable overlapping of the envelopes and no clear distinction between the behavior of immediately adjacent soil groups. It will be noted that for a relatively low percentage of 0.02 mm size, the gravel groups exhibit higher rates of heave than similar sand groups.

The use of percent finer than the 0.02 mm particle size present in a soil gradation as a criterion for frost susceptibility was introduced by Dr. Arthur Casagrande[4], based on frost heaving experiments at the Massachusetts Institute of Technology and in New Hampshire in 1927 - 1930. Based on the above studies Dr. Casagrande concluded that:

> "Under natural freezing conditions and with sufficient water supply one should expect considerable ice segregation in non-uniform soils containing more than three percent of grains smaller than 0.02 mm, and in very uniform soils containing more than ten percent smaller than 0.02 mm. No ice segregation was observed in soils containing less than one percent of grains smaller than 0.02 mm, even if the ground water level was as high as the frost line."

These criteria are fairly well borne out by the test results obtained at ACFEL except that in the laboratory tests, considerable heaving has been observed in some well-graded gravelly soils containing less than 3 percent of 0.02 mm size. However, it must be remembered that the laboratory tests are performed under exceptionally severe conditions as far as availability of unlimited free water is concerned. Such a condition is unlikely to be duplicated normally in the field in the base course of a well-designed pavement. Therefore, it is concluded from the data presented and related field experience, that the gradation of a soil and the percentage finer than the 0.02 mm size still present the most expedient means of recognizing a potentially frost-susceptible soil.

Several other soil properties, many of them interrelated and interdependent, are believed to greatly influence the frost behavior of soils in addition to gradation, such as permeability, particle shape, mineral composition, particle arrangement, void size between particles, surface area, and molecular surface forces. An optimum combination of these various factors evidently occurs in the silts and lean clays to produce conditions conducive to extremely high frost susceptibility observed in these soils.

In fat clays (CH, CH-OH), the rate of heaving has been observed to be considerably less than in the silts and lean clays as illustrated by the lower position of the envelope shown on Sheet 3 of Plate 7, encompassing the results obtained with the highly plastic clays. This is attributed to the greater imperviousness of the clay due to its particle shape and arrangement, surface area, and to the strong molecular surface adsorptive forces which attract and hold pore water with great tenacity.

The remolded silt material from Whitehorse, Yukon Province, Canada, identified as specimen YS-1, gives results out of line with the rather similar Fairbanks and Indiana silts. The test data in Table B7 indicate that the Yukon silt specimen (YS-1) was tested for frost susceptibility at a density of 122.6 pcf, or 98% of modified AASHO density; this is about 9 pcf higher than the test density of the Indiana silt specimens and about 24 pcf higher than the undisturbed Fairbanks silt specimen. It is an exceptionally high density for a silt. Since it has been concluded that the average rate of heave increases with increasing density for silt soils, one might expect that the rate of heave for the Yukon specimen would be higher than for the Fairbanks or Indiana silt specimens, but the test data indicate the reverse. It is believed, therefore, that it might be worthwhile to make a detailed analysis of these silts to determine effect of density variations and organic content on frost susceptibility, in addition to the mineralogical and structural differences in these silts which cause such a wide difference in rates of heave.

As an objective in the future, it is also suggested that plots similar to Plate 7 of this report be developed for field rather than laboratory heave conditions, for specific ground water table positions below the subgrade surface and other specific conditions, and that efforts to establish relationships between the laboratory results and actual field performance be continued.

3-07. Freezing Point of Soil Moisture. Information on the freezing point of moisture in soils is necessary because of the influence of this factor on the prediction of depths of freeze and thaw penetration. Present theoretical methods either assume the soil moisture freezes at 32°F. or at some constant temperature below 32°F. Increased knowledge of the freezing point of soil moisture will also aid in understanding the phenomena of ice segregation.

Previous laboratory studies by Bouyoucos[2] at Michigan State College, Beskow[1], and others, have demonstrated that the freezing point of soil moisture in fine-grained soils is generally below 32°F. and for a given fine-grained soil, the freezing point decreases with decrease in water content. Most investigators attribute the depressed freezing point of soil moisture to (a) soluble salts in the pore water and (b) the adsorptive forces by which the water is held to the soil grains. Pore water at the center of the interstices is considered to freeze at a higher temperature than the water closer to the surfaces of the fine soil grains.

In previous investigations by the Arctic Construction and Frost Effects Laboratory, the freezing point of soil moisture has been determined by measuring with thermocouples the temperature at the visual boundary between frozen and unfrozen soils in test pits and cold room test specimens. For proper correlation and application of these results, however, comprehensive laboratory studies are required to analyze the effects of such factors as moisture content, dry unit weight, soil mineral characteristics, and the dynamics of the freezing process. Exploratory laboratory studies, therefore, were initiated in F.Y. 1952 to work out test techniques and instrumentation, and to obtain the freezing history of several soil types at varying moisture content. The soils selected for this exploratory test series were Lowell Sand, Manchester Fine Sand, New Hampshire Silt and Boston Blue Clay. Each soil type was prepared at several water contents by adding distilled water to the oven-dried materials, except that the tests with the clay soil started with air-dried material. Test specimens were prepared by placing each specimen into a copper tube, 3/4-in. in diameter and 3-1/2 in. in length, with a wall thickness of 0.065 in. A 24 gage copper constant thermocouple was inserted along the longitudinal axis of the specimen to its midpoint to measure temperature changes within the specimen, and the ends of the tube were sealed with asphalt mastic to prevent loss of moisture by evaporation. A relatively long specimen container was selected, and the thermocouple wire was run lengthwise down the middle of the specimen, to avoid erroneous readings due to flow of heat along the thermocouple wire. A cross-section showing test specimen details is shown on Plate 8.

The specimens were suspended inside the freezing cabinet so that all surfaces were exposed to the atmosphere of the chamber. The freezing cabinet was held at a relatively constant temperature, and the temperature change within the specimen was measured continuously at 1-minute intervals during the freezing cycle with a Leeds and Northrup type K-2 laboratory potentiometer. Typical temperature-time plots for specimens of the selected soils are shown on Plate 8, together with pertinent test conditions. It is noted that during the initial stages of cooling, the temperature of each specimen dropped at a relatively steady rate to a temperature considerably below 32°F., and then suddenly rose to a higher temperature. In the case of Manchester Fine Sand, the temperature rose to 32.0°F. and remained constant for approximately 30 minutes and then the temperature dropped off at a relatively constant rate. On the other hand, the temperature of the clay specimen rose to 30.2°F., then immediately began to decrease with time.

The sudden temperature rise observed after the specimens had been lowered somewhat below 32°F., is attributed to the start of crystallization of the super-cooled pore water. The temperature at which the crystallization starts has been observed to vary considerably for specimens of the same soil and test conditions. Outside effects, such as vibrations, may influence the temperature of initial crystallization in the pore water. It is recognized that the characteristics of the pore water and the presence of nuclei for initiation of crystal formation have an important influence on the temperature of initial crystallization. Dorsey[5] has similarly reported that the temperature of spontaneous freezing of water varies, i.e., same results are not obtained when tests are repeated, as shown by a long series of freeze and thaw tests on water specimens. Possibly the "mote" at which the freezing first starts varies within the same water specimen with the result that the temperature of spontaneous freezing is not the same in every case.

The same phenomenon of supercooling has been observed in the cold room test specimens that are frozen at a constant rate of penetration of the 32°F. temperature. Unless counter measures are taken, there normally occurs a sudden, spontaneous freezing of the upper portion of the specimen after the 32°F. temperature has penetrated 2 to 3 inches below the surface of the specimen. In order to prevent this effect and attain a more uniform rate of freezing temperature penetration in the standard freezing tests, positive steps, including seeding, are taken to insure initiation of crystallization at the time the 32°F. temperature penetrates slightly below the surface of the specimens.

The typical temperature-time plots on Plate 8, and the exploratory tests of this series summarized in Table 3, indicate that the level to which temperature rises after start of crystallization is a function of soil type and water content. The specimens prepared using the two sand soils and the inorganic silt soil, rose to a temperature of

32.0^{O}F. and the temperature remained constant for a period of time which was a direct function of moisture content. It is visualized that in these soils, after the start of crystallization and rise of temperature, a major portion of the pore water froze at 32^{O}F., with the progressive release of latent heat maintaining constant specimen temperature. In the specimens of clay soil, the temperature to which the specimens rose after start of crystallization is a function of moisture content. For moisture contents of 11%, 17%, and 21.5%, the maximum temperature reached after start of crystallization were 27.4^{O}F, 30.2^{O}F, and 31.3^{O}F, respectively. After reaching these temperatures, the specimen temperatures then gradually decrease, indicating that the latent heat of soil moisture was not being released at constant temperature but that soil moisture was being gradually and progressively made available for freezing as the specimen temperature was lowered. The increasing steepness of the temperature-time curve for this portion of the freezing cycles for Boston Blue Clay shown on Plate 8, indicates that a smaller and smaller quantity of water is available to freeze as the temperature decreases.

Prior to the initiation of the above test series, temperature measurements were obtained near the boundary and at the center of a remolded Boston Blue Clay specimen during a freezing cycle. The objective of this test was to establish the degree to which the temperature at the midpoint of the specimen was representative of temperature at the boundaries of the specimen. The clay specimen was molded at its water content in a lucite container, 1-1/2-in. in diameter and 1-1/2-in. long, sealed at both ends with paraffin, and with thermocouples placed at the midpoint of the sample and 1/8-in. from the inside perimeter of the container. Correlating properties, i.e., dry unit weight and water content, were not determined for this specimen. The temperature changes within the specimen at the two locations were obtained at 1-minute intervals and are plotted on Plate 9.

It was visualized that freezing would be most likely to start at the boundaries of the specimen since these surfaces must be cooler than the interior for outward heat flow to occur. In case of such inward progressive freexing, the edges would, at the start, experience little pressure due to freezing expansion, but the center which would be the last to freeze could possibly experience a substantial pressure. Also, there might be some tendency to concentrate dissolve salts in the pore water at the center as freezing progressed inward. These factors would theoretically result in a slightly depressed true freezing point of the soil moisture at the center in comparison with that at the edge. The temperature plots on Plate 9 indicate, however, that crystallization occurred more or less instantaneously (though presumably not quite simultaneously) everywhere over the cross section of the specimen, within the precision of the observations, and that the temperature at the center, in the first observation immediately after initial crystallization, was essentially the same as at the edge. The temperature at the center then rose an additional 0.3°F. by the second reading, after which it gradually decreased with time. At the edge, the temperature decreased steadily after the instantaneous crystallization rise, a gradient from center to edge being maintained, which gradually increased. The slightly more rapid drop in temperature in the outer thermocouple indicates a more rapid loss of heat near the edge. The 0.3°F. secondary rise in temperature at the center after start of crystallization is not easily explained. However, it is logical that the center should rise to a slightly higher temperature than the edge. The temperature at the edge was about 0.7°F. lower than at the center just before initial crystallization. The temperature at the edge jumped up from 26.1°F. to 30.8°F., or a rise of 4.7 degrees in the initial crystallization. In warming to the same temperature 30.8°F., the center, therefore, gave off $\frac{0.7}{4.7}$ x 100=15% less heat, and 15% less ice was formed. Since less water has been converted to ice at this temperature, the freezing point of the still-liquid water at the center should have been slightly higher than at the edge, and the temperature at the inner thermocouple should have continued to rise to a slightly higher level than at the outer thermocouple, which is what actually occurred. This reasoning indicates that the true freezing temperature is <u>not entirely</u> independent of the level to which the immediately preceeding supercooling has occurred.

Based on the results of this preliminary test, it was concluded that temperature changes measured at the specimen midpoint would be reasonably representative of the soil moisture freezing conditions, within the requirements of this investigation, provided the diameter of the container was relatively small, so as to preclude significant temperature differences between the center and the edge.

As a result of these studies, it is suggested that the following points should be considered or evaluated in a comprehensive study of the freezing point of soil moisture among other factors:

a. Effect, if any, of the specimen container; that is the restraining effect of a rigid container, possible chemical effects of a non-inert container, and effect of discontinuities at container-soil boundary.

b. Types of minerals present in the soil as affecting the thickness of the adsorbed films and the adsorption characteristics with respect to water, various ions, and organic molecules.

c. The surface area of the soil grains.

d. Thawing phenomena, as contrasted with freezing phenomena, these being not necessarily the same.

e. Correlation of heave measurements with temperature measurements vs time to determine the extent to which heaving is uniformly continuous or erratic during freezing.

f. Percentage of moisture frozen at any given point in the freeze-thaw cycle.

3-08. Mineralogical and Chemical Studies. Previous studies by others, the Fiscal Year 1951 studies by the Arctic Construction and Frost Effects Laboratory, and advances in the knowledge of clay mineral properties and base exchange characteristics of soils have all demonstrated that the nature of the fines influences the frost susceptibility of soils. These studies have indicated the possibility of developing admixtures to prevent or minimize frost action in soils. Therefore, Dr. T. William Lambe, Director of the Soils Stabilization Laboratory of the Massachusetts Institute of Technology, was retained by contract to:

a. Study the effect of composition of soil fines on the frost susceptibility of soils.

b. Search for suitable admixtures which in trace amounts would reduce or minimize frost action.

c. Recommend freezing tests, as deemed necessary, to substantiate the studies.

The detailed results of these studies during Fiscal Year 1953 are presented in Appendixes C and D, in Volume II of this report. The data, which in most cases are explained in terms of mineral structure, demonstrate that :

a. The composition of the soil fines has a great influence on the frost behavior of soil.

b. The nature of the exchangeable ion has a pronounced effect on the frost heave potential of montmorillonoid fines.

c. Dispersant additives, which alter soil structure, show considerable promise as frost modifiers, i.e., a one percent treatment of sodium tetraphosphate reduced the average rate of heave in one specimen of Belvoir sandy clay from 2 mm per day to 0.1 mm per day, a reduction of 95%.

It is necessary, however, before placing too much emphasis on the effectiveness of the dispersants, to investigate thoroughly their permanence after repeated freeze-thaw cycles, their resistance to bacterial attack, and their stability against chemical reaction and deterioration. Their effect on the peremeability of the soil should also be thoroughly investigated.

These studies are being continued in expectation that it will be possible to predict the frost action potential of a soil on basis of the mineral composition of the fines, among other factors, and in the hope that economical and effective methods of modifying the frost susceptibility of soils can be developed.

3-09. Crystal Structure of Ice Phase in Frozen Soil. A microscopic examination was made of several ice lenses taken from a frozen specimen of New Hampshire silt. This specimen was the untreated control sample (NH-79A) of a group frozen to establish the effectiveness of admixtures in reducing or preventing ice segregation. (See Table D3, Appendix D, Vol. II).

Ice lenses were separated from the specimen by sawing out soil sections which included ice lenses, perpendicular to the longitudinal axis of the specimen. The soil was removed from the ice lenses by rubbing the sections with emery cloth. Each side of the ice lens was hand ground to attain a uniform thickness. Next, the ice lens was frozen onto a glass slide. The glass was warmed to permit a slight melting of the ice. Upon cooling, the melt water refroze and secured the ice to the glass. By controlling the degree of melting and the rate of recrystallization, the melt water was observed to refreeze in the same orientation as the existing crystals. Further polishing was performed with fine emery paper until the final thickness of the ice section was between 0.03 mm and 0.4 mm. The average area under examination was approximately 5 sq cm. A cover glass was then placed over the thin section and the glass edges were sealed to prevent sublimation, by freezing water around and under the cover glass up to the boundaries of the thin section.

The thin ice sections were examined under polarized light using two types of microscopes, namely, a Spencer polarizing microscope and a Bausch and Lomb stereoscopic wide field microscope. The light source was a microscope illuminator equipped with a single mercury vapor lamp.

There was a greater variation in size of the crystals seen in transverse sections from this silt specimen than existed in the transverse sections from frozen Boston Blue Clay studied in another investigation by this office.* The largest crystals were about the same size as the largest crystals from ice lenses in the clay, viz, the longest cross-sectional axes of any of the ice crystals did not exceed 5 mm. Since the silt specimen contained numerous small crystals, however, the average diameter of the crystals in transverse sections was only of the order of 1.5 mm in the silt, as compared to an average crystal diameter of the order of 2.0 to 2.5 mm in the clay. The orientation of the c-axes of these crystals varied a great deal.

In longitudinal sections from the silt specimen, the crystals appeared elongated in the vertical direction. The estimated average length of crystals observed in these longitudinal sections was between 3 mm and 4 mm. The largest crystal observed was 6 mm in length. The greatest crystal width observed was 1.3 mm with an estimated average width about 0.8 mm.

In general, it was noted that more random crystal orientation existed in the ice lenses from the silt specimen than in lenses studied from the frozen Boston Blue Clay specimens. This factor is attributed to the large silt particles or groups of particles which were embedded in the lenses, causing local divergencies of the heat gradient away from the vertical direction.

Photomicrographs of sections from ice lenses in the New Hampshire **Silt** specimen are shown on Plate 10.

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*See footnote on page 11.

PART IV - SUMMARY OF RESULTS

4-01. Summarized below are the indicated key results of those phases of the cold room studies which were completed during Fiscal Years 1952 and 1953. Some of the trends reported are based on limited data and may be modified after additional results are obtained.

a. Effect of Variation in Dry Unit Weight (Degree of Compaction).

(1) Verifying a previously reported conclusion, the rate of heave in frost-susceptible, well-graded, gravelly soils increases moderately with initial dry unit weight up to a peak value. The dry unit weight at this peak is of the order of 95 percent of the Providence Vibrated Density and/or the Corps of Engineers Airfield Density. Above this weight, there is a decrease in rate of ice segregation with increase in dry unit weight.

(2) Verifying a previously reported conclusion, the rate of heave in inorganic silt soils increases with initial dry unit weight up to 100% of the modified AASHO Density.

(3) For clay or clayey soils tested to date, limited results indicate decrease in rate of heave with increase in density at initial dry unit weights equal to or greater than about 90 percent of the Corps of Engineers Airfield Density.

(4) In tests completed to date (which have included principally materials other than clay or clayey soils), the gradation characteristics appear to be the main controlling factor in determining whether rate of heave will increase or decrease with increase in dry unit weight, or whether it will show an "optimum", in the normal range of compacted densities.

(5) In inorganic silt soils, the effect of decrease of permeability with increase in dry unit weight is greatly outweighed by other inadequately understood factors acting to increase the rate of heave.

b. Effect of Surcharge.

(1) Laboratory tests to date indicate that the rate of heave is appreciably

to moderately decreased in all soils by an increase in overburden pressure. The measured rate of decrease with surcharge was least in two (remolded) specimens which contained appreciable clay materials.

(2) Available evidence is insufficient to date to adequately evaluate the effect of the side friction on observed laboratory heave rates.

(3) Frictional restraint on the sides of specimens subjected to laboratory heave tests can be markedly reduced by various techniques. Lapped dental dam lubricated with molybdenum compound has given minimum frictional resistance but involves a difficult and time consuming procedure in specimen preparation. Use of squares or strips of acetate lubricated with silicone grease is simpler and produces relatively low frictional side resistance.

(4) Doubling of diameter-height ratio and coating sides of container with cellulose acetate strips plus silicone to reduce total force of frictional restraint produced the same rate of heave as obtained in 1951 Fiscal Year tests with 6-inch diameter cardboard containers lubricated with petrolatum.

c. Closed System Tests.

(1) In most soils, the water content at the bottom of specimen after freezing in the closed system decreases to a value which appears to be relatively insensitive to, and, in some cases, independent of, the initial degree of saturation. In the present tests on undisturbed and remolded lean clay specimens, the water content at bottom of specimen was reduced considerably. In highly plastic clay, little or no reduction of moisture content occurred at bottom of specimen and any moisture migration was extremely localized. In remolded and undisturbed silt, and in remolded glacial till, the water content at the bottom of the specimens also decreased considerably below the critical water content, with the greatest decrease occurring in the silt.

(2) Evidence to date indicates that reduction of initial percent saturation to about 70 percent does not eliminate ice segregation and heave but does reduce it substantially, as well as reducing moisture gain in the top inch of the specimen.

d. Effect of Specimen Remolding. For at least the first freezing cycle, the intensity of ice segregation in undisturbed, homogeneous fine-grained soils is markedly reduced by remolding if the soil has free access to water. However, if the natural material is stratified, remolding may increase the percentage heave.

e. Effect of Proximity of Water Table. The following conclusions are applicable at a degree of compaction of approximately 100% of the Corps of Engineers Airfield Density Test; results may be quantitatively different at lower degrees of compaction. They should also be considered limited to normal rates of frost penetration, i.e., approximately 1/4 inch per day.

(1) The rate of heave and as a result, ice segregation, is markedly decreased in remolded East Boston Glacial Till when the depth to an unlimited supply of water is increased. (Range explored was 0.5 ft to 3.5 ft.)

(2) Test results on remolded East Boston Till indicate that withdrawal of moisture from the voids of the specimen itself, in order to satisfy the suction at the freezing plane, does not extend more than about 18 inches below the plane of freezing in this material.

(3) Unless an unlimited source of water is available within about 4 to 6 inches of the plane of freezing, ice segregation in remolded East Boston Till is limited largely to the volume of moisture which it can obtain from the amount already present in the soil below the level of freezing.

f. Gradations of Natural Soils Used for Frost Susceptibility Tests. Although there is an appreciable scatter of results, average rates of heave of soils of similar types fall into definite envelopes. A rather wide range of rates of heave may be obtained for any given percentage finer than 0.02 mm. In general, there is a progressive increase in the percentage of minus 0.02 mm material at which a given rate of heave is obtained, as soil types change from coarse towards fine*.

g. Freezing Point of Soil Moisture. The exploratory laboratory studies indicate that:

(1) The temperature of initial crystallization of soil moisture is not a function of soil type and moisture content.

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*Note, however, that rate of heave is not a direct measure of potential spring frost weakening. A fine-grained soil may weaken more than a coarse-grained material, even though it may have developed less ice segregation.

(2) The temperature to which the soil moisture rises immediately after start of crystallization, and the duration of this temperature, are dependent on the soil type and water content.

(3) Soil moisture in sands and silts is apparently completely frozen at approximately 32^{O}F.

(4) In clay soils, the proportion of the soil moisture frozen at any given temperature level appears to increase progressively as the temperature decreases.

h. Mineralogical and Chemical Studies. (See Appendix C, Vol. II).

(1) The composition of the soils fines has a marked influence on the frost behavior of soil.

(2) The nature of the exchangeable ion has a pronounced effect on the frost heave potential of montmorillonite fines when added to a clean cohesionless sand. Sodium as an exchangeable ion caused the lowest rate of heave, while the ferric ion produced the highest.

(3) Dispersant additives which alter soil structure have considerable promise as frost modifiers.

i. Crystal Structure of Ice Phase. Examination of crystal structure in ice lenses taken from frozen New Hampshire Silt showed crystals to average between 1 and 2 mm in cross-section and to be elongated in the direction of freezing. Although crystals were about same size as in sections taken from Boston Blue Clay in another study, there was greater variation in size and more random orientation of crystal axes in the New Hampshire Silt ice lenses.

PART V - RECOMMENDATIONS

5-01. Long Range Program. It is recommended that the long range program of cold room studies outlined in the Fiscal Year 1951 Interim Report be continued.

5-02. Effect of Variations in Dry Unit Weight.

a. It is recommended that additional tests be performed on clay soils of a considerable range of characteristics and over wider ranges of compacted densities in order to round out the picture of effect of dry unit weight.

b. It is recommended that simple experiments be considered for purpose of measuring and evaluating effect of variations in dry unit weight in relation to such basic factors as the suction force with which moisture is attracted to the growing ice lenses and the number of soil-ice contacts per unit of soil cross-section area.

5-03. Effect of Surcharge.

a. It is recommended that full scale field surcharge experiments be carried out following study of existing and available data.

b. It is recommended that the measurements of side frictional resistance of specimen containers be extended by measurement of the friction in standard cardboard containers supplemented by measurements of lateral expansion and contraction during freezing tests.

c. It is recommended that a series of laboratory heave tests be performed with side frictional resistance of container as the only variable, preparing containers especially so as to achieve a range of values.

5-04. Effect of Repetitive Freeze-Thaw Cycles. It is recommended that tests be performed in the laboratory for several freeze-thaw cycles on both undisturbed, unweathered clay soils, and on remolded specimens to evaluate the changes that may occur in the structure and permeability of the soil under simulated field conditions.

5-05. Effect of Proximity of Water Table.

a. It is recommended that additional tests on effect of proximity of water table be performed on silts and other key soil types, at various degrees of compaction.

b. It is recommended that tests be performed which simulate the effect of a water table within an infinitely deep soil mass, rather than an unlimited source of water at a finite depth.

c. It is recommended that a study be made of the present standard freezing test in the light of the results of tests on effect of proximity of water table, to determine whether the present standard test is giving results which are satisfactory for its purpose and whether or not modifications are in order.

d. It is recommended that the degree of saturation be measured in addition to water content in future tests.

e. It is recommended that laboratory tests be run to correlate temperature gradient with the suction force of attraction of moisture to ice lenses, using a range of soil types, with the eventual objective of developing methods by which rates and patterns of moisture flow can be computed for any set of freezing conditions.

f. It is recommended that laboratory tests be performed to evaluate the following effects in natural soils under conditions typical of frost and permafrost areas:

(1) Comparative moisture movements with and without freezing conditions.

(2) Movement of moisture entirely by vapor flow under various temperature gradients.

(3) Movement of moisture by combined vapor and liquid flow.

(4) Range of moisture contents in which all movement is by liquid transfer.

Above studies should be coordinated with comparable studies of the Flexible Pavement Laboratory and SIPRE.

5-06. Gradations of Natural Soils Used in Frost Susceptibility Tests.

a. It is recommended that a plot similar to Plate 7 of this report be developed in which all test points represent a single degree of compaction, such as 95 percent or 100 percent of Modified AASHO, in place of the present general range of 90 to 100 percent.

b. It is recommended that consideration be given to development of a plot comparable to Plate 7 of this report, which can be used to estimate heave which will occur under field conditions, knowing water table position and similar factors. Another similar plot should eventually be prepared covering in some manner thaw weakening rather than heave.

c. It is recommended that a special study be made of the test points on Plate 7 of this report which show wide scatter from the average amount, to determine the reasons therefor.

5-07. Freezing Point of Soil Moisture.

a. It is recommended that percentage of soil moisture frozen at various temperatures below 32^{o}F. during both freezing and thawing phases of the freeze-thaw cycle, be determined on typical natural soils.

b. It is recommended that measurements of total surface area per mass of soil be made in future freezing point studies, for correlation purposes.

c. It is recommended that heave vs time measurements be obtained in addition to temperature vs time records in future tests to determine the extent of which heave occurs smoothly or in abrupt increments.

d. It is recommended that simultaneous tests be run in a rubber or soft plastic jacket and in a copper tube, in order to investigate the possible effects of lateral restraint and container materials on the results.

e. It is recommended that the effect of discontinuities on the freezing point characteristics be examined by deliberately inserting discontinuities, such as large drops of free water, in soils of various types.

f. It is recommended that freezing point tests be performed on key clay mineral soils and treated materials in the mineralogical and chemical studies (below), to assist analysis of observed freezing phenomena in these materials.

5-08. Mineralogical and Chemical Studies. It is recommended that these studies be continued to improve methods of predicting frost action potential in soils and to further explore the possibility of modification of frost characteristics by admixtures, particularly in soils of borderline frost susceptibility.

5-09. Crystal Structure of Ice Phase in Frozen Soil. It is recommended that limited photomicrograph studies be continued with the objective of determining differences which may exist between ice structures in the major soil types.

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COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEARS 1952 AND 1953

TABLE 1

NATURAL SOILS SUBJECTED TO COLD ROOM TESTS

TEST IDENTIFICATION SYMBOL	SOURCE	CORPS OF ENGINEERS UNIFIED SOIL CLASSIFICATION		PERCENTAGE FINER THAN		SPECIFIC GRAVITY (TOTAL SAMPLE)	COMPACTION CHARACTERISTICS		ATTERBERG LIMITS (1)	
		DESCRIPTION	SYMBOL	0.074 mm.	0.02 mm.		MAXIMUM DRY DENSITY pcf.	OPTIMUM WATER CONTENT %	LIQUID LIMIT %	PLASTICITY INDEX %
PBJ	Project Blue Jay, TP-250	Sandy GRAVEL	GW	4	2	2.72	148.2(2)		Non-plastic	
KA	Keflavik Airfield, Iceland	Silty, Sandy GRAVEL (Crusher Run)	GW-GM	6	2	3.06	145.0(2)		"	
LSG	Loring AFB, Limestone, Maine	Silty Sandy GRAVEL	GW-GM	6	5	2.71	139.1(2) *		"	
PBJ	Project Blue Jay, TP-275	Silty Sandy GRAVEL	GP-GM	10	4	2.73	143.4(2)		"	
PBJ	Project Blue Jay, TP-274	Sandy GRAVEL	GP	3	1	2.74	148.2(2)		"	
KA	Keflavik Airfield, Iceland	Sandy GRAVEL (Pit Run)	GP	3	1	3.04	153.0(2)		"	
EBT	Revere, Massachusetts (Referred to as East Boston Till-B)	Sandy Clayey GRAVEL (Glacial Till)	GC	36	26	2.75	135.0(4)	9.1	22.7	8.3
PAF	Plattsburg AFB, Plattsburg, New York	Gravelly SAND (Washed Screenings)	SW	0	0	2.96	127.1(2)		Non-plastic	
PAF	Plattsburg AFB, Plattsburg, New York	Gravelly SAND (Unwashed Screenings)	SW	3	1	3.20	138.6(2)		"	
AG	Peabody, Massachusetts	Gravelly SAND	SP	< 1	-	2.72	131.6(2)		"	
LS	Lowell, Massachusetts	SAND	SP	< 1	-	2.68	109.0(2)		"	
MS	Needham, Massachusetts (Referred to as McNamara Sand)	SAND	SP	2	< 1	2.74	122.4(2)		"	
PAF	Plattsburg AFB, Plattsburg, New York	Gravelly SAND (Bank Run Gravel-A)	SP	2	1	2.67	132.4(2)		"	
PAF	Plattsburg AFB, Plattsburg, New York	Gravelly SAND (Bank Run Gravel-B)	SP	4	2	2.67	125.0(2)		"	
PBJ	Project Blue Jay, TP-248	Silty Gravelly SAND	SP-SM	10	4	2.70	142.6(2)		"	
MFS	Manchester, New Hampshire	Silty SAND	SP-SM	7	1	2.68	109.1(2)		"	
PBJ	Project Blue Jay, TP-262	Silty Gravelly SAND	SM	21	7	2.71	136.0(4)	7.0	"	
WWS	Fairchild AFB, Spokane, Washington	Silty Gravelly SAND	SM	18	9	2.77	142.1(2)		21.6	2.9
PAFB	Portsmouth AFB, Portsmouth, New Hampshire	Silty Gravelly SAND	SM	23	14	2.71	128.6(2)		Non-plastic	
PBJ	Project Blue Jay, TP-256	Silty Gravelly SAND	SM	31	18	2.70	137.3(4)	7.5	16.0	3.7
TD	Truax AFB, Madison, Wisconsin	Drumlin Soil, Gravelly Silty SAND	SM	32	19	2.72	139.0(4)	5.3	14.4	1.6
PAF	Plattsburg AFB, Plattsburg, New York	Silty SAND (TP-2)	SM	28	2	2.68	109.9(2)		Non-plastic	
PAFB	Portsmouth AFB, Portsmouth New Hampshire	Silty SAND	SM	29	8	2.73	111.6(3)	12.5	"	
WWC	Fairchild AFB, Spokane, Washington	Silty Gravelly SAND	SM-SC	20	10	2.79	144.4(2)		24.6	6.3
PBJ	Project Blue Jay, TP-244	Gravelly Clayey SAND	SC	35	23	2.73	133.1(4)	9.4	24.7	8.1
PBJ	Project Blue Jay, TP-276	Gravelly Clayey SAND	SC	44	35	2.75	139.6(4)	7.0	18.6	9.3
FA	Fargo Municipal Airport, Fargo, North Dakota	Clayey SAND	SC	16	9	2.70	127.0(4)	8.0	30.7	10.5
VIS	Valparaiso, Indiana	SILT	ML	99	53	2.72	115.8(3)	13.5	23.7	4.0
YS	Whitehorse, Yukon Province, Canada (Referred to as Yukon Silt)	Clayey SILT	CL-ML	98	60	2.73	124.5(3)	11.5	25.3	5.8
NH	Goff's Falls, New Hampshire (Referred to as New Hampshire Silt)	Clayey SILT (A) Clayey SILT (B) SILT (C)	CL-ML CL-ML ML	86 99 96	61 73 58	2.76 2.74 2.70	107.3(3) 110.1(3) 107.0(3)	17.8 14.7 17.0	24.1 23.7 26.6	5.9 6.0 0.1
LF	Ladd Field, Fairbanks, Alaska	SILT	ML-OL	90	37	2.74	101.6(3)	18.1	31.6	0.8
LFT	Field Research Area, Fairbanks, Alaska (Referred to as Fairbanks Silt)	SILT	ML-OL	94-99	40-48	2.68	107.4(3) 97.1-101.5(5)	17.1 22.9-26.9(6)	25.8-32.6	3.8-6.2
PAFB	Portsmouth AFB, Portsmouth, New Hampshire	Stratified CLAY	CL	86-96	46-49	2.73	96.1-108.6(5)	19.8-27.7(6)	30.0	11.7
FB	Fort Belvoir, Virginia	Sandy CLAY	CL	61	49	2.73	115.3(3)	15.1	43.8	20.3
SC	Searsport, Maine	CLAY	CL	100	81	2.77	95.3-99.2(5)	25.6-30.2(6)	36.5	17.9
WASHO	WASHO Road Test Section, Malad, Idaho	CLAY	CL-OL	96	65	2.58	99.6(3)	21.0	37.0	13.0
BC	North Cambridge, Massachusetts (Referred to as Boston Blue Clay)	CLAY	CH	100	94	2.78	85.1-86.5(5)	34.0-36.1(6)	52.7	26.4
FA(C)	Fargo Municipal Airport, Fargo, No. Dakota	CLAY	CH-OH	98	85	2.76	85.5-88.5(5)	28.5-31.8(6)	67.8	45.8

NOTES:

(1) On material passing the U.S.Standard #40 sieve.
(2) Providence Vibrated Density Test.
(3) Modified AASHO Density Test.
(4) Corps of Engineers Airfield Density Test.
(5) Undisturbed dry density.
(6) Natural water content.
* On (-3/4) inch material.

TABLE 2

CLOSED SYSTEM TESTS

SAMPLE NUMBER	NAME AND SOURCE OF SOIL	CORPS OF ENGINEERS UNIFIED SOIL CLASSIFICATION		GRAIN SIZE PERCENTAGE FINER THAN					ATTERBERG LIMITS (1)				DRY UNIT WEIGHT	WATER CONTENT DETERMINATIONS IN PER CENT						PER CENT HEAVE
														TOTAL SAMPLE BEFORE FREEZING		AFTER FREEZING				
																FROZEN ZONE			UNFROZEN ZONE OR BOTTOM FROZEN INCH	
																	SOIL BETWEEN ICE LENSES			
		DESCRIPTION	LETTER SYMBOL	#4 SIEVE	#40 SIEVE	#200 SIEVE	0.02 mm.	0.005 mm.	Lw	Pw	Iw	Sw	pcf.	WATER CONTENT	G (2)	TOP INCH	PER CENT	LOCATION (3)		
*TD-15	Truax Drumlin Soil Truax AFB, Wisconsin	-3/4" Gravelly, Silty SAND (Remolded)	SM	93	78	35	21	11	14	12	2	10	130	7.8	70	8.3			5.6	0.0
*TD-16													130	7.7	69	9.3			6.3	0.0
*TD-17													130	9.7	89	10.0			9.0	1.0
*TD-18													130	10.9	99	13.7			6.5	5.1
PAFB- 9	Portsmouth AFB, Till Portsmouth, New Hampshire	-3/4" Silty Gravelly SAND (Remolded)	SM	87	58	29	18	8	Non-plastic			16	126	8.9	71	15.5			5.2	1.3
PAFB-10													128	9.3	80	15.1			4.8	1.7
PAFB-12													125	11.4	88	22.4			4.7	6.8
PAFB-11													128	11.0	92	22.0			4.6	7.1
*NH- 5	New Hampshire Silt Goff's Falls, New Hampshire	SILT-C (Remolded)	ML	100	99	96	58	10	27	27	0	-	99	17.5	68	24.9			6.1	1.3
*NH- 6													100	20.0	79	27.1			6.1	4.8
*NH--7													100	22.5	88	28.0			4.8	5.5
*NH- 8													100	25.0	100	36.0			5.5	9.5
NH-48		SILT-A (Remolded)	ML	100	100	85	61	16	24	18	6	22	102	22.8	91	38.2	33.7	0-1	2.2	7.8
NH-49													103	23.4	96	43.5	34.3	0-3/4	2.7	9.1
LFT- 1	Fairbanks Silt Fairbanks, Alaska	SILT (Undisturbed)	ML	100	100	94	40	12	33	27	6	22	97	26.8	100	45.0			6.8	15.1
EBT-40	East Boston Till-C Revere, Massachusetts	-3/4" Gravelly Sandy CLAY (Remolded)	CL	82	65	46	32	22	23	15	8	12	128	11.9	96	20.2	15.9 13.2 12.7	0-1 1-2 2-3	7.6	8.6
EBT-41													128	12.2	98	20.6	22.1 19.6 15.1 15.4	0-1 1-2 2-3 3-4	10.0	7.3
*EBT- 5	East Boston Till-A Revere, Massachusetts	-3/4" Gravelly Sandy CLAY (Remolded)	CL	84	72	56	43	26	23	16	7	17	125	9.5	70	10.6			6.8	0.3
*EBT- 6													126	10.9	81	13.7			7.1	1.8
*EBT- 7													125	12.2	90	13.7			8.3	2.3
*EBT- 8													127	12.9	100	20.9			7.1	4.7
*DFC- 1	Dow Field Clay, Dow AFB, Maine	CLAY (Remolded)	CL	99	98	93	72	40	34	17	17	17	115	18.0	100	23.1			14.9	9.7
*DFC- 2													111	13.3	68	18.4			11.5	2.0
*DFC- 3													113	15.2	82	21.5			12.9	1.5
*DFC- 4													113	17.1	92	20.9			13.6	2.7
*DFC- 5													119	16.3	100	23.9			13.9	7.5
SC- 4	Searsport Clay Searsport, Maine	CLAY (Undisturbed)	CL	100	100	99	80	12	36	18	18	-	95	28.0	95	33.8			18.1	5.8
SC- 5													97	27.0	95	28.8			15.8	7.3
SC- 3													97	27.3	96	34.6			17.5	4.5
SC- 8		CLAY (Remolded)	CL	100	100	99	80	12	36	18	18	18	97	27.0	95	35.6			17.5	9.7
BC-19	Boston Blue Clay North Cambridge, Massachusetts	CLAY (Undisturbed)	CL	100	100	100	94	81	53	27	26	25(4)	86	34.3	94	51.1			21.8	11.1
BC-18													86	34.0	94	46.5			21.5	8.9
BC-22													85	35.8	96	52.3	29.1-33.4		18.9	10.7
BC-21		CLAY (Remolded)	CL	100	100	100	94	81	53	27	26	21	88	35.2	100	48.0	20.1-21.2		19.9	11.0
FA(C)- 2	Fargo Clay Fargo, North Dakota	CLAY (Undisturbed)	CH-OH	100	100	98	85	65	68	22	46	15(4)	83	38.8	100	36.9			31.8	2.0
FA(C)- 4													86	35.0	100	38.9			29.2	2.2
FA(C)- 5		CLAY (Remolded)	CH-OH	100	100	98	85	65	68	22	46	8	85	37.1	100	35.3			41.5	8.6
FA(C)- 6													85	37.1	100	36.1			34.8	9.7

<u>NOTES:</u> * Indicates F.Y. 1951 tests from previous report.
All specimens 6-inches in diameter and 6-inches high except for DFC 2 thru 5 which were only 4-inches high.

(1) Lw - Liquid Limit   Pw-Plastic Limit
Iw - Plasticity Index
Sw - Shrinkage Limit (ASTM method)

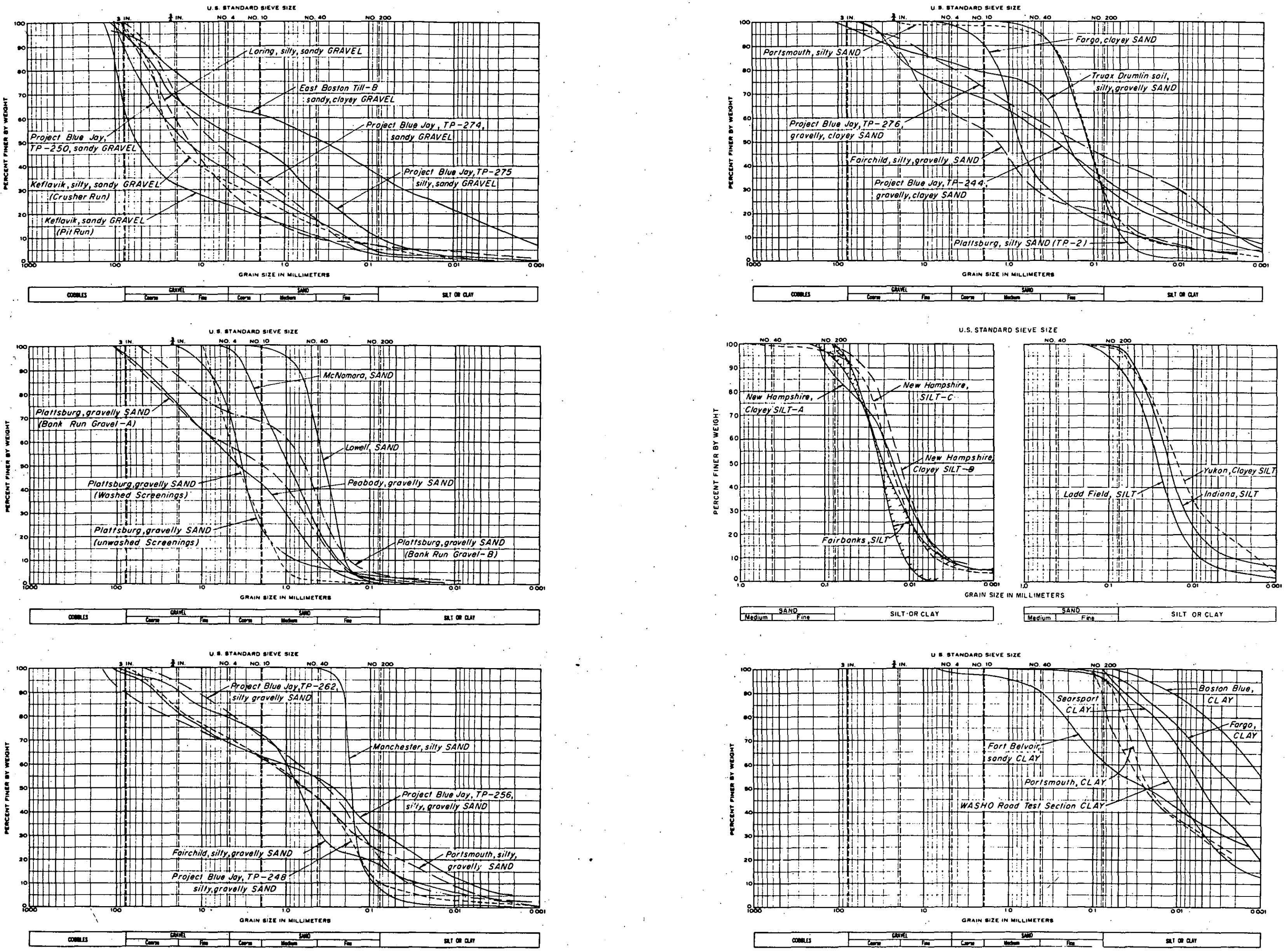
(2) Degree of Saturation in Per Cent.
(3) Measured From Top of Sample in Inches.
(4) Undisturbed Shrinkage Limit.

TABLE 3

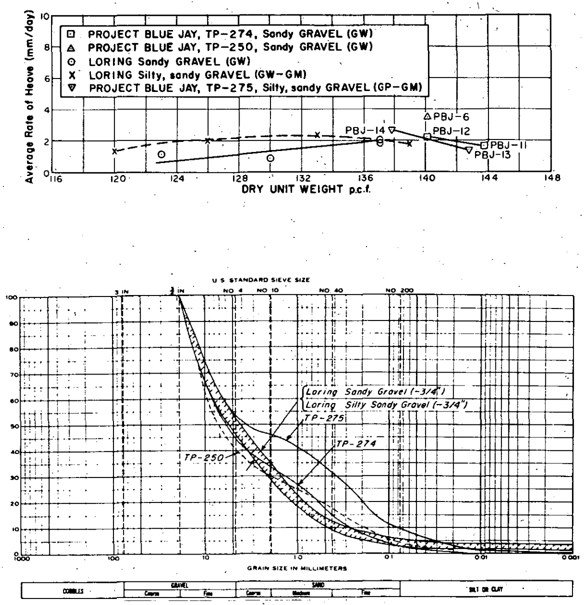
SUMMARY OF EXPLORATORY TESTS FOR DETERMINING FREEZING POINT OF SOIL MOISTURE

MATERIAL	DRY UNIT WEIGHT pcf	WATER CONTENT %	DEGREE OF SATURATION %	AVERAGE CABINET TEMPERATURE °F.	INITIAL CABINET TEMPERATURE °F.	INITIAL CRYSTALLIZATION TEMPERATURE °F.	INDICATED INITIAL FREEZING TEMPERATURE °F.	DURATION OF INITIAL FREEZING TEMPERATURE min
Lowell Sand	99.2	6.0	23.4	3.3	40.6	27.0	32.0	5
		10.6	41.3	3.6	38.2	26.9	32.0	12
		14.7	57.4	1.2	36.6	26.9	32.0	20
		19.5	76.0	1.0	40.1	26.6	32.0	28
Manchester Fine Sand	98.4	6.4	24.3	4.6	39.8	25.7	32.0	8
		10.6	40.3	4.3	45.8	25.2	32.0	18
		15.6	59.4	4.3	39.3	25.6	32.0	30
		19.6	74.6	4.2	37.1	25.2	32.0	37
New Hampshire Silt	92.4	5.0	15.9	14.3	43.7	24.8	32.0	5
		10.9	34.6	18.5	38.2	26.4	32.0	27
		18.2	57.8	21.5	41.6	25.4	32.0	31
		20.7	65.8	16.4	36.7	26.2	32.0	43
Boston Blue Clay	76.3	11.0	22.6	7.4	44.8	26.0	27.4	**Momentary**
		17.0	34.9	3.6	42.6	27.6	30.2	"
		21.5	44.2	12.0	35.6	27.2	31.3	"

PLATE I

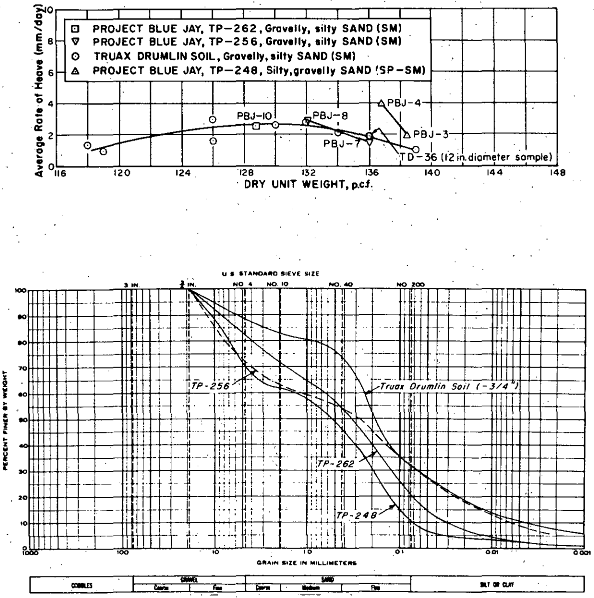


GRADATION CURVES OF NATURAL SOILS USED IN STUDIES



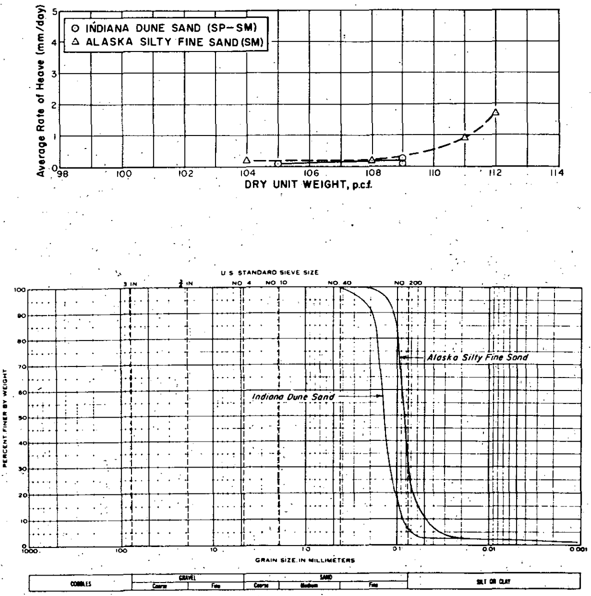
SANDY GRAVEL (GW) AND SILTY SANDY GRAVEL (GW-GM, GP-GM)

FIGURE 1



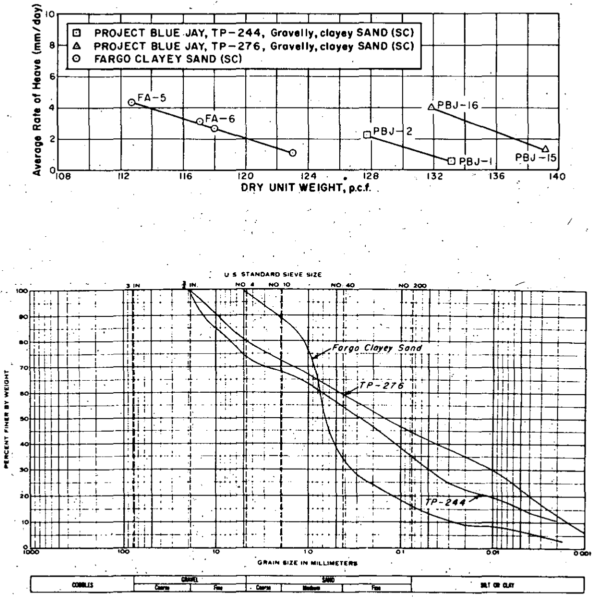
GRAVELLY SILTY SAND (SM) AND SILTY GRAVELLY SAND (SP-SM)

FIGURE 2



SAND (SP-SM) AND SILTY SAND (SM)

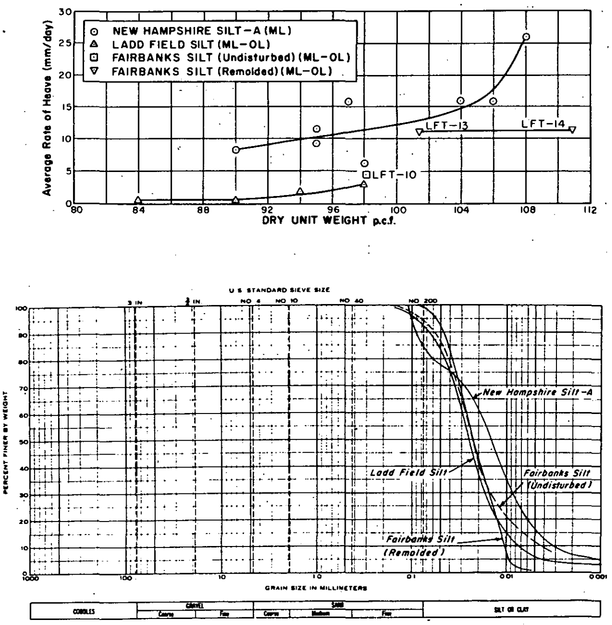
FIGURE 3



GRAVELLY CLAYEY SAND (SC) AND CLAYEY SAND (SC)

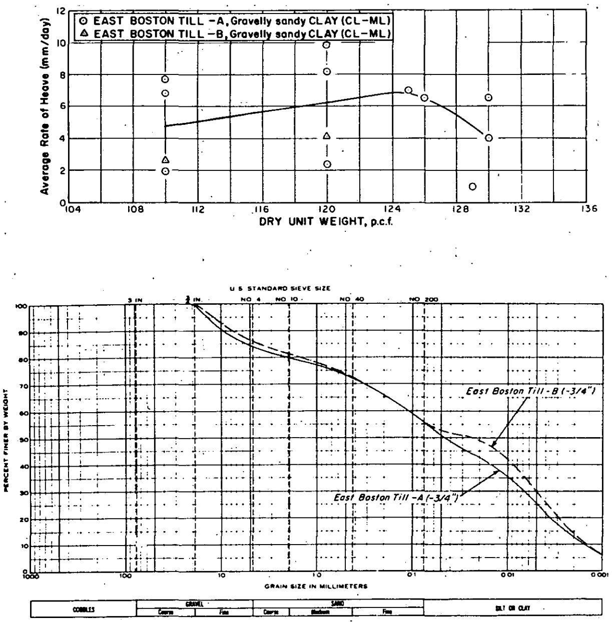
FIGURE 4

EFFECT OF VARIATIONS IN DRY UNIT WEIGHT



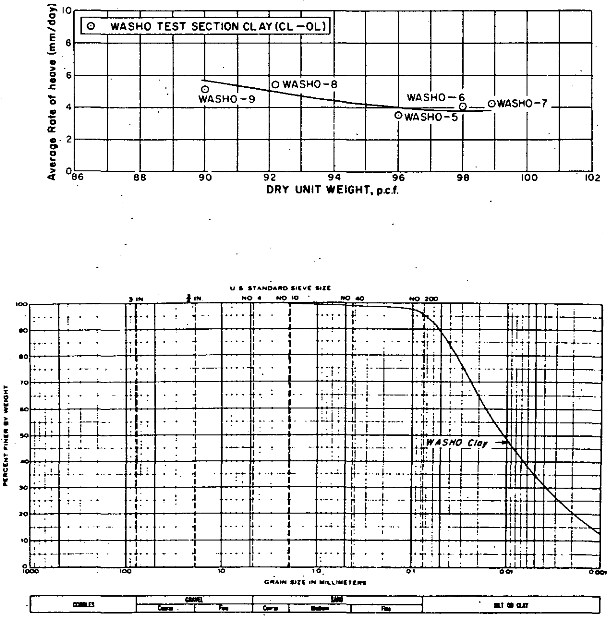
SILT (ML, ML-OL)

FIGURE 5



GRAVELLY SANDY CLAY (CL-ML)

FIGURE 6



CLAY (CL-OL)

FIGURE 7

MATERIALS	COMPACTION CHARACTERISTICS	
	MAXIMUM DRY DENSITY pcf	OPTIMUM WATER CONTENT %
Project Blue Jay, TP-274	148.2 (1)	
Project Blue Jay, TP-250	148.2 (1)	
Loring Sandy Gravel	139.1 (1)	
Project Blue Jay, TP-275	143.4 (1)	
Indiana Dune Sand	107.1 (1)	
Project Blue Jay, TP 248	142.6 (1)	
Project Blue Jay, TP-262	136.0 (2)	7.0
Project Blue Jay, TP-256	137.3 (2)	7.5
Truax Drumlin Soil	139.0 (2)	5.3
Alaska Silty Fine Sand	105.7 (1)	
Project Blue Jay, TP-244	133.1 (2)	9.4
Fargo Clayey Sand	127.0 (2)	8.0
New Hampshire Silt-A	107.3 (3)	17.8
Ladd Field Silt	101.6 (3)	18.1
Fairbanks Silt	107.4 (3) 97.1-101.5 (4)	17.1 22.9-26.9 (5)
East Boston Till -A	131.6 (2)	9.0
Project Blue Jay, TP-276	139.6 (2)	7.0
WASHO Road Test	99.6 (3)	21.0
Section Clay	85.5-88.5 (4)	28.5-31.8 (5)

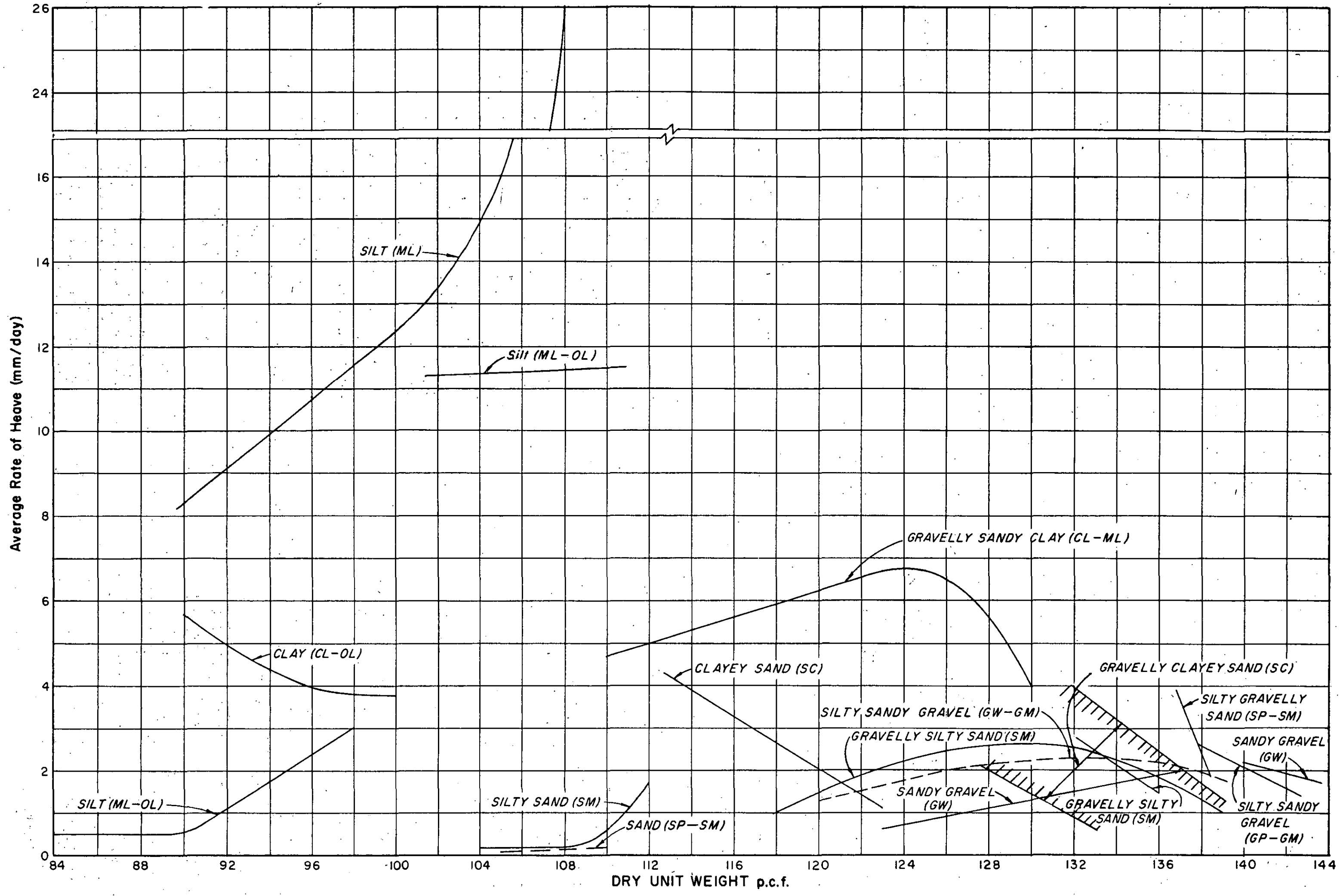
(1) Providence Vibrated Density
(2) Corps of Engineers Airfield Density
(3) Modified AASHO Method
(4) Undisturbed Dry Density
(5) Natural Water Content

NOTE:

The relationship between the average rate of heave and dry unit weight for the various soil types is reproduced from Plate 4 of the Second Interim Report of Cold Room Studies, Fiscal Year 1951, Volume I. The numbered points are tests conducted in Fiscal Years 1952 and 1953, all other points are tests conducted during and prior to Fiscal Year 1951.

EFFECT OF VARIATIONS IN DRY UNIT WEIGHT

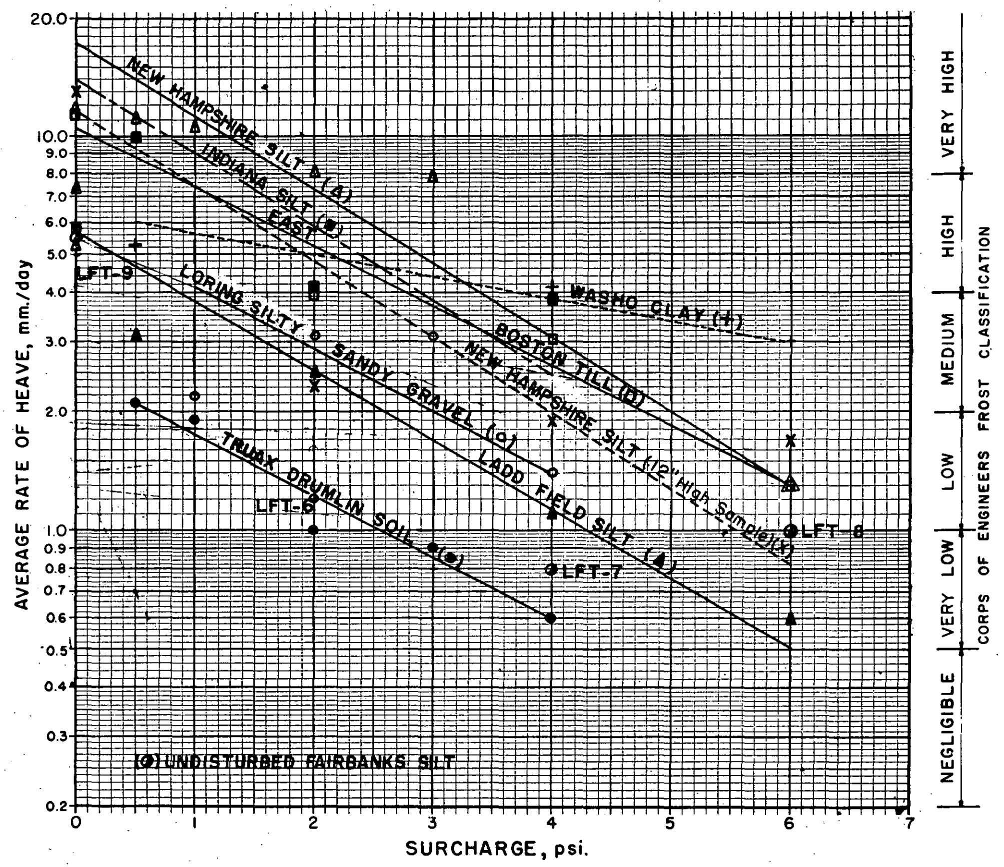
PLATE 2 Sheet 3 of 3



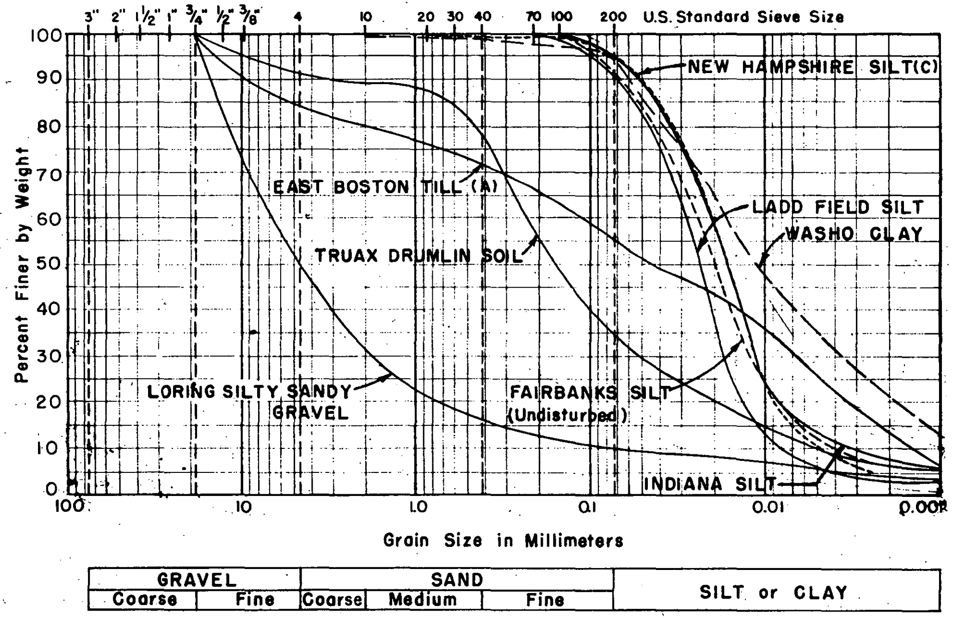
SUMMARY PLOT OF AVERAGE RATE OF HEAVE vs DRY UNIT WEIGHT

FIGURE 8

EFFECT OF VARIATIONS IN DRY UNIT WEIGHT



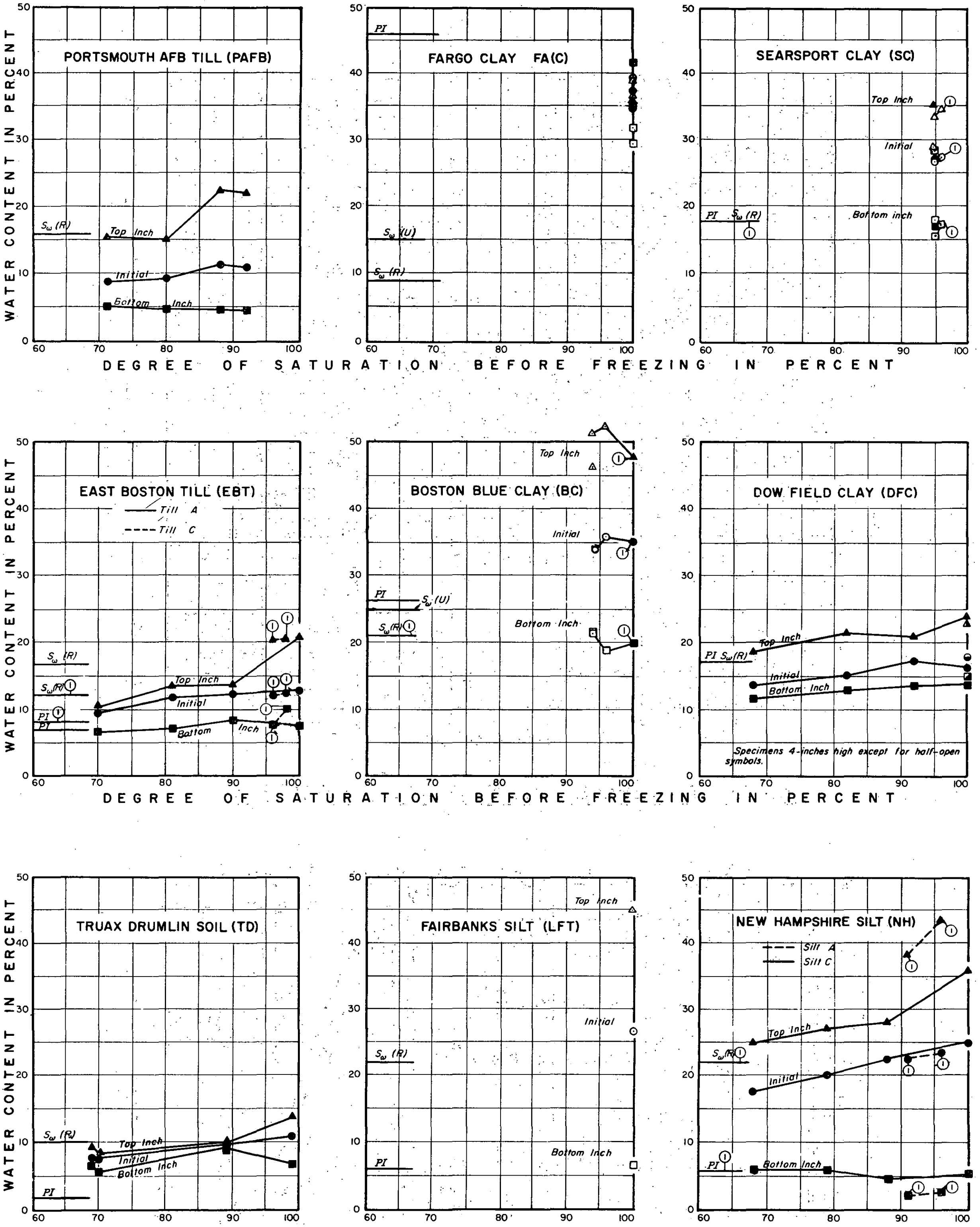
PLOTS OF AVERAGE RATE OF HEAVE vs SURCHARGE



GRADATION CURVES

EFFECT OF SURCHARGE

PLATE 3



LEGEND:

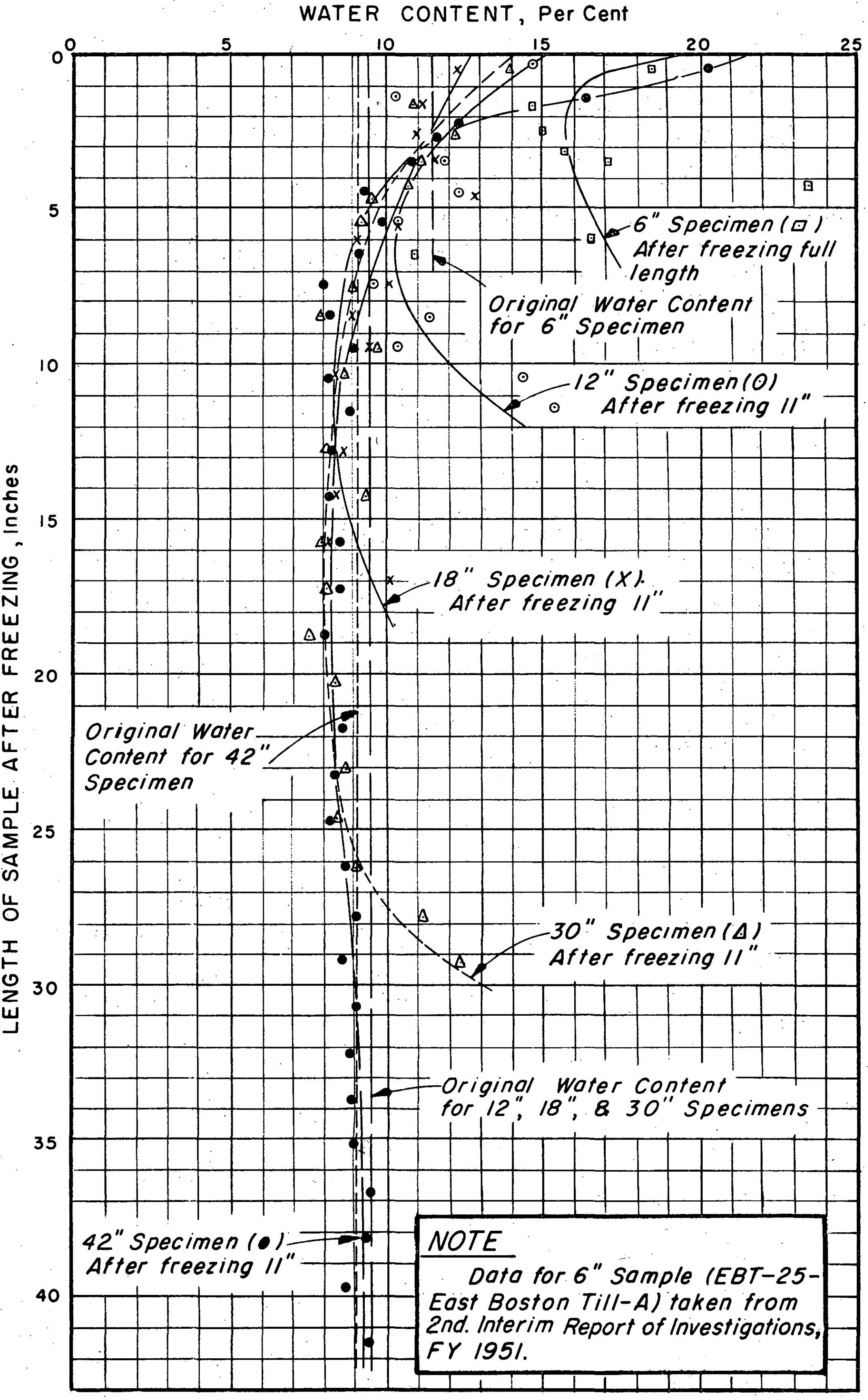
▲△	Water Content of Top inch after freezing.
●⊙	Original Water Content of test specimen before freezing
■□	Water Content of unfrozen zone at bottom (or bottom frozen inch).
PI	Plasticity Index
S_ω *(R)*	Shrinkage limit (remolded)
S_ω *(U)*	Shrinkage limit (undisturbed)

NOTE:

Open symbols denote undisturbed test specimens.
Closed symbols denote remolded test specimens.
All specimens are 6-inches in diameter and 6-inches high, except as noted.

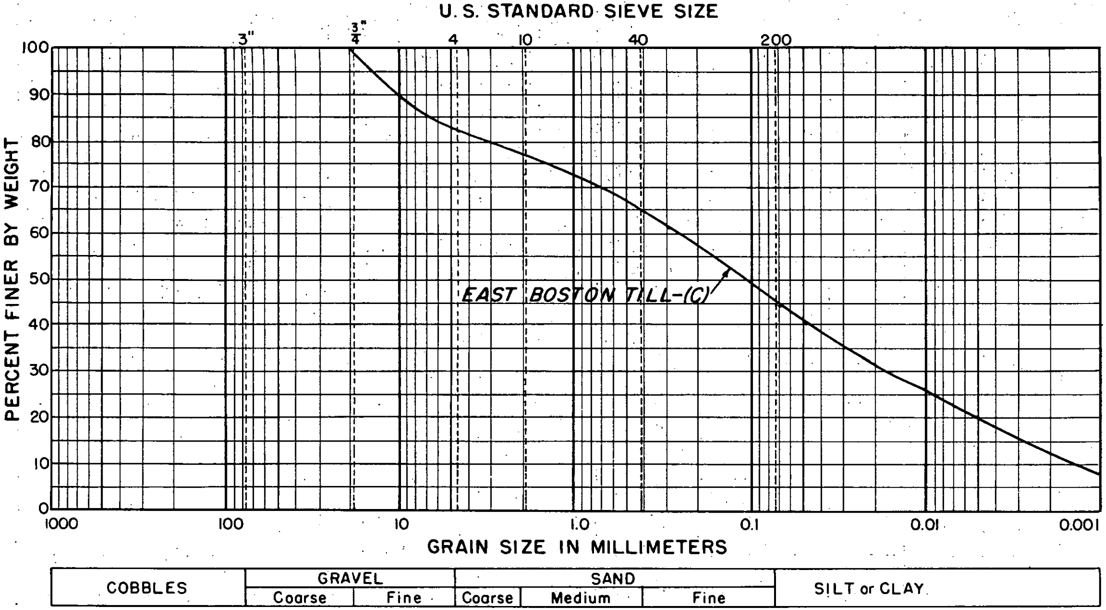
SUMMARY OF CLOSED SYSTEM FREEZING TESTS

PLATE 4

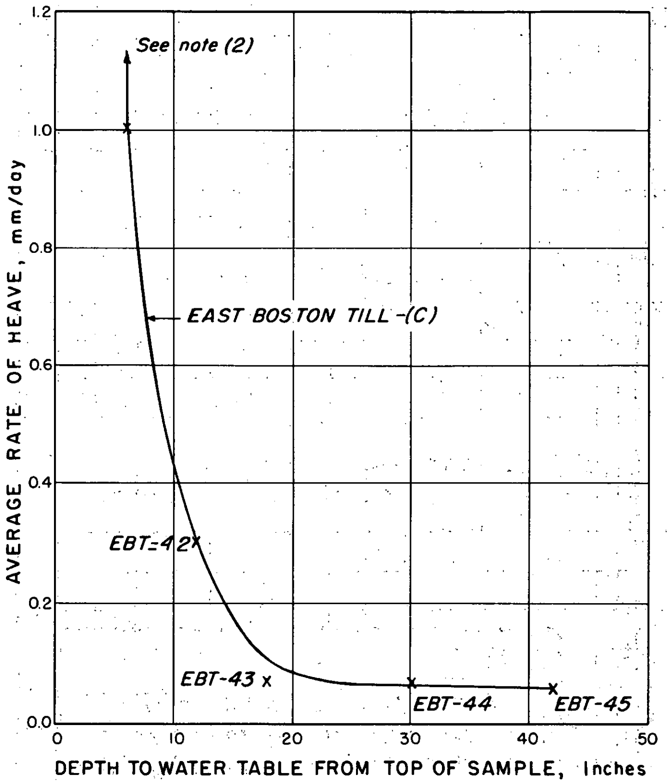


COMPOSITE PLOT OF MOISTURE DISTRIBUTION IN EAST BOSTON TILL SPECIMENS OF VARIOUS LENGTHS

PLATE 5



GRADATION CURVE



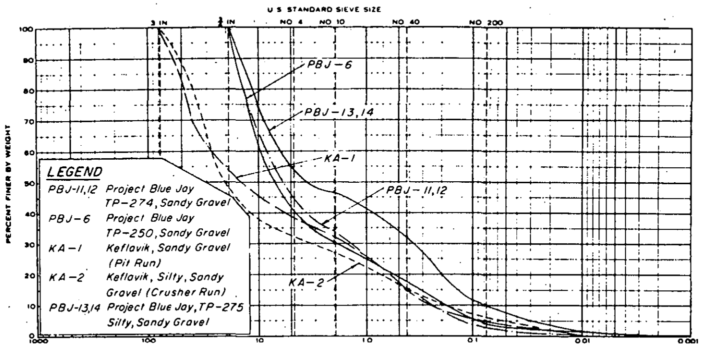
NOTES:

(1) The 32°F temperature was allowed to penetrate 11-inches into the East Boston Till samples.

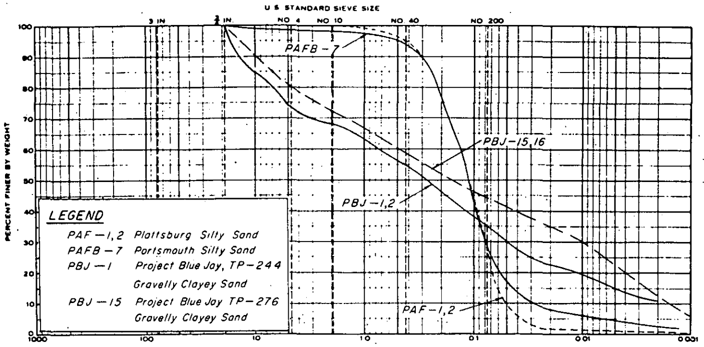
(2) Average rate of heave varies from 1.0 to 7.3 mm/day for similar East Boston Till with depth to water table 6-inches from top of sample. Test data from 2nd Interim Report of F. Y. 1951. 32°F temperature allowed to penetrate 6-inches into these samples.

EFFECT OF PROXIMITY OF WATER TABLE

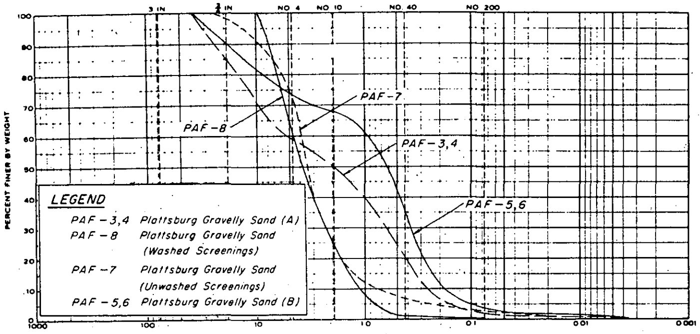
PLATE 6



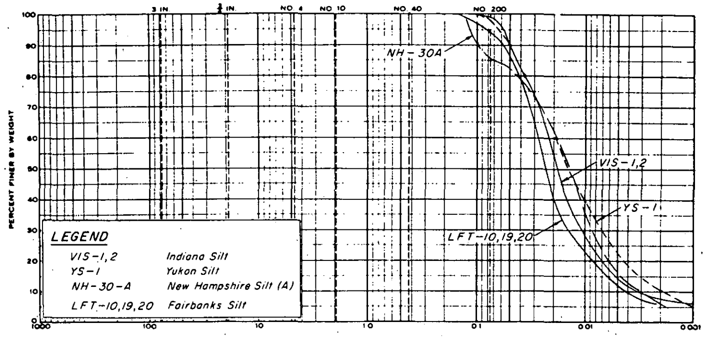
GRADATION CURVES FOR SANDY GRAVEL (GW,GP) AND SILTY SANDY GRAVEL (GW-GM) (GP-GM)



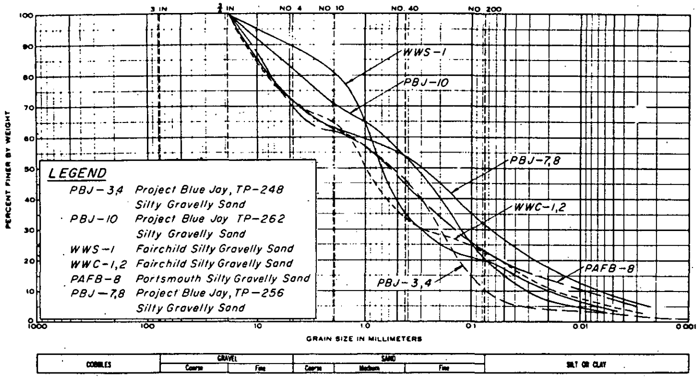
GRADATION CURVES FOR SILTY SAND (SM) AND GRAVELLY CLAYEY SAND (SC)



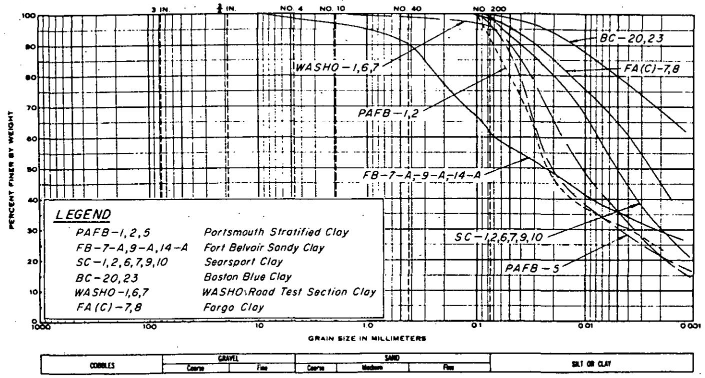
GRADATION CURVES FOR GRAVELLY SAND (SW,SP)



GRADATION CURVES FOR SILT (ML,ML-OL) AND CLAYEY SILT (ML-CL)



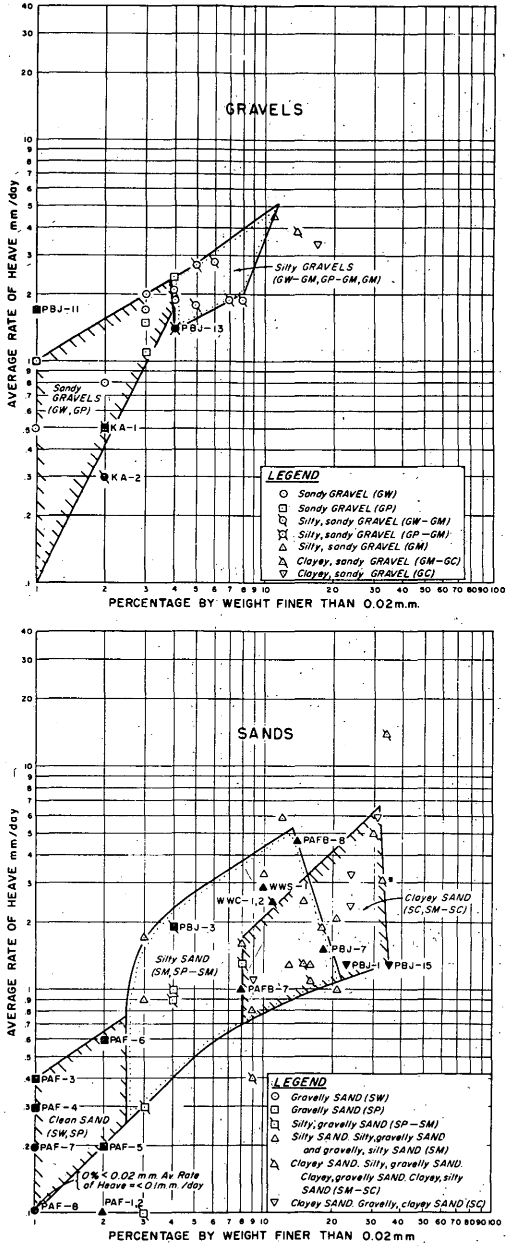
GRADATION CURVES FOR SILTY, GRAVELLY SAND (SM, SP-SM)



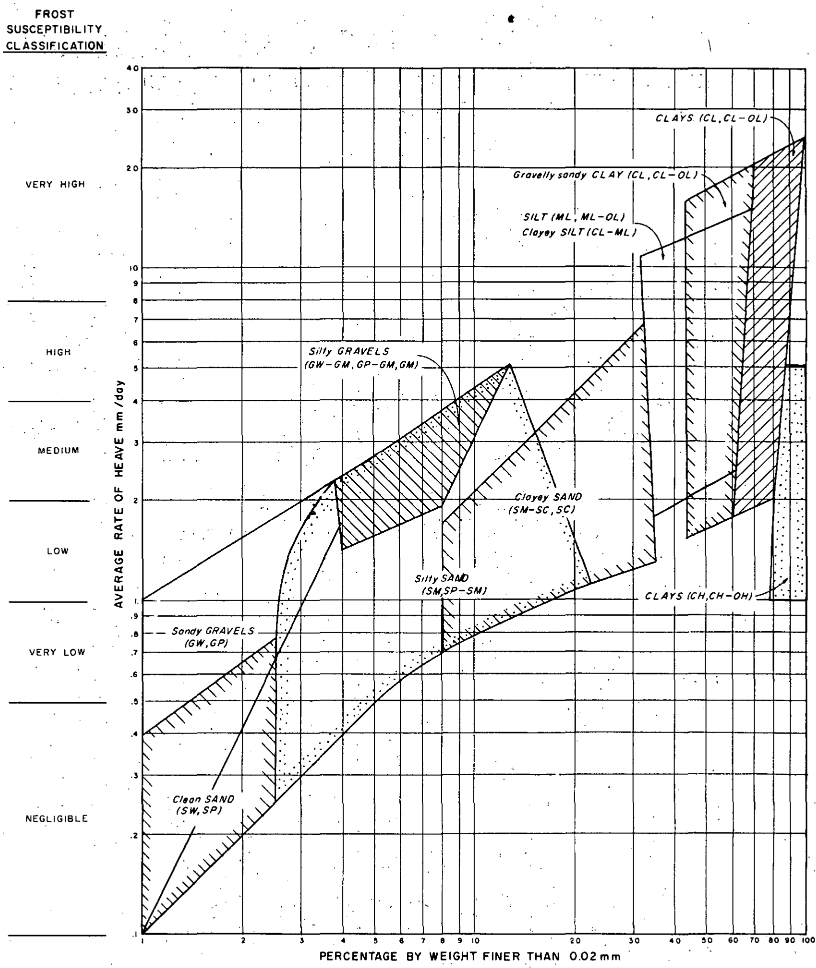
GRADATION CURVES FOR CLAY AND SANDY CLAY (CL,CH,CL-OL,CH-OH)

GRADATIONS OF NATURAL SOILS USED IN FROST SUSCEPTIBILITY TESTS

Sheet 1 of 3 PLATE 7



PLOTS OF AVERAGE RATES OF HEAVE VS PERCENTAGE FINER BY WEIGHT THAN 0.02 mm.



SUMMARY OF ENVELOPES OF AVERAGE RATE OF HEAVE VS PERCENTAGE FINER BY WEIGHT THAN 0.02 mm SIZE FOR VARIOUS SOIL GROUPS

NOTES:

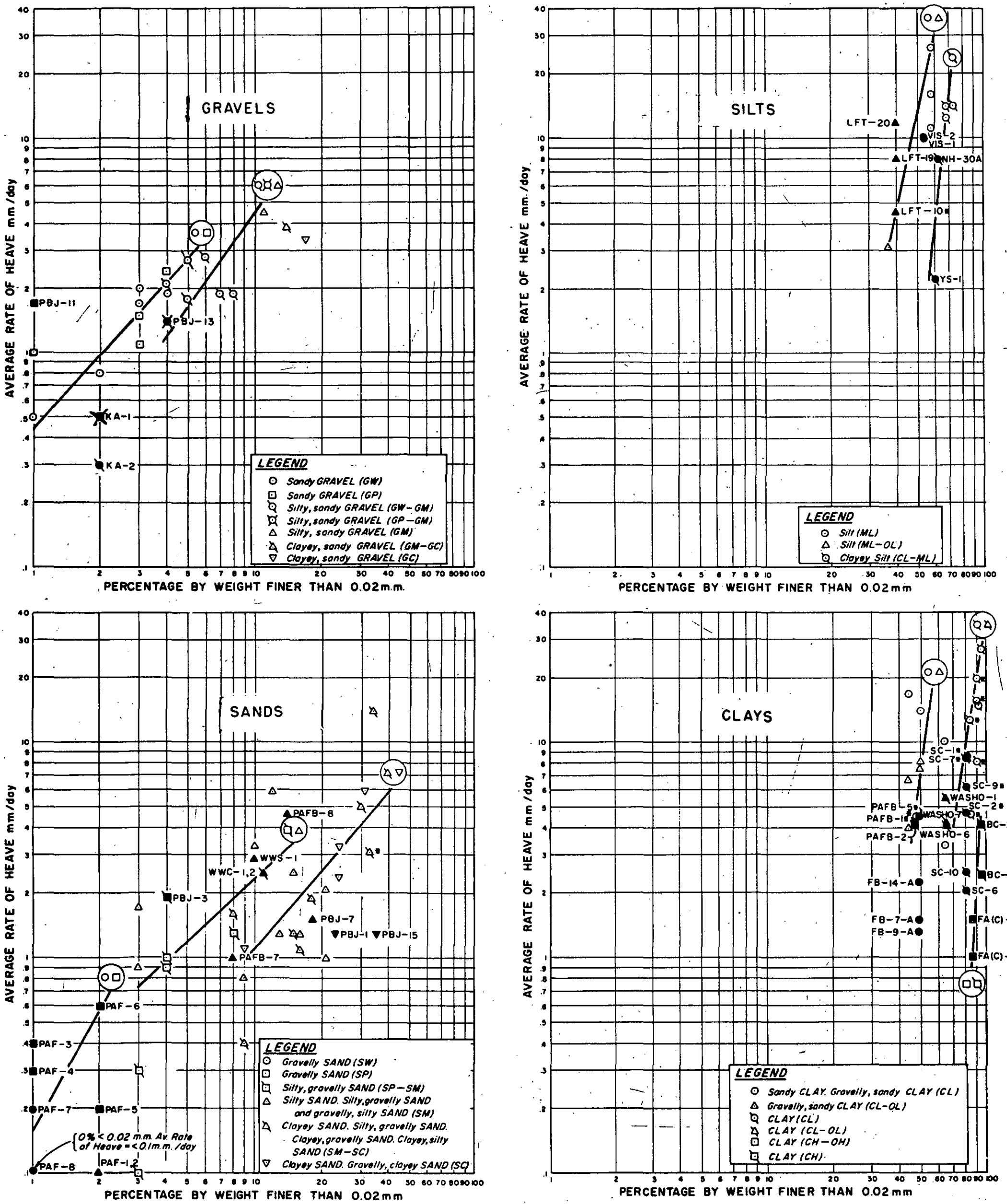
Tests conducted during and prior to Fiscal Year 1951 are shown by open symbols. Tests conducted during Fiscal Years 1952 and 1953 are shown by solid symbols.

Plotted values represent test results on soils compacted to 90% or greater of maximum density.

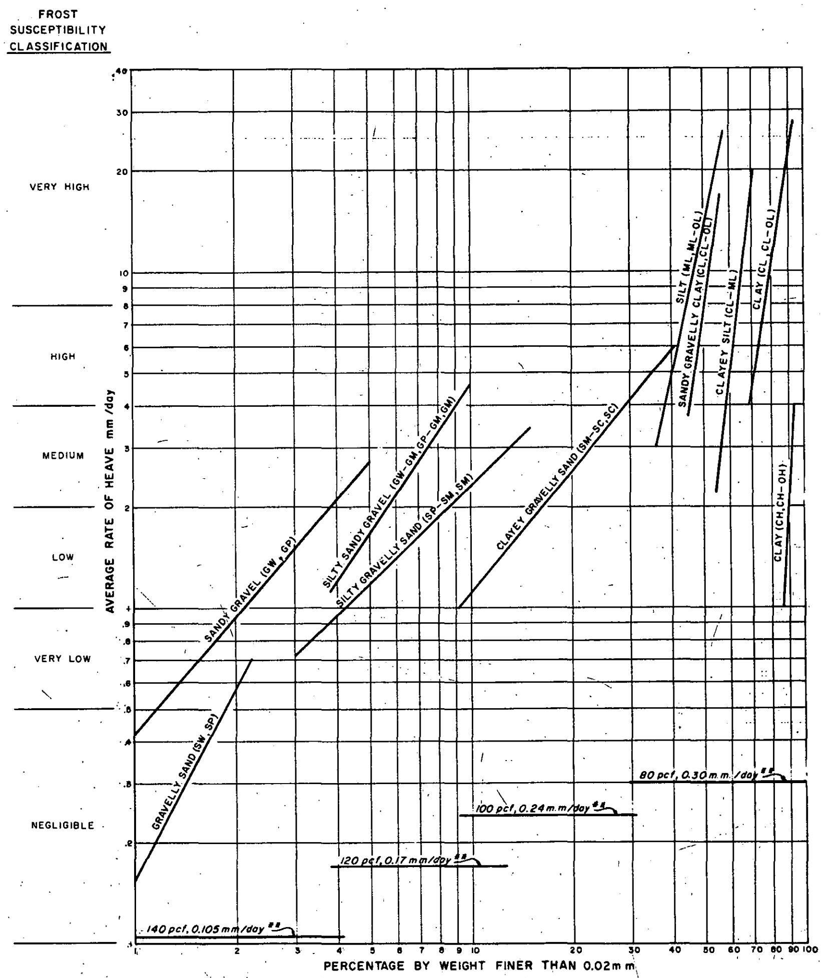
** Tests performed on undisturbed specimens*

*** Computed heave rate due solely to expansion in volume, if all original water in 100% saturated specimen were to freeze, with rate of frost penetration 0.25 inch per day.*

SUMMARY OF AVERAGE RATE OF HEAVE vs PERCENT FINER THAN 0.02 mm SIZE IN NATURAL SOIL GRADATIONS



PLOTS OF AVERAGE RATES OF HEAVE VS PERCENTAGE FINER BY WEIGHT THAN 0.02mm.



SUMMARY PLOT OF AVERAGE RATE OF HEAVE
VS
PERCENTAGE FINER BY WEIGHT THAN 0.02mm

NOTES:

Tests conducted during and prior to Fiscal Year 1951 are shown by open symbols. Tests conducted during Fiscal Years 1952 and 1953 are shown by solid symbols.

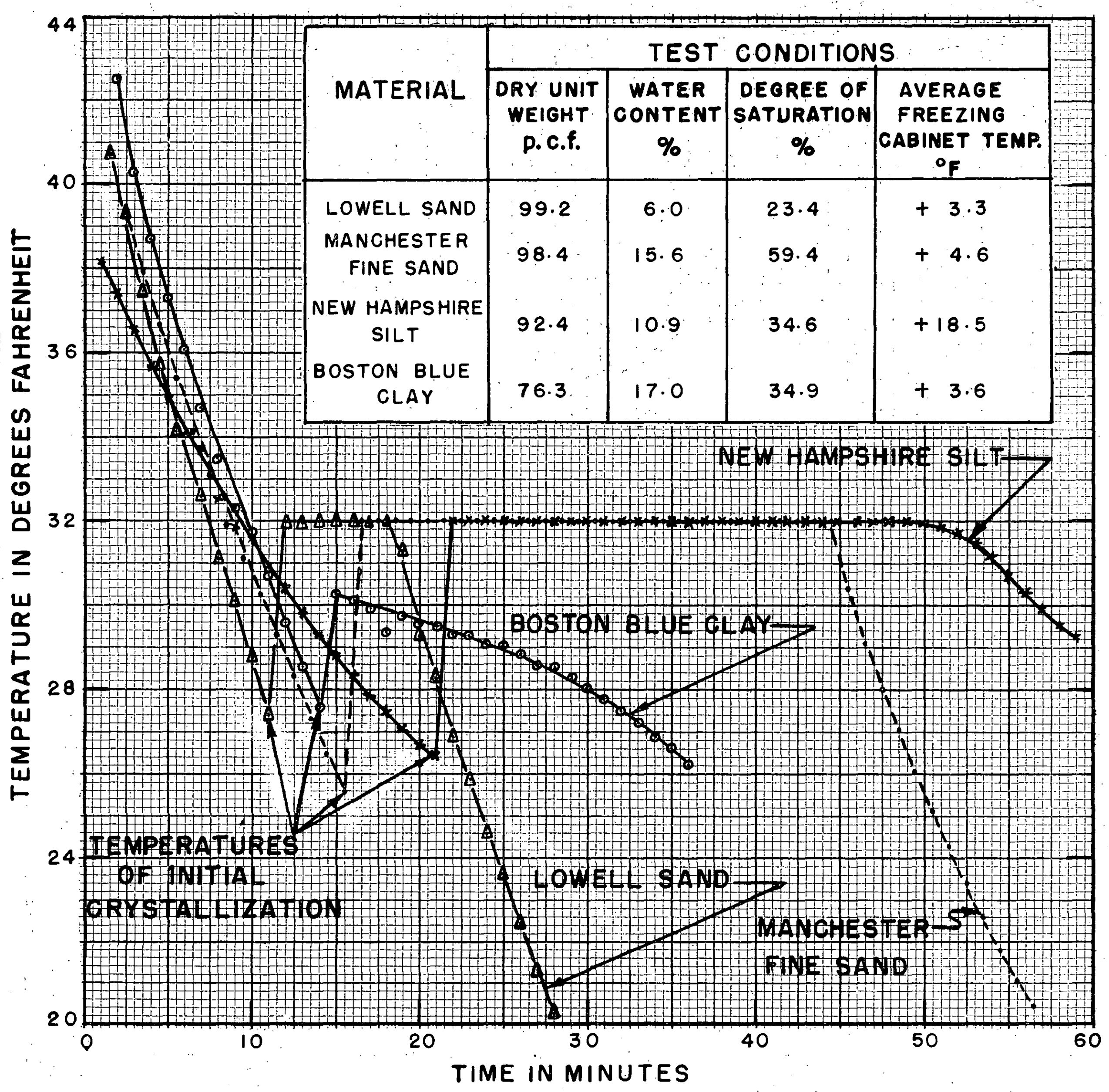
Plotted values represent test results on soils compacted to 90% or greater of maximum density.

* *Tests performed on undisturbed specimens*

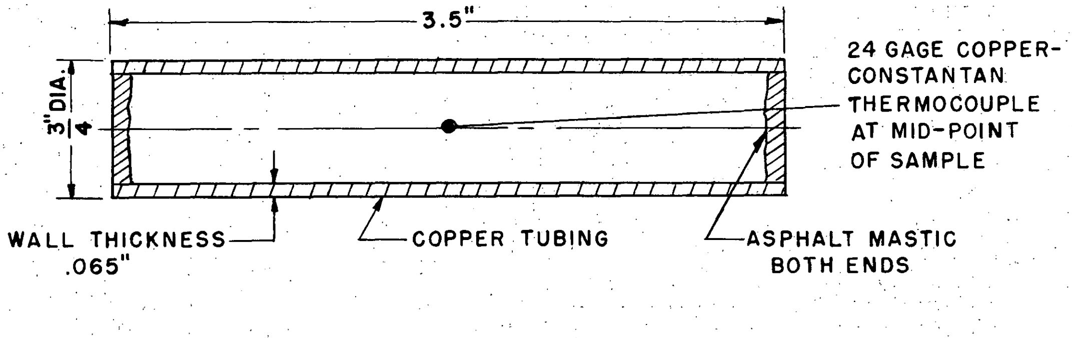
** *Computed heave rate due solely to expansion in volume, if all original water in 100% saturated specimen were to freeze, with rate of frost penetration 0.25 inch per day.*

SUMMARY OF AVERAGE RATE OF HEAVE vs PERCENT FINER THAN 0.02mm SIZE IN NATURAL SOIL GRADATIONS

Sheet 3 of 3 PLATE 7

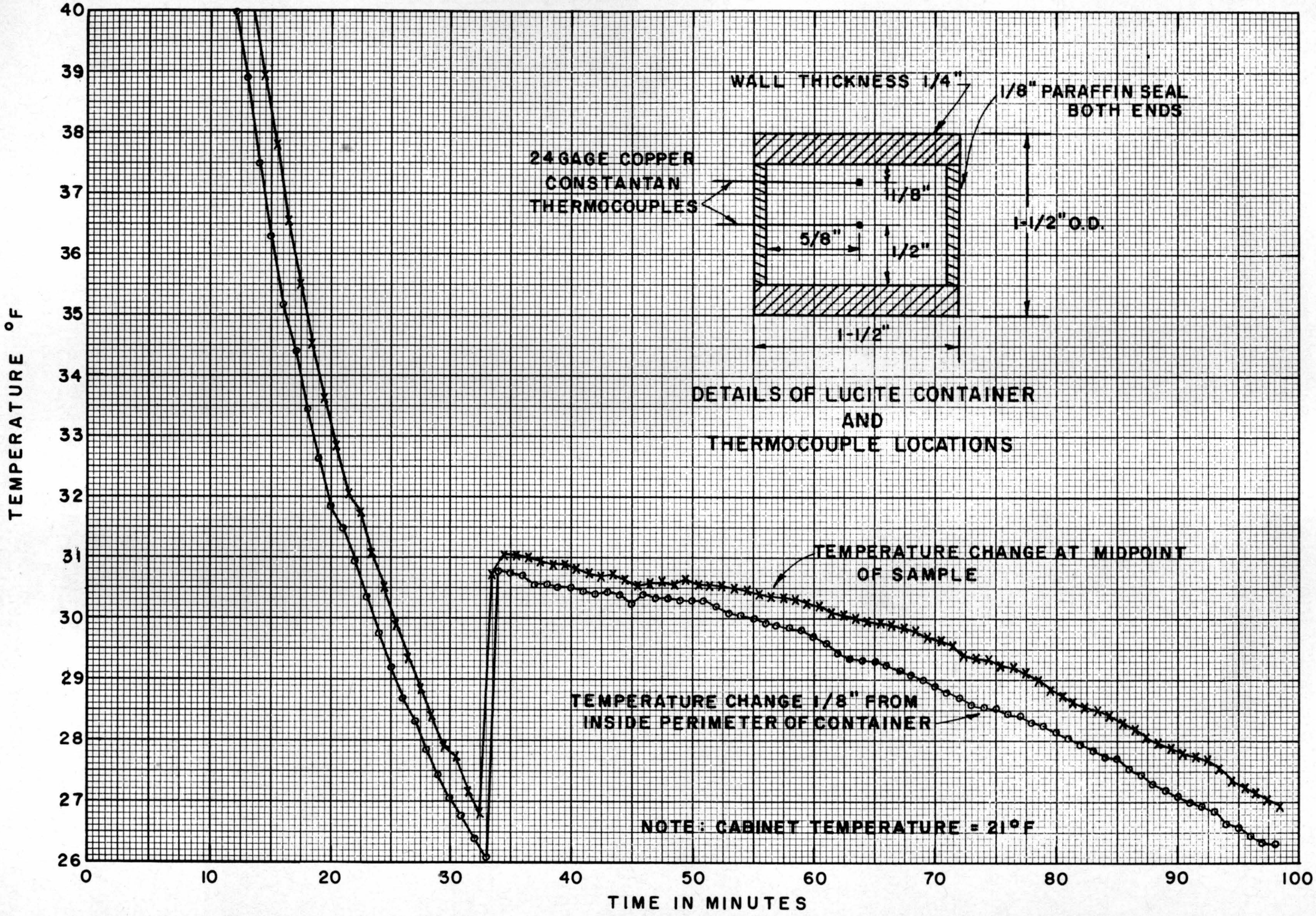


MATERIAL	TEST CONDITIONS			
	DRY UNIT WEIGHT p.c.f.	WATER CONTENT %	DEGREE OF SATURATION %	AVERAGE FREEZING CABINET TEMP. °F
LOWELL SAND	99.2	6.0	23.4	+ 3.3
MANCHESTER FINE SAND	98.4	15.6	59.4	+ 4.6
NEW HAMPSHIRE SILT	92.4	10.9	34.6	+18.5
BOSTON BLUE CLAY	76.3	17.0	34.9	+ 3.6



TYPICAL PLOTS OF TEMPERATURE CHANGE DURING FREEZING CYCLE

PLATE 8



PLOTS OF TEMPERATURE CHANGE IN REMOLDED BOSTON BLUE CLAY DURING FREEZING CYCLE

PLATE 9

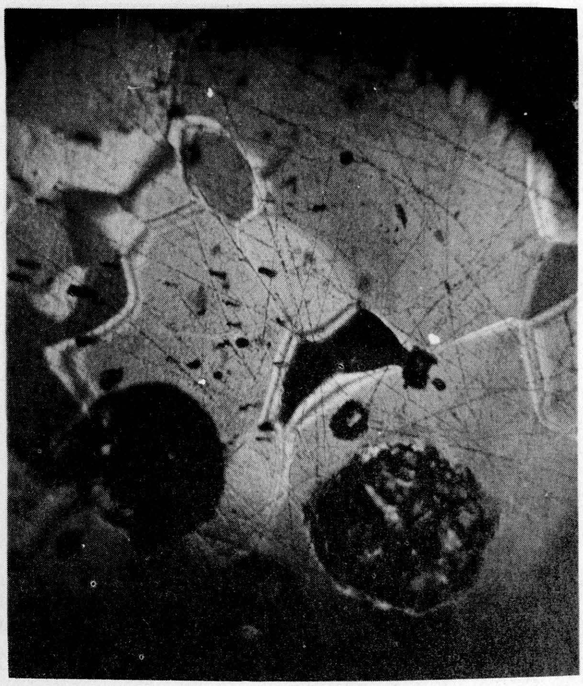


FIGURE 1
11X

FIGURE 2
11X

FIGURE 3
6.5X

FIGURE 4
13X

PHOTOMICROGRAPHS OF THIN SECTIONS FROM ICE LENSES OCCURRING IN NEW HAMPSHIRE SILT

Figures 1-3 are transverse sections. Figure 4 is a longitudinal section. The black spot in Figure 1 is where melting took place. The black areas in Figure 4 are silt lenses and the narrow lines are air bubbles.

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APPENDIX A

PART I - DESCRIPTION OF COLD ROOM AND EQUIPMENT

1-01. Cold Room. The cold room used in these tests is a walk-in type refrigerator with inside dimensions approximately 9 ft. wide by 20 ft. long and 6.5 ft. high, insulated on all sides with 6 in. of mineral wool. It is constructed of 22 separate panels which are bolted together to permit ease in assembly and dismantling and to provide flexibility for enlargement. The panels are faced on both sides with painted 20-gage galvanized sheet metal.

A 1-1/2-hp water-cooled condensing unit, located outside the cold room, furnishes Freon gas refrigerant to two unit coolers mounted inside the cold room. Room temperature is controlled with a Minneapolis-Honeywell bimetallic mercury bulb thermostat within limits of ±2°F. The cold room is designed to operate between +10°F. and +40°F.

1-02. Test Cabinets. Nine individual test cabinets with inside dimensions of 19 in. by 19 in., which can accommodate soil specimens up to 12 in. in height, are located in the cold room. The cabinets are equipped with hinged covers on top, facilitating access to cabinets for observation and for necessary measurements with insignificant disturbance of cabinet temperatures. Insulation in the sides and covers consists of 6 in. of compressed cork board. Refrigerant is provided separately to each test cabinet by 1/4-hp air-cooled condensing units. Cooling inside the cabinets, at temperatures ranging from +40°F. to -20°F. is accomplished by passing the refrigerant (Freon) through single-embossed coils inside a 14 in. wide, zinc-coated, copper refrigerating plate fitted to three sides of the cabinet, beginning 13 in. from the bottom and continuing to the top. Temperatures are controlled by a DeKhotinsky bimetallic thermoswitch in each cabinet with an accuracy of +0.5F.

The bottom of each freezing cabinet consists of open grill work to allow the +35-38°F. cold room temperature to be applied to the bottom of the soil specimens during freezing while the tops of the specimens are subjected to any desired cabinet temperature. Facilities for furnishing de-aired water to the freezing specimens at a definite water level are provided by adjustable constant water level devices. Details of these test cabinets are shown on Plate A1.

A tenth test cabinet in the cold room is designed for the special purpose of determining the effect of the relative proximity of water table on ice segregation in frost-susceptible soils. This cabinet has inside dimensions of 17 in. by 17 in. and can accommodate soil specimens 42 in. in length. The cabinet has a removable cover and front face for observations and placement of specimens. Freon refrigerant is supplied to the cabinet by a 1/3-hp air-cooled condensing unit. Other construction and temperature control details are similar to that of the nine individual test cabinets discussed in Paragraph 1-02 above. A photograph of this special cabinet is shown in Figure 1 and a general view of the individual cabinets in Figure 2 of Plate A2.

1-03. Temperature Measuring Equipment. The temperatures in soil specimens are measured by means of copper- constantan thermocouples. The thermal electromotive force produced by the thermocouples is measured by electrical instruments consisting of a standard cell, sensitive galvanometer, and a Leeds and Northrup type K-2 potentiometer. Temperatures are read and recorded to $0.1^{\circ}F$. Two toggle switchboards enable any one of 172 available thermocouples to be placed rapidly in the measuring circuit. This equipment is conveniently placed in an instrument room adjacent to the cold room as shown in Figure 1 of Plate A3.

Two Leeds and Northrup, Speedomax, type "G", model "S", multipoint temperature recording and indicating units, with an operating range of $-20^{\circ}F$. to $+40^{\circ}F$. are available for a continuous temperature record of 32 thermocouples. A Leeds and Northrup 160 point Speedomax Recorder and Multi-Bank Switch Unit is also located in the instrument room for continuous or timed temperature records.

The nine individual test cabinets are each equipped with a glass thermometer which can be read from the outside through the thermopane window. A close check of the temperature is also maintained by means of a thermocouple inserted in a glycerin-filled glass vial, 3/8 in. in diameter and 1-1/2 in. long, suspended near the top of the specimens, in each cabinet. The glycerin damps out the small temperature fluctuations occurring in the test cabinet during the normal operating cycle of the compressor, thus permitting an average temperature to be read and recorded. The value of the average daily cabinet temperature is determined from the average of several readings with the thermocouple in the vial.

PART II - STANDARD TEST PROCEDURES*

2-01. Molding of Specimens. Standard soil specimens for cold room studies are generally prepared in a 5.91 in. inside diameter steel molding cylinder. The soil is compacted to an approximate height of 6 in. and to a predetermined dry unit weight by means of a static load and/or vibration. Undisturbed specimens of cohesive soils are prepared by trimming to a like size.

Two methods are used in molding specimens to the desired dry unit weight. Relatively cohesionless, coarse grained soils, such as sands and sandy gravels, are generally prepared by an adaptation of the Providence Vibrated Density Test method. In this method, a predetermined weight of soil is placed in the steel cylinder and a load of approximately 1000 lbs. is applied by a piston at each end and a heavy spring at the top. The soil within the steel cylinder is compacted by vibrating the cylinder with hammer blows on the sides. Fine-grained soils, such as uniform fine sands, silts and glacial tills are prepared in an open-ended steel cylinder by applying pressure to movable pistons at both ends with a 60,000-lb. Southwark-Emery compression machine using an average pressure of 1500 lbs. and a maximum of 4000 lbs. Some specimens are molded by a combination of the two methods or by either the modified AASHO or Corps of Engineer Airfield Density Test procedure. Specimens are removed from the cylinders by piston pressure at the bottom of the specimen. The inside walls of the cylinder are lubricated with a thin coating of petrolatum followed by paraffin before molding to facilitate ejection of the soil specimen.

Cohesionless soils are molded at a low moisture content, which improves the apparent cohesion and aids specimen handling after molding. The soils are molded to a dry unit weight approximately equal to the Providence Vibrated Density value. Cohesive soils are molded at the optimum moisture content and to the dry unit weight determined by the modified AASHO test procedure or Corps of Engineer Airfield Density Test, depending upon the anticipated field conditions or requirements. Base and subgrade soils obtained from beneath airfield pavements are compacted to approximately natural field dry unit weights.

The trimmed or molded specimens are then placed in a 6 in. inside diameter, heavy, open-ended cardboard container, the interior of which is coated with silicone to reduce friction between the specimens and container walls during heaving. In more recent tests the container walls have been lined with 0.007 in. thick cellulose acetate, coated on both sides with silicone grease.

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*Standard procedures are always followed unless special objectives require deviation; in latter event, deviations are specially described in report.

2-02. Saturation of Specimens. All specimens tested in the open system are saturated prior to freezing. Saturation is carried out in the cold room at a temperature of $38^{\circ}F$. Filter papers, porous discs 3/8 in. thick, and brass caps, which serve as specimen receptacles in the freezing cabinet, are fitted to both ends of the soil specimens in the cardboard containers. Rubber sleeves and bands are used to seal against air and water leakage. Specimens are evacuated and saturated with de-aired water. The degree of saturation for each specimen is computed from weights of specimen and container before and after saturation. Specimens undergoing saturation are shown in Figure 2 of Plate A3.

2-03. Placing of Specimens in Test Cabinets. After saturation, the specimens are placed in the test cabinet with the upper brass receptacle removed and the bottom receptacle kept in place. The de-aired water supply is connected to the bottom of each receptacle, the constant water level device having been previously adjusted to a height such that the water in receptacle would rise to approximately 1/8 in. above the porous stone and be in contact with the soil specimen. The specimens are then insulated from each other for their full height with granulated cork.

2-04. Surcharge. Most specimens are tested under a surcharge load of 0.5 psi to simulate field conditions consisting of a 6 in. combined thickness of base and pavement. A steel surcharge base plate is set on top of the specimen and firmly seated to provide a uniform contact. Four lugs are attached to the base plate to raise the lead weights 1-1/2 in. so that the air may circulate over the top of the specimen. A typical soil specimen with surcharge weights, ready for placing into a test cabinet, is shown in Figure 1 of Plate A4.

2-05. Thermocouples in Specimens. Thermocouples are inserted at 1-in. intervals along the longitudinal axis, including top and bottom, in one of the four specimens in a test cabinet, and at the top and bottom only, in one additional specimen. The former installation provides a means of checking the temperatures within the specimen and observing the progress of freezing temperature into the specimen. The latter installation provides a means of checking the start and completion of the freezing test. The thermocouples are inserted through the side of the specimen and the entrance points are sealed with sealing wax.

2-06. Specimen Freezing Procedure. Prior to initiation of the freezing tests, the specimens are tempered at $35^{\circ}F$. Actual freezing of the specimens is started by lowering the temperature in the test cabinet to $20^{\circ}F$. until crystallization is visible on the top surface of the specimens. If necessary, crystallization in specimens is artificially instigated by seeding with ice crystals. The base plates and surcharge weights, which are tempered to 28^{O}F., are then placed on top of each specimen and the cabinet temperature is raised to 28^{O}F. The specimens are then frozen from the top by gradually decreasing the temperature in the freezing cabinet while the bottoms of the specimens are exposed to the cold room temperature which is maintained between 35^{O}F. and 38^{O}F. Temperatures within the soil specimens are read by means of the thermocouples in the control specimen, and the cabinet temperature is adjusted to maintain a rate of penetration of the 32^{O}F. temperature into the specimens at 1/4 in. per day. Heave measurements are taken daily with a meter stick or an extensometer placed on a designated point on the surcharge weights over the specimens.

Plots showing the heave, degree-hours, and the penetration of the 32^{O}F. temperature versus time for all test specimens are shown in Appendix B.

2-07. Examination of Specimens. Upon completion of the freezing tests, usually after 24 days, the specimens are removed from their containers, weighed to determine the change in water content, and then split in two,longitudinally, in the compression machine with the aid of a steel wedge. A photograph of a specimen being split is shown in Figure 2 of Plate A4. Measurements for amount of heave, and observations for the location, distribution and magnitude of ice lens formations are made on one-half of each specimen. The remaining half of the specimen is photographed and retained for supplemental laboratory tests. The water content distribution is obtained for every inch of specimen depth. The water content determinations on all test specimens are shown in Appendix B.

2-08. Supplementary Laboratory Tests. The following standard laboratory tests were performed on all materials tested, for correlation with the average rate of heave :

a. Gradation

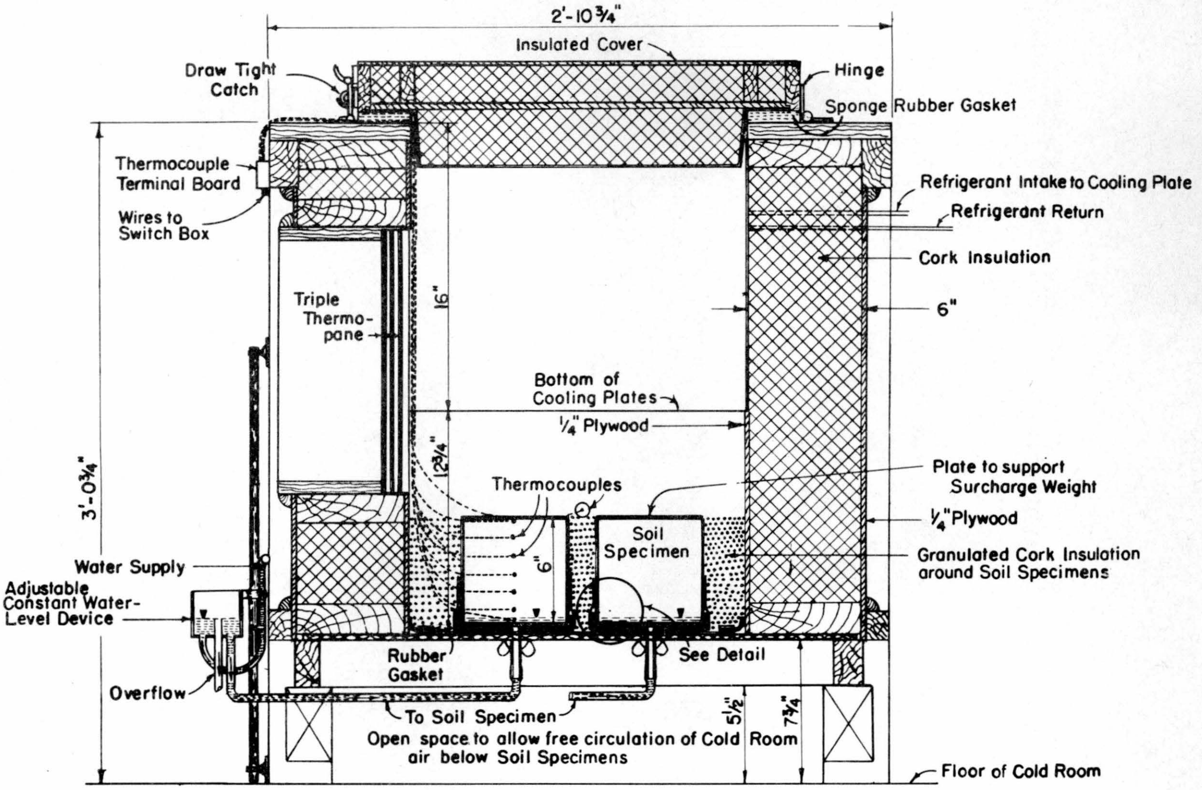
b. Permeability

c. Specific gravity

d. Atterberg limits (if applicable)

e. Compaction characteristics

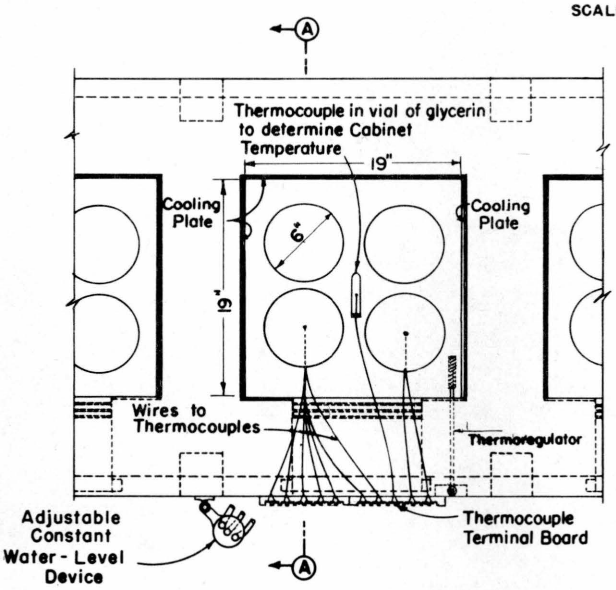
The results of these tests are presented in the various tables and plates of the main report and in Appendix B.



SECTION A-A

1" 0 2" 4" 6" 8" 10" 12" 14" 16"

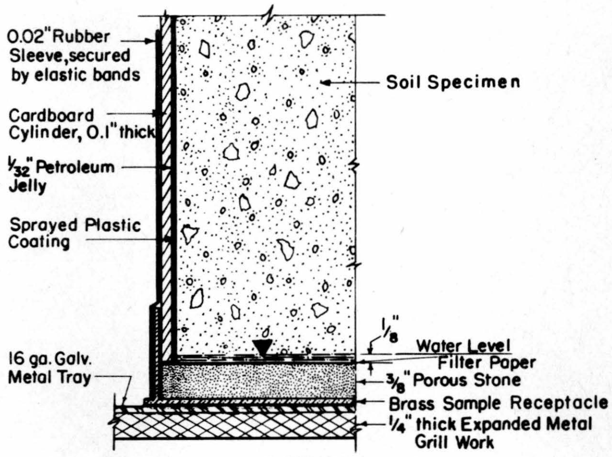
SCALE IN INCHES



PLAN
(COVERS REMOVED)

1" 0 4" 8" 12" 16" 20"

SCALE IN INCHES



DETAIL

1" 0 1" 2"

SCALE IN INCHES

NOTE:

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

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

DETAILS OF TEST CABINET
AND
SPECIMENS

PLATE A1

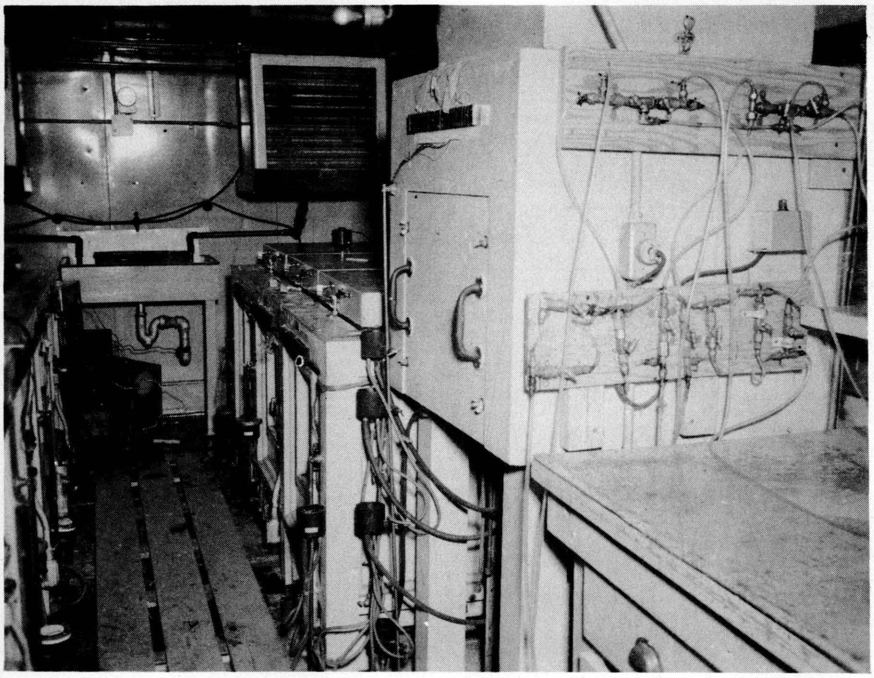


FIG. 1. RIGHT SIDE OF COLD ROOM SHOWING SPECIAL TEST CABINET TO DETERMINE THE EFFECT OF RELATIVE PROXIMITY OF WATER TABLE ON ICE SEGREGATION.

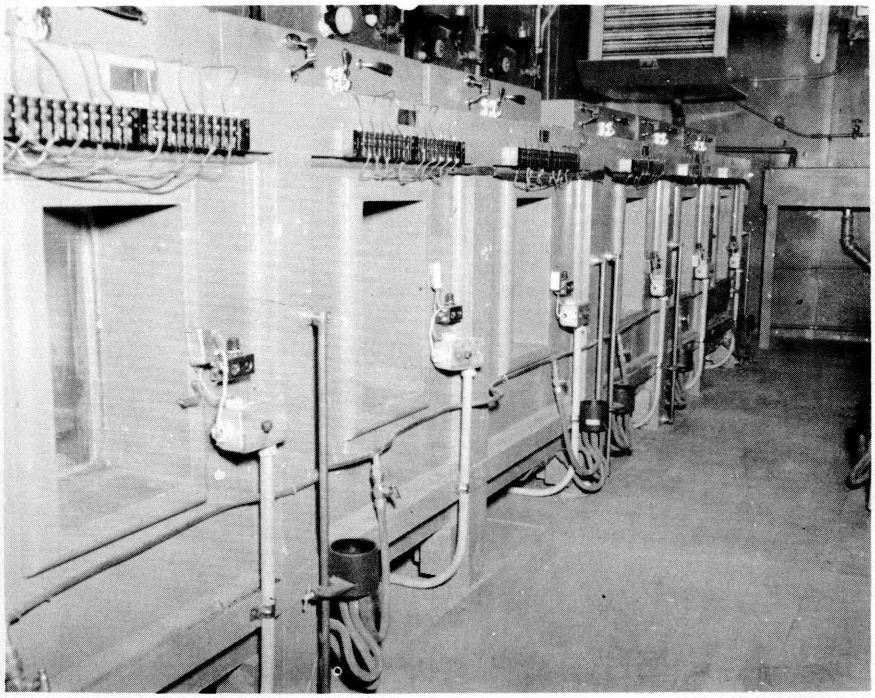


FIG. 2. LEFT SIDE OF COLD ROOM SHOWING TEST CABINETS EQUIPPED WITH CONSTANT WATER LEVEL DEVICES, THERMO-REGULATORS AND THERMOCOUPLE TERMINAL BOARDS.

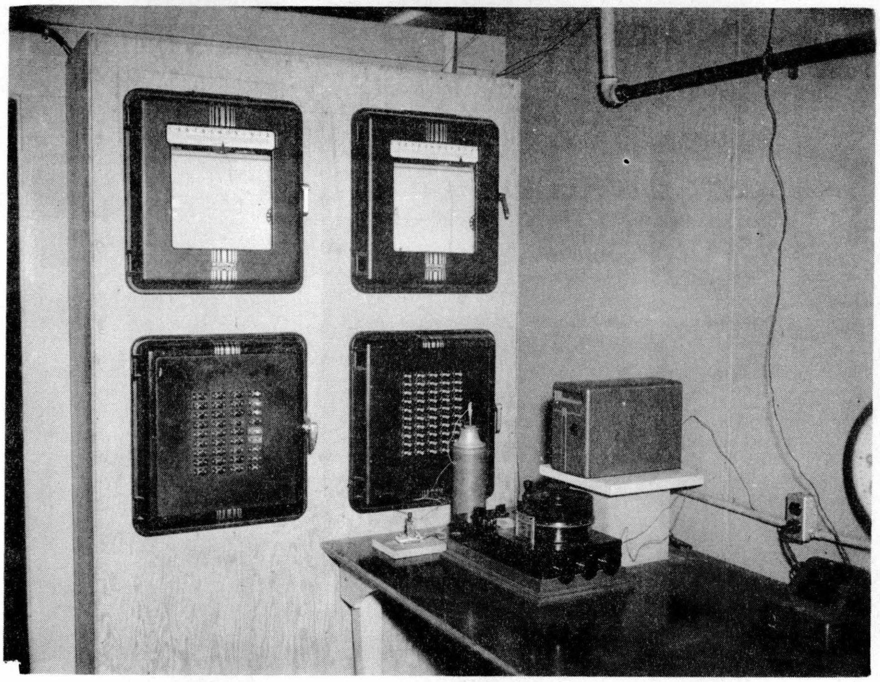


FIG. 1. TEMPERATURE MEASURING EQUIPMENT FOR USE WITH THERMOCOUPLES.

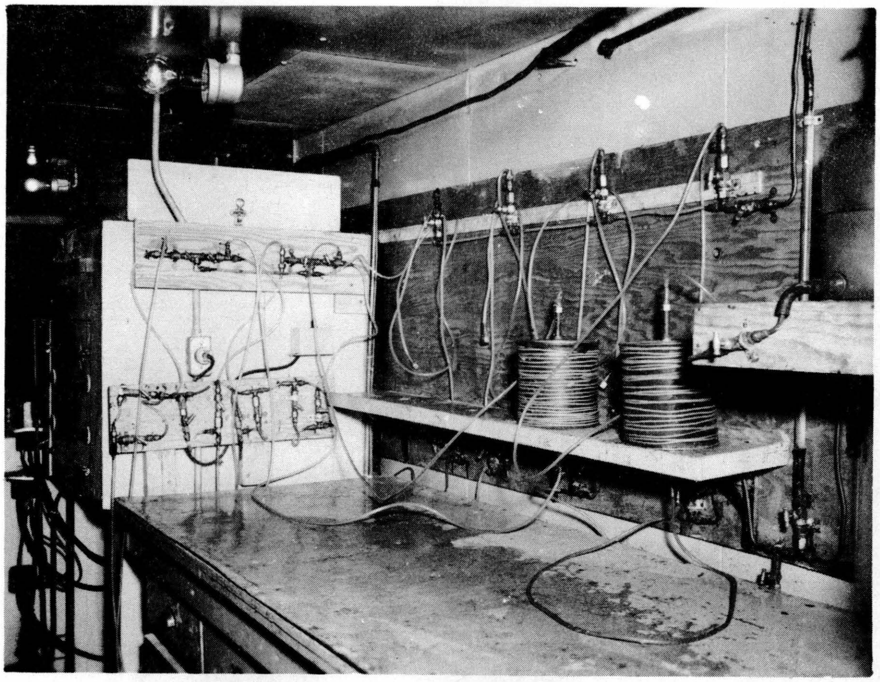


FIG. 2. SOIL SPECIMENS BEING SATURATED IN COLD ROOM.

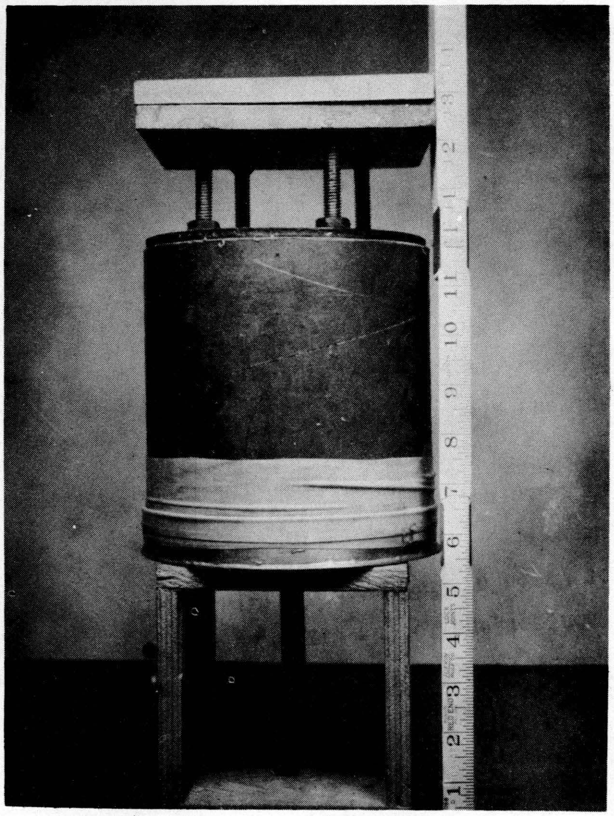


FIG. 1. TYPICAL SOIL SPECIMEN WITH SURCHARGE WEIGHTS, READY FOR PLACING IN TEST CABINET.

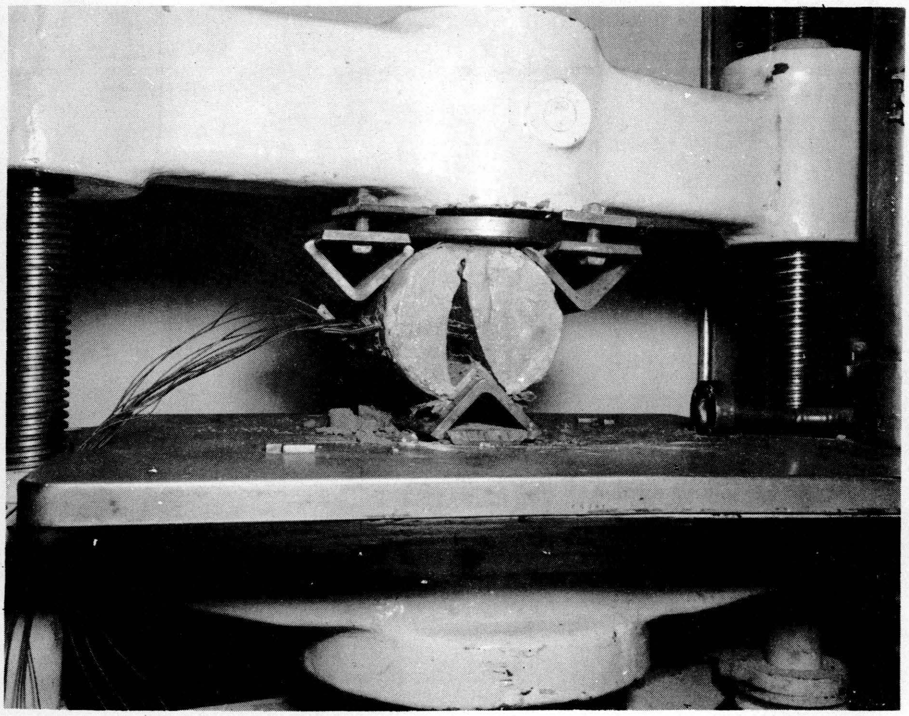


FIG. 2. SOIL SPECIMEN BEING SPLIT IN THE COMPRESSION MACHINE. NOTE THERMOCOUPLE WIRES IN PLACE.

PLATE A4

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FISCAL YEARS 1952 AND 1953

TABLE B I

TESTS FOR EFFECT OF VARIATIONS IN DRY UNIT WEIGHT

(DEGREE OF COMPACTION)

(OPEN SYSTEM)

SAMPLE NUMBER	MATERIAL	GRAIN SIZE mm. - % Finer				PER CENT HEAVE	AVERAGE RATE OF HEAVE	DRY UNIT WEIGHT	VOID RATIO	PERMEABILITY $k \times 10^{-4}$	G AT START OF TEST	ATTERBERG LIMITS (3)		PLATE REFERENCE	
		2.0	0.42	.074	0.02	(1)	mm./day	pcf.	e	cm./sec.	(2)	L.L.	P.I.	HEAVE AND TEMPERATURE DATA	WATER CONTENT DATA
PBJ-6	Project Blue Jay TP-250 Sandy Gravel (GW)	31	18	4	2	51.8	3.5	140.1	0.212	1.58	100.0	Non-Plastic		B22	B49
PBJ-11	Project Blue Jay, TP-274	34	16	3	1	16.0	1.7	143.7	0.188	0.11	100.0	"	"	B19	B46
	Sandy Gravel (GW)	34	16	3	1	43.0	2.2	140.1	0.218	0.21	91.3	"	"	B20	B47
PBJ-13	Project Blue Jay, TP-275	47	32	10	4	19.6	1.4	142.8	0.194	0.14	100.0	"	"	B19	B46
PBJ-14	Silty Sandy Gravel (GP-GM)	47	32	10	4	47.4	2.6	137.8	0.238	0.23	79.3	"	"	B20	B47
PBJ-3	Project Blue Jay, TP-248	63	46	10	4	29.0	1.9	138.4	0.215	0.50	100.0	"	"	B21	B48
PBJ-4	Silty gravelly sand (SP-SM)	63	46	10	4	69.4	3.9	136.8	0.230	0.61	100.0	"	"	B22	B49
PBJ-10	Project Blue Jay, TP-262 Silty Gravelly Sand (SM)	71	53	21	7	36.9	2.5	128.7	0.312	0.53	88.0	"	"	B20	B47
PBJ-7	Project Blue Jay, TP-256	63	54	31	18	15.7	1.5	136.0	0.238	0.0036	72.7	16.0	3.7	B19	B46
PBJ-8	Silty Gravelly Sand (SM)	63	54	31	18	37.4	2.8	132.1	0.275	0.0014	67.6	16.0	3.7	B22	B49
TD-36(4)	Truax Drumlin Soil, Silty Gravelly Sand (-3/4") (SM)	83	73	32	19	21.0	1.9	136.0	0.246	0.0085	100.0	14.4	1.6	B1	B32
PBJ-15	Project Blue Jay, TP-276	72	58	44	35	26.3	1.3	139.1	0.234	0.0027	100.0	18.6	9.3	B19	B46
PBJ-16	Gravelly Clayey Sand (SC)	72	58	44	35	83.0	4.0	131.9	0.301	0.0046	100.0	18.6	9.3	B20	B47
PBJ-1	Project Blue Jay, TP-244	68	55	35	23	25.3	1.3	133.1	0.272	0.033	100.0	24.7	8.1	B21	B48
PBJ-2	Gravelly Clayey Sand (SC)	68	55	35	23	77.1	4.5	127.7	0.334	0.078	83.4	24.7	8.1	B22	B49
FA-5	Fargo Clayey Sand (SC)	89	34	16	9	52.6	4.3	112.7	0.494	0.36	86.8	30.7	10.5	B2	B33
FA-6		89	34	16	9	40.8	3.1	177.1	0.438	0.19	88.8	30.7	10.5	B2	B33
LFT-10	Fairbanks Silt (Undisturbed)	100	100	94	40	124.0	4.5	98.1	0.702		95.8	25.8	3.8	B29	B53
LFT-13	(ML-OL) (Remolded)	100	100	99	41	223.6	11.3	101.4	0.646	0.20	100.0	32.6	6.2	B3	B34
LFT-14	(Remolded)	100	100	99	41	281.2	11.5	110.9	0.505	0.09	100.0	32.6	6.2	B3	B34
WASHO-5	WASHO Road Test Section	100	99	96	65	61.0	3.5	96.0	0.678		100.0	37.0	13.0	B4	B59
WASHO-6	Clay (CL-OL)	100	99	96	65	42.3	4.1	98.0	0.644		100.0	37.0	13.0	B4	B60
WASHO-7		100	99	96	65	45.0	4.2	98.9	0.627		100.0	37.0	13.0	B4	B60
WASHO-8		100	99	96	65	63.3	5.4	92.2	0.745		100.0	37.0	13.0	B4	B60
WASHO-9		100	99	96	65	58.6	5.1	90.0	0.790		100.0	37.0	13.0	B4	B60

NOTES:
(1) Based on original height of frozen portion.
(2) Degree of Saturation in percent at start of test
(3) Tests made on material passing the U. S. Standard No. 40 Sieve
(4) This sample was prepared 12-inches in diameter and 6-inches in height

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEARS 1952 AND 1953

TABLE B2

TESTS TO EVALUATE SIDE FRICTION

(OPEN SYSTEM)

SAMPLE NUMBER	MATERIAL	CONTAINER	LINER TYPE AND LUBRICANT	GRAIN SIZE mm. - % Finer				DRY UNIT WEIGHT pcf.	VOID RATIO e	PERMEABILITY k x 10^{-4} cm./sec.	G AT START OF TEST (1)	ATTERBERG LIMITS (2)		RATE OF STRESS INCREASE psi./min.	MAXIMUM NORMAL STRESS psi.	FRICTIONAL SIDE RESTRAINT psi.
				2.0	0.42	.074	0.02					L.L.	P.I.			
AG-1	Peabody Sandy GRAVEL (-3/4")	Micarta	Petrolatum	58	24	3	1	130.1	0.303	26.0	100	Non-plastic		10	26.5	6.6
AG-3		Micarta	Sheet Acetate w/Silicone	58	24	3	1	127.2	0.333	47.0	100	"		10	25.8	5.8
AG-4		Micarta	1" Acetate Squares (lapped) w/Silicone	58	24	3	1	126.9	0.337	51.0	100	"		4	5.0	1.2
AG-5		Micarta	1" Acetate Strips (lapped) w/Silicone	58	24	3	1	124.3	0.365	87.0	100	"		4	12.4	3.1
AG-6		Micarta	Dental Dam (lapped) w/Liqui-Moly	58	24	3	1	123.4	0.373	100.0	100	"		4	1.1	0.3
AG-7		Micarta	1" Acetate Strips (lapped) w/Liqui-Moly	58	24	3	1	120.4	0.408	200.0	100	"		4	3.7	0.9
AG-8		Tapered Lucite	Silicone	58	24	3	1	122.8	0.382	75.0	100	"		5	6.3	1.4
NH-1E	New Hampshire SILT-B	Tapered Lucite	Sheet Acetate w/Liqui-Moly	100	100	99	73	98.8	0.705	0.27	92.4	23.7	6.0	10	8.3	1.8
NH-2E		"	Liqui-Moly	100	100	99	73	99.6	0.691	0.26	85.0	"	"	9	118.6	23.8

NOTES:

(1) Degree of saturation in per cent at start of test.
(2) Tests made on material passing the U. S. Standard No. 40 Sieve.

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEARS 1952 AND 1953

TABLE B3

TESTS FOR EFFECT OF SURCHARGE

(OPEN SYSTEM)

SAMPLE NUMBER	MATERIAL	SURCHARGE lbs./in²	GRAIN SIZE mm. - % Finer				PER CENT HEAVE	AVERAGE RATE OF HEAVE mm./day	DRY UNIT WEIGHT pcf.	VOID RATIO e	PERME-ABILITY k x 10^{-4} cm./sec.	G AT START OF TEST	ATTERBERG LIMITS (3)		PLATE REFERENCE	
			2.0	0.42	.074	0.02	(1)					(2)	L.L.	P.I.	HEAVE AND TEMPERATURE DATA	WATER CONTENT DATA
TD-36(4)	Truax Drumlin Soil Silty Gravelly Sand (-3/4")	0.5	83	73	32	19	21.0	1.9	136.0	0.246	0.0085	100.0	14.4	1.6	B1	B32
LFT-9	Fairbanks SILT (Undisturbed)	0	100	100	92	50	55.7	5.5	104.2	0.602		100.0	25.8	3.8	B5	B35
LFT-6		2	100	100	92	50	43.8	1.2	100.3	0.665	0.010(5)	100.0	"	"	B5	B35
LFT-7		4	100	100	92	50	23.1	0.8	97.6	0.710	0.013(5)	100.0	"	"	B5	B35
LFT-8		6	100	100	92	50	29.2	0.1	97.1	0.719	0.015(5)	100.0	"	"	B5	B35
VIS-7	Indiana SILT	0	100	100	99	55	142.3	5.8	111.9	0.516	0.026	93.6	23.7	4.0	B6	B36
VIS-1		0.5	100	100	99	55	95.3	9.8	113.1	0.501	0.024	100.0	"	"	B28	B51
VIS-2		0.5	100	100	99	55	100.0	10.0	113.1	0.501	0.024	97.8	"	"	B28	B51
VIS-4		2	100	100	99	55	67.3	4.1	112.5	0.508	0.025	72.5	"	"	B6	B36
VIS-5		4	100	100	99	55	54.6	3.8	111.9	0.516	0.026	71.0	"	"	B6	B36
WASHO-1	WASHO Road Test Section CLAY	0.5	100	99	96	65	20.9	5.3	98.6	0.630		100.0	37.0	13.0	B7	B58
WASHO-2		2	100	99	96	65	44.6	5.0	98.8	0.629		100.0	"	"	B7	B59
WASHO-3		4	100	99	96	65	24.0	4.1	98.8	0.629		100.0	"	"	B7	B59
WASHO-4		6	100	99	96	65	25.2	3.0	100.0	0.611		100.0	"	"	B7	B59

TABLE B4

CLOSED SYSTEM TESTS

SAMPLE NUMBER	MATERIAL	GRAIN SIZE mm. - % Finer				PER CENT HEAVE	DRY UNIT WEIGHT pcf.	VOID RATIO e	PERME-ABILITY k x 10^{-4} cm./sec.	G AT START OF TEST	ATTERBERG LIMITS (3)		PLATE REFERENCE	
		2.0	0.42	.074	0.02	(1)				(2)	L.L.	P.I.	HEAVE AND TEMPERATURE DATA	WATER CONTENT DATA
PAFB-9	Portsmouth Silty Gravelly SAND (-3/4")	80	58	29	18	1.3	125.9	0.344		70.6	Non-plastic		B8	B37
PAFB-10		80	58	29	18	1.7	128.6	0.316		80.1	"	"	B8	B37
PAFB-12		80	58	29	18	6.8	125.1	0.353		87.8	"	"	B8	B37
PAFB-11		80	58	29	18	7.1	127.6	0.326		91.7	"	"	B8	B37
NH-48	New Hampshire SILT - A	100	100	85	61	7.8	101.7	0.693	0.071	90.8	24.1	5.9	B9	B38
NH-49		100	100	85	61	9.1	103.0	0.672	0.063	96.2	"	"	B9	B38
LFT-1	Fairbanks SILT (Undisturbed)	100	100	94	40	19.1	97.2	0.717		100.0	25.8	3.8	B29	B53
EBT-40	East Boston Till - C (-3/4")	77	65	46	32	8.6	128.2	0.343	0.044	96.0	22.7	8.3	B9	B38
EBT-41		77	65	46	32	7.3	128.2	0.343	0.044	98.3	"	"	B9	B38
SC-4	Searsport CLAY (Undisturbed)	100	100	99	80	5.8	95.3	0.813	.00046(5)	95.2	36.5	17.9	B10	B39
SC-5		100	100	99	80	7.3	96.9	0.784	.00041(5)	95.4	"	"	B15	B43
SC-3		100	100	99	80	4.5	96.8	0.785	.00041(5)	96.4	"	"	B10	B39
SC-8	(Remolded)	100	100	99	80	9.7	96.8	0.785		95.1	"	"	B15	B43
BC-19	Boston Blue CLAY (Undisturbed)	100	100	100	94	11.1	86.5	1.005	.0066(5)	93.9	52.7	26.4	B10	B39
BC-18		100	100	100	94	8.9	86.2	1.012	.0066(5)	94.3	"	"	B10	B39
BC-22		100	100	100	94	10.7	85.1	1.038	.0066(5)	96.0	"	"	B17	B40
BC-21		100	100	100	94	11.0	87.7	0.978		100.0	"	"	B17	B40
FA(C)-2	Fargo CLAY (Undisturbed)	100	100	98	85	2.0	83.2	1.071		100.0	67.8	45.8	B11	B61
FA(C)-4		100	100	98	85	2.2	86.1	0.996		100.0	"	"	B11	B61
FA(C)-5	(Remolded)	100	100	98	85	8.6	85.1	1.024		100.0	"	"	B12	B61
FA(C)-6		100	100	98	85	9.7	85.1	1.021		100.0	"	"	B12	B61

NOTES:
(1) Based on original height of frozen portion.
(2) Degree of saturation in per cent at start of test.
(3) Tests made on material passing the U. S. Standard No. 40 sieve.
(4) This sample was prepared 12-inches in diameter and 6-inches in height.
(5) Determined from consolidation characteristics of undisturbed sample.

TABLES B3 and B4

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEARS 1952 AND 1953

TABLE B5

TESTS FOR EFFECT OF REMOLDING

(OPEN AND CLOSED SYSTEMS)

SAMPLE NUMBER	MATERIAL	TEST CONDITIONS		GRAIN SIZE mm. - % Finer				PER CENT HEAVE (1)	AVERAGE RATE OF HEAVE mm./day	DRY UNIT WEIGHT pcf.	VOID RATIO e	PERME-ABILITY k x 10^{-4} cm./sec.	G AT START OF TEST (2)	ATTERBERG LIMITS (3)		PLATE REFERENCE	
		SAMPLE	SYSTEM	2.0	0.42	.074	0.02							L.L.	P.I.	HEAVE AND TEMPERATURE DATA	WATER CONTENT DATA
LFT-10	Fairbanks SILT	Undisturbed	Open	100	100	94	40	124.0	4.5	98.1	0.702		95.8	25.8	3.8	B29	B52
LFT-19		Remolded	Open	100	100	94	40	81.8	7.9	98.0	0.703		100.0	"	"	B13	B41
LFT-20		Remolded	Open	100	100	94	40	102.1	11.6	97.2	0.717		100.0	"	"	B13	B41
PAFB- 1	Portsmouth CLAY	Undisturbed	Open	100	100	92	47	95.3	4.2	96.1	0.772		97.8	30.0	11.7	B14	B42
PAFB- 2		Remolded	Open	100	100	92	47	114.9	4.1	94.7	0.798		94.8	"	"	B14	B42
PAFB- 3		Undisturbed	Closed	100	100	86	50	6.8	-	97.0	0.750		100.0	"	"	B14	B42
PAFB- 4		Remolded	Closed	100	100	86	50	5.0	-	97.0	0.750		100.0	"	"	B14	B42
SC- 7	Searsport CLAY	Undisturbed	Open	100	100	99	80	240.3	8.4	95.6	0.808	.00046(4)	93.5	36.5	17.9	B15	B43
SC- 9		Undisturbed	Open	100	100	99	80	155.2	6.2	98.5	0.755	.00037(4)	98.2	"	"	B16	B44
SC- 6		Remolded	Open	100	100	99	80	47.2	2.1	95.8	0.804		93.1	"	"	B15	B43
SC-10		Remolded	Open	100	100	99	80	38.6	2.5	98.5	0.755		98.2	"	"	B16	B44
SC- 5		Undisturbed	Closed	100	100	99	80	7.3	-	96.9	0.784	.00041(4)	95.4	"	"	B15	B43
SC-11		Undisturbed	Closed	100	100	99	80	4.8	-	97.1	0.837	.00065(4)	90.7	"	"	B16	B44
SC- 8		Remolded	Closed	100	100	99	80	9.7	-	96.8	0.786		95.1	"	"	B15	B43
SC-12		Remolded	Closed	100	100	99	80	6.8	-	97.1	0.837		90.7	"	"	B16	B44
BC-20	Boston Blue CLAY	Undisturbed	Open	100	100	100	94	111.8	4.1	85.4	1.031	.0066(4)	97.3	52.7	26.4	B17	B40
BC-23		Remolded	Open	100	100	100	94	58.9	2.4	87.4	0.989		100.0	"	"	B17	B40
BC-22		Undisturbed	Closed	100	100	100	94	10.7	-	85.1	1.038	.0066(4)	96.0	"	"	B17	B40
BC-21		Remolded	Closed	100	100	100	94	11.0	-	87.7	0.978		100.0	"	"	B17	B40
FA(C)- 7	Fargo CLAY	Remolded	Open	100	100	98	85	18.4	1.0	86.8	0.988		100.0	67.8	45.8	B12	B62
FA(C)- 8		Remolded	Open	100	100	98	85	24.0	1.5	86.8	0.988		100.0	"	"	B12	B62
FA(C)- 2		Undisturbed	Closed	100	100	98	85	2.0	-	83.2	1.071		100.0	"	"	B11	B61
FA(C)- 4		Undisturbed	Closed	100	100	98	85	2.2	-	86.1	0.996		100.0	"	"	B11	B61
FA(C)- 5		Remolded	Closed	100	100	98	85	8.6	-	85.1	1.024		100.0	"	"	B12	B61
FA(C)- 6		Remolded	Closed	100	100	98	85	9.7	-	85.1	1.024		100.0	"	"	B12	B61

TABLE B6

TESTS FOR EFFECT OF PROXIMITY OF WATER TABLE

(OPEN SYSTEM)

SAMPLE NUMBER	MATERIAL	DEPTH TO WATER TABLE BELOW TOP OF SAMPLE (Inches)	GRAIN SIZE mm. - % Finer				PER CENT HEAVE (1)	AVERAGE RATE OF HEAVE mm./day	DRY UNIT WEIGHT pcf.	VOID RATIO e	PERME-ABILITY k x 10^{-4} cm./sec.	G AT START OF TEST (2)	ATTERBERG LIMITS (3)		PLATE REFERENCE	
			2.0	0.42	.074	0.02							L.L.	P.I.	HEAVE AND TEMPERATURE DATA	WATER CONTENT DATA
EBT-42	East Boston Till - C (-3/4")	12	77	65	46	32	5.5	0.3	134.9	0.277	0.022	95.0	22.7	8.3	B18	B45
EBT-43		18	77	65	46	32	0.7	0.1	136.6	0.261	0.019	100.0	"	"	B18	B45
EBT-44		30	77	65	46	32	3.2	0.1	136.6	0.261	0.019	100.0	"	"	B18	B45
EBT-45		42	77	65	46	32	2.8	0.1	136.6	0.261	0.019	96.8	"	"	B18	B45

NOTES:
(1) Based on original height of frozen portion.
(2) Degree of saturation in per cent at start of test.
(3) Tests made on material passing the U. S. Standard No. 40 sieve.
(4) Determined from consolidation characteristics of undisturbed sample.

TABLES B5 and B6

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEARS 1952 AND 1953

TABLE B7

TEST DATA FOR NATURAL SOIL SPECIMENS USED FOR FROST SUSCEPTIBILITY TESTS

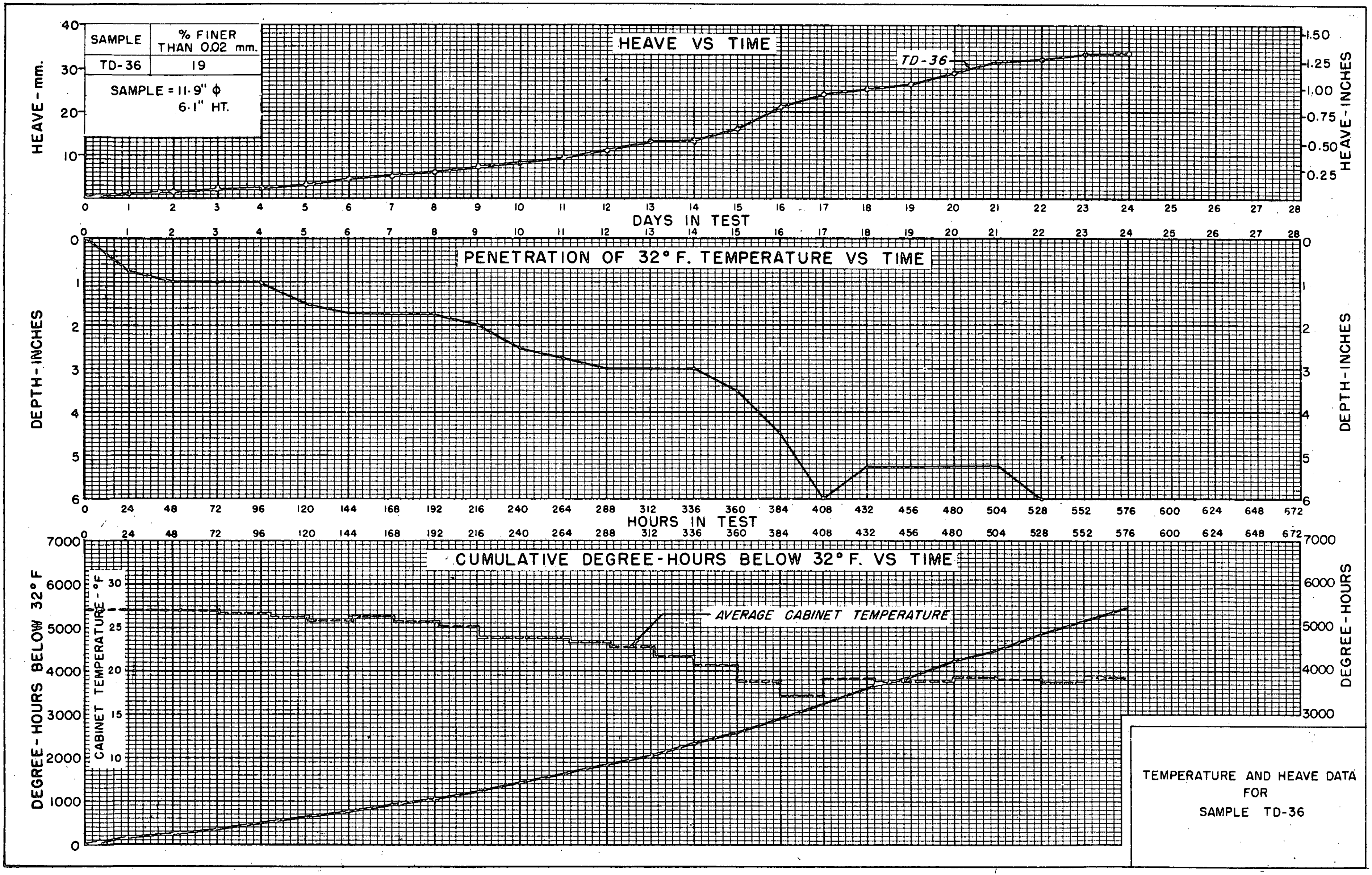
(OPEN SYSTEM)

SAMPLE NUMBER	MATERIAL	GRAIN SIZE mm. - % Finer				PERCENT HEAVE (1)	AVERAGE RATE OF HEAVE mm/day	DRY UNIT WEIGHT pcf.	DEGREE OF COMPACTION (2)	VOID RATIO e	PERMEABILITY k x 10^{-4} cm./sec.	S AT START OF TEST (3)	ATTERBERG LIMITS (4)		PLATE REFERENCE	
		2.0	0.42	.074	0.02								L.L.	P.I.	HEAVE AND TEMPERATURE DATA	WATER CONTENT DATA
PBJ-11	Project Blue Jay, TP-274 Sandy GRAVEL (5)	34	16	3	1	16.0	1.7	143.7	97.0	0.188	0.11	100.0	Non-plastic		B19	B46
PBJ-6	Project Blue Jay, TP-250 Sandy GRAVEL (5)	31	18	4	2	51.8	3.5	140.1	94.6	0.212	1.58	100.0	"	"	B22	B49
KA-1	Keflavik Sandy GRAVEL (Pit Run-3")	32	15	5	2	7.8	0.5	136.8	89.5	0.390		99.5	Non-plastic		B23	(*)
KA-2	Keflavik Silty Sandy GRAVEL (Crusher Run)	27	15	6	2	2.6	0.3	137.7	95.0	0.380		94.2	"	"	B23	(*)
PBJ-13	Project Blue Jay, TP-275 Silty Sandy GRAVEL (5)	47	32	10	4	19.6	1.4	142.8	99.6	0.194	0.14	100.0	"	"	B19	B46
PAF-3	Plattsburg Gravelly SAND (A)(8)	51	20	2	1	6.0	0.4	130.0	98.3	0.281		100.0	"	"	B25	B56
PAF-4	(8)	51	20	2	1	9.6	0.3	129.7	97.8	0.283		100.0	"	"	B26	B56
PAF-8	Plattsburg Gravelly SAND (Washed Screenings)	26	1	0	0	1.4	< 0.1	126.8	99.7	0.455		80.00	"	"	B26	B57
PAF-7	Plattsburg Gravelly SAND (Unwashed Screenings)	24	7	3	1	7.5	0.2	138.6	100.0	0.440		86.0	"	"	B25	B57
PAF-5	Plattsburg Gravelly SAND (D)	68	36	4	2	5.3	0.2	124.2	99.4	0.338		95.0	"	"	B25	B57
PAF-6		68	36	4	2	9.8	0.6	125.0	100.0	0.329		90.4	"	"	B26	B57
PBJ-3	Project Blue Jay, TP-248 Silty Gravelly SAND (5)	63	46	10	4	29.0	1.9	138.4	97.2	0.215	0.50	100.0	"	"	B21	B48
PBJ-10	Project Blue Jay, TP-262 Silty Gravelly SAND (5)	71	53	21	7	36.9	2.5	128.7	94.6	0.312	0.53	88.0	"	"	B20	B47
WMS-1	Fairchild Silty Gravelly SAND (7)	81	35	20	10	29.0	2.9	131.3	92.4	0.314		93.9	21.6	2.9	B24	B58
WMC-1	Fairchild Silty Gravelly SAND (7)	65	34	23	11	56.6	2.5	135.4	93.8	0.287		100.0	24.6	6.3	B24	B58
WMC-2	(7)	65	34	23	11	27.1	2.5	136.1	94.4	0.280		100.0	24.6	6.3	B24	B58
PAFB-8	Portsmouth Silty Gravelly SAND (5)	62	45	23	14	81.8	4.7	127.0	98.8	0.333		100.0	Non-plastic		B27	B50
PBJ-7	Project Blue Jay, TP-256 Silty Gravelly SAND (5)	63	54	31	18	15.7	1.5	136.0	98.9	0.238	0.0036	72.7	16.0	3.7	B19	B46
PAF-1	Plattsburg Silty SAND (TP-2)	100	95	28	2	4.4	0.1	106.7	97.1	0.567		84.7	Non-plastic		B25	B56
PAF-2		100	95	28	2	4.0	0.1	108.5	98.8	0.540		95.5	"	"	B26	B56
PAFB-7	Portsmouth Silty SAND (7)	98	94	29	8	13.5	1.0	109.0	97.8	0.560	3.6	96.1	"	"	B27	B50
PBJ-1	Project Blue Jay, TP-244 Gravelly Clayey SAND (5)	68	55	35	23	25.3	1.3	133.1	100.0	0.272	0.033	100.0	24.7	8.1	B21	B48
PBJ-15	Project Blue Jay, TP-276 Gravelly Clayey SAND (5)	72	58	44	35	26.3	1.3	139.1	99.8	0.254	0.0027	100.0	18.6	9.3	B19	B46
VIS-1	Indiana SILT	100	100	99	53	95.3	9.8	113.1	97.8	0.501	0.024	100.0	23.7	4.0	B28	B51
VIS-2		100	100	99	53	100.0	10.0	113.1	97.8	0.501	0.024	97.8	23.7	4.0	B28	B51
YS-1	Yukon SILT	100	100	98	60	37.0	2.2	122.6	98.5	0.389	0.0031	100.0	25.3	5.8	B29	B52
NH-79-A	New Hampshire SILT (A)	100	100	95	61	150.2	7.9	104.8	97.6	0.643	0.054	88.0	24.1	5.9	D10. Vol. II	TABLE D15 Vol. II
LFT-10	Fairbanks SILT (Undisturbed)	100	100	94	40	124.0	4.5	98.1		0.702		95.8	25.8	3.8	B29	B53
LFT-19	(Remolded)	100	100	94	40	81.8	7.9	98.0	91.2	0.703		100.0	25.8	3.8	B13	B41
LFT-20	(Remolded)	100	100	94	40	102.1	11.6	97.2	90.5	0.717		100.0	25.8	3.8	B13	B41
PAFB-1	Portsmouth CLAY (Undisturbed)	100	100	92	47	95.3	4.2	96.1		0.772		97.8	30.0	11.7	B14	B42
PAFB-2	(Remolded)	100	100	92	47	114.9	4.1	94.7		0.798		94.8	30.0	11.7	B14	B42
PAFB-5	(Undisturbed)	100	100	96	49	112.7	4.5	108.6		0.569		95.1	30.0	11.7	B30	B55
FB-7-A-	Fort Belvoir Sandy CLAY	97	90	61	49	18.2	1.5	117.0	101.5	0.456	0.098	89.8	43.8	20.3	D10. Vol. II	TABLE D15 Vol. II
FB-9-A		97	90	61	49	22.1	1.3	113.3	98.3	0.504	0.130	100.0	43.8	20.3	D14 "	"
FB-14-A		97	90	61	49	27.6	2.2	118.2	102.5	0.441	0.089	100.0	43.8	20.3	D15 "	"
SC-1	Searsport CLAY (Undisturbed)	100	100	99	81	182.2	8.6	90.2		0.742	.00036(6)	95.5	36.5	17.9	B31	B55
SC-2	(Undisturbed)	100	100	99	81	131.3	4.7	98.6		0.753	.00037(6)	100.0	36.5	17.9	B31	B55
SC-6	(Remolded)	100	100	99	81	47.2	2.1	95.8		0.804		93.1	36.5	17.9	B15	B43
SC-7	(Undisturbed)	100	100	99	81	240.3	8.4	95.6		0.808	.00046(6)	93.5	36.5	17.9	B15	B43
SC-9	(Undisturbed)	100	100	99	81	155.2	6.2	98.5		0.755	.00037(6)	98.2	36.5	17.9	B16	B44
SC-10	(Remolded)	100	100	99	81	38.6	2.5	98.5		0.755		98.2	36.5	17.9	B16	B44
BC-20	Boston Blue Clay (Undisturbed)	100	100	100	94	111.8	4.1	85.4		1.031	.0066 (6)	97.3	52.7	26.4	B17	B40
BC-23	(Remolded)	100	100	100	94	58.9	2.4	87.4		0.989		100.0	52.7	26.4	B17	B40
WASHO-1	WASHO Road Test Section CLAY	100	99	96	65	20.9	5.3	98.6	99.0	0.630		100.0	37.0	13.0	B7	B58
WASHO-6		100	99	96	65	42.3	4.1	98.0	98.4	0.644		100.0	37.0	13.0	B4	B60
WASHO-7		100	99	96	65	45.0	4.2	98.9	99.3	0.627		100.0	37.0	13.0	B4	B60
FA(C)-7	Fargo CLAY (Remolded)	100	100	98	85	18.4	1.0	86.8		0.988		100.0	67.8	45.8	B12	B62
FA(C)-8	(Remolded)	100	100	98	85	24.0	1.5	86.8		0.988		100.0	67.8	45.8	B12	B62

(*) Water Content distribution not obtained due to large gravel content of specimen.

NOTES:
(1) Based on original height of frozen portion.
(2) Based on maximum density given in Table 1 of main report.
(3) Degree of saturation in percent at start of test.
(4) Tests made on material passing the U. S. Standard No. 40 sieve.
(5) +3/4" material replaced with -3/4" to +#4.
(6) Determined from consolidation characteristics of undisturbed sample.
(7) Tests performed on -3/4" portion of original sample.
(8) Tests performed on -1-1/2" portion of original sample.

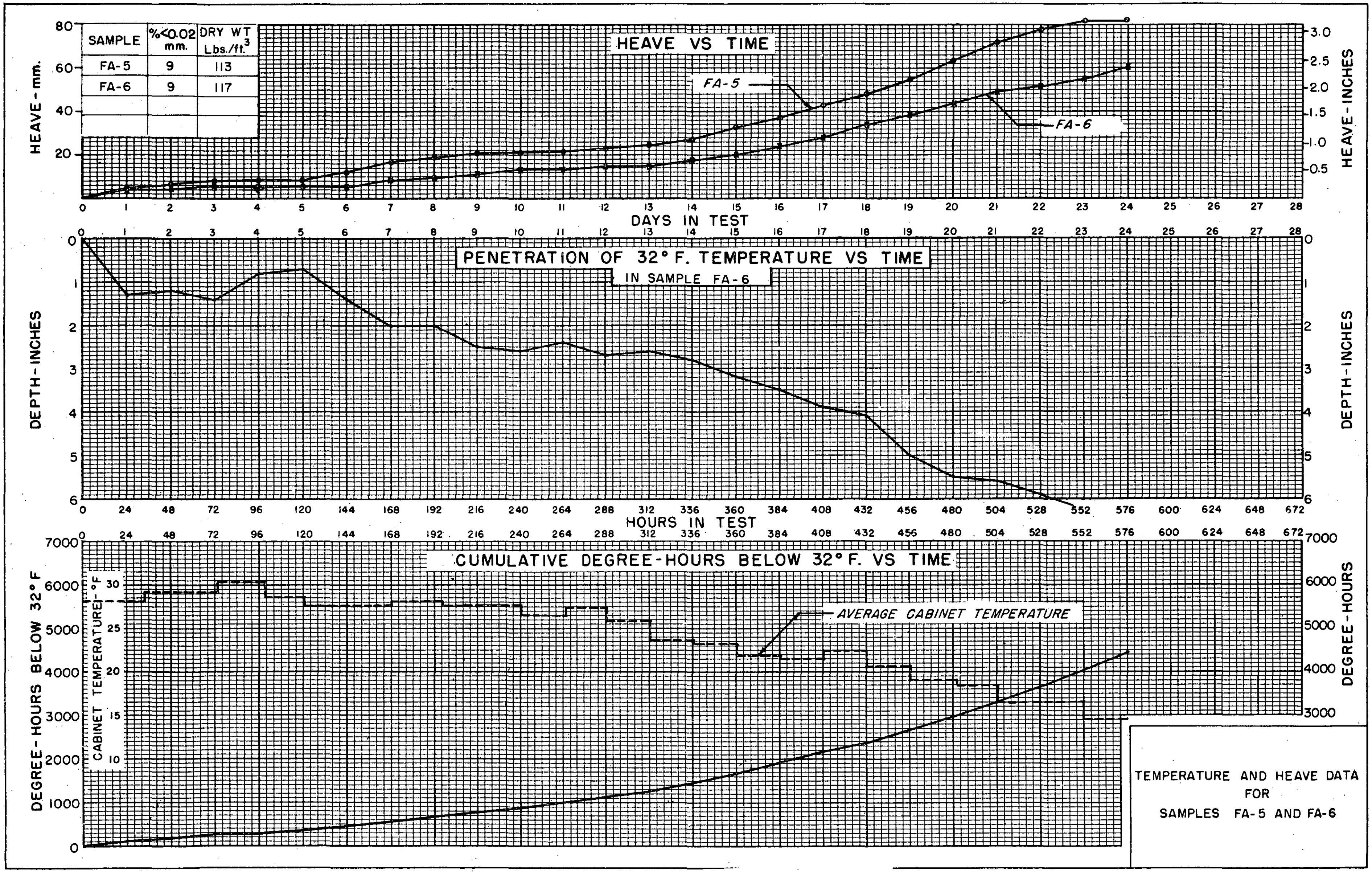
TABLE B7



TEMPERATURE AND HEAVE DATA
FOR
SAMPLE TD-36

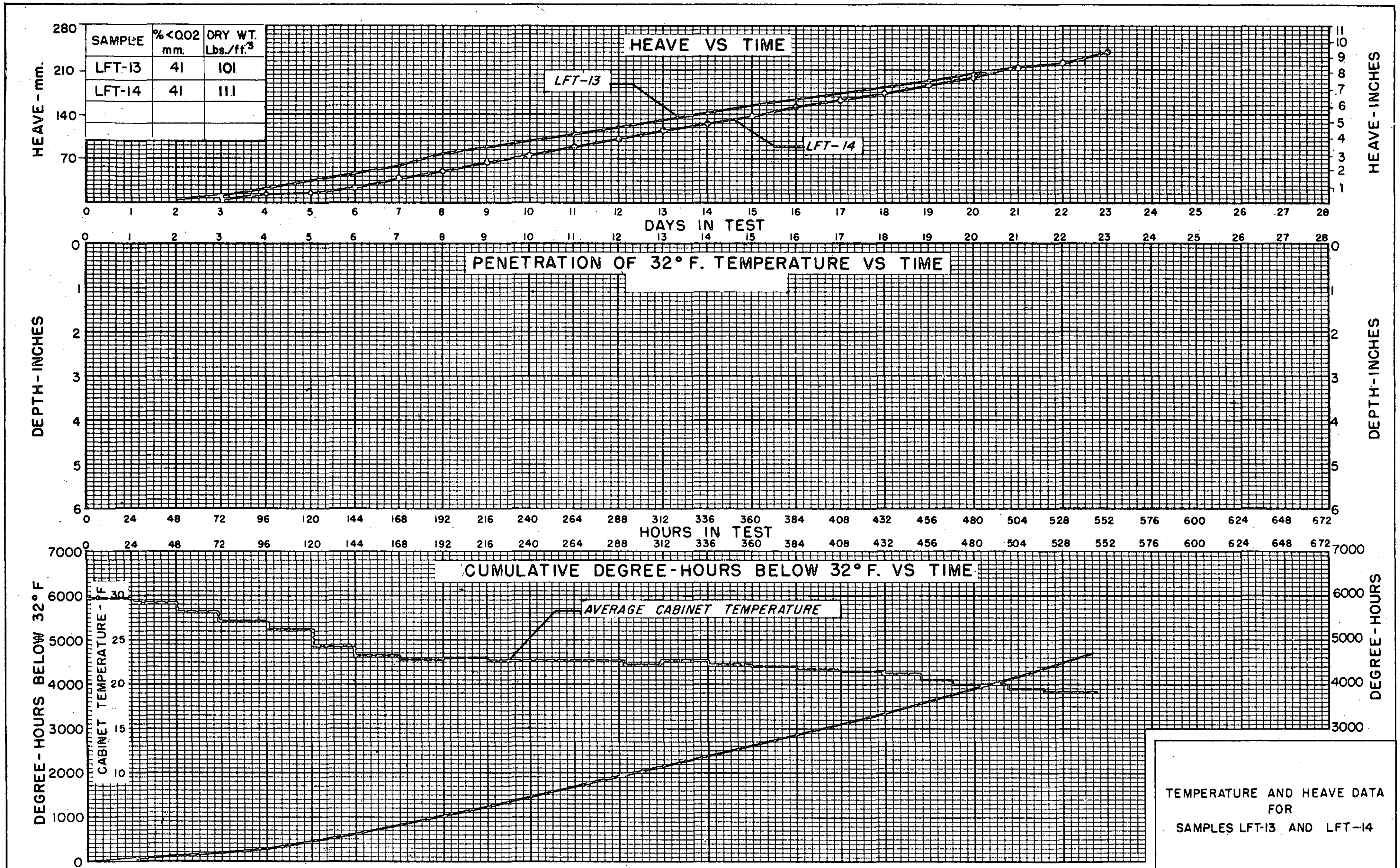
PLATE B1

PLATE B2



SAMPLE	%<0.02 mm.	DRY WT Lbs./ft.^{3}
FA-5	9	113
FA-6	9	117

TEMPERATURE AND HEAVE DATA
FOR
SAMPLES FA-5 AND FA-6

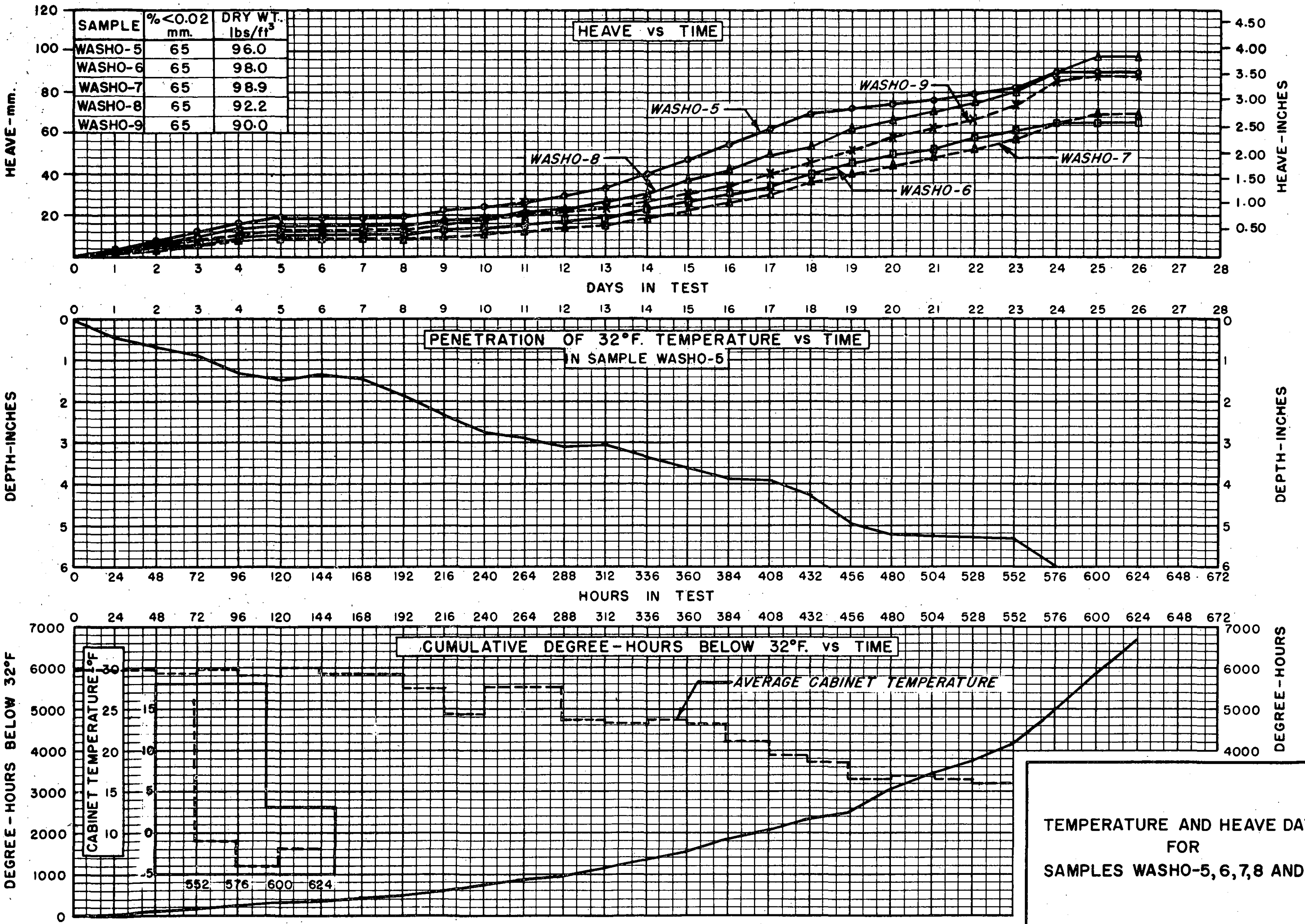


SAMPLE	% < 0.02 mm.	DRY WT. Lbs./ft.^{3}
LFT-13	41	101
LFT-14	41	111

TEMPERATURE AND HEAVE DATA
FOR
SAMPLES LFT-13 AND LFT-14

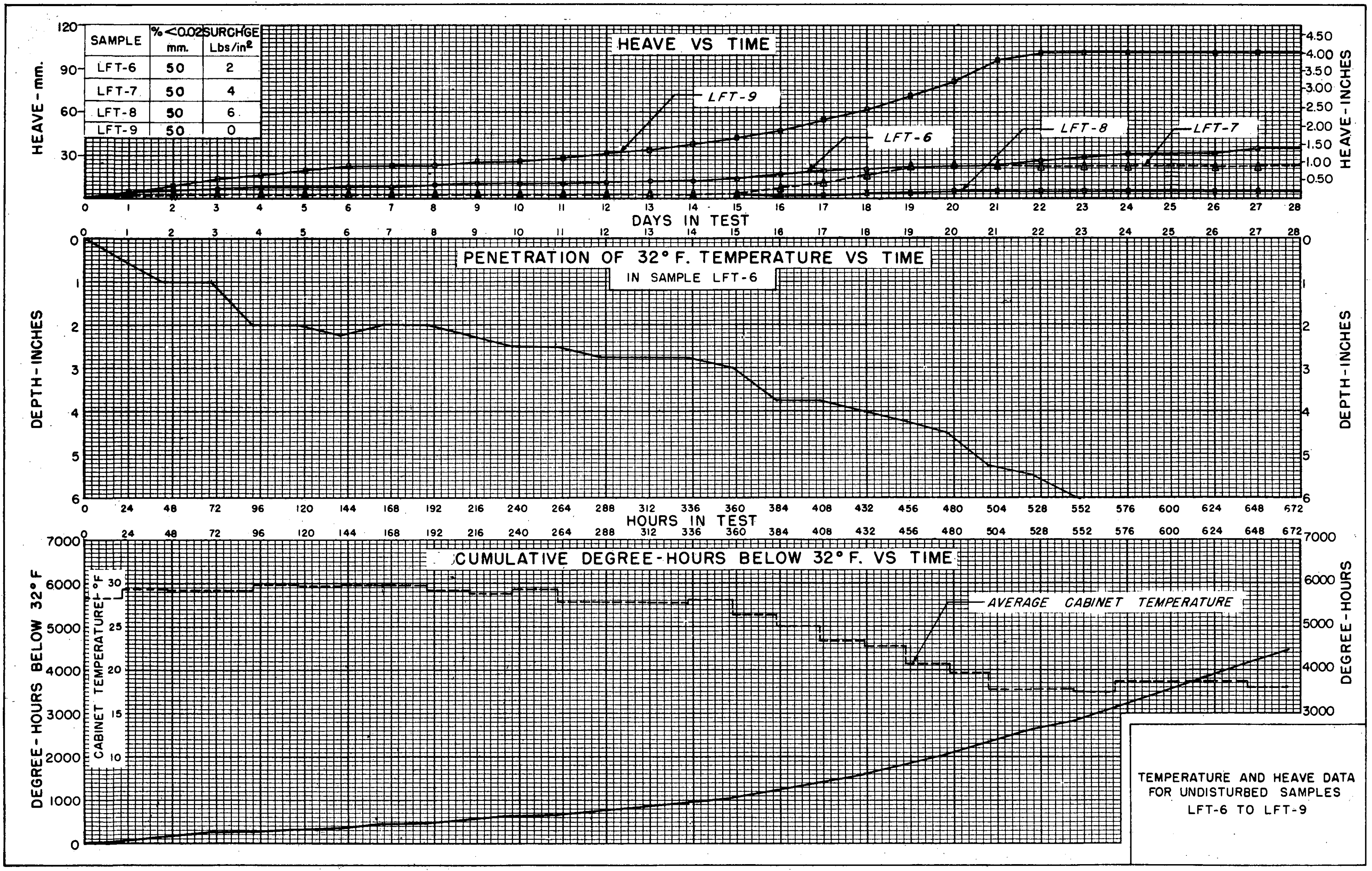
PLATE B3

PLATE B4



SAMPLE	%<0.02 mm.	DRY WT. lbs/ft^3
WASHO-5	65	96.0
WASHO-6	65	98.0
WASHO-7	65	98.9
WASHO-8	65	92.2
WASHO-9	65	90.0

TEMPERATURE AND HEAVE DATA
FOR
SAMPLES WASHO-5, 6, 7, 8 AND 9

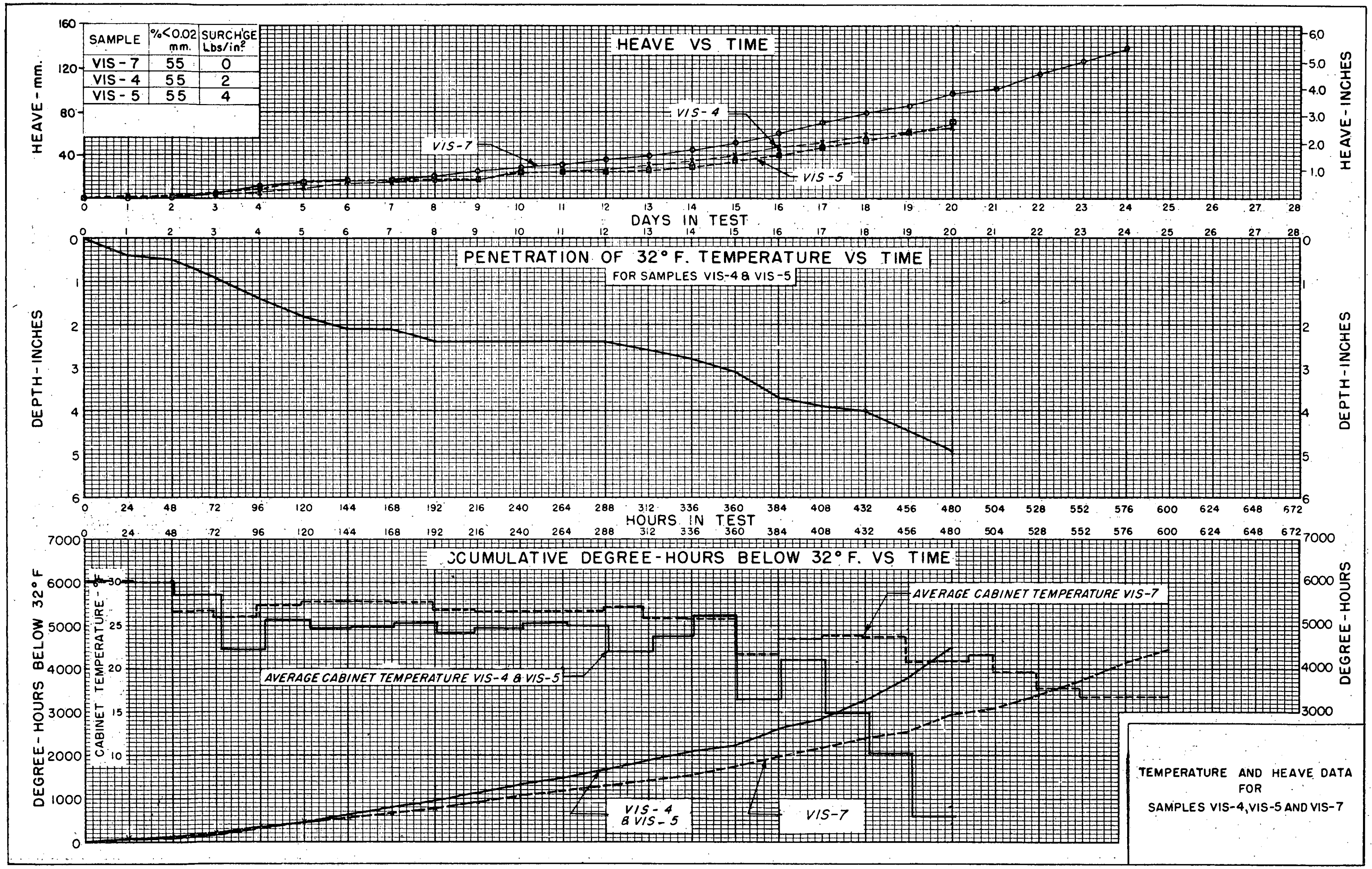


SAMPLE	% < 0.02 mm.	SURCHGE Lbs/in²
LFT-6	50	2
LFT-7	50	4
LFT-8	50	6
LFT-9	50	0

TEMPERATURE AND HEAVE DATA
FOR UNDISTURBED SAMPLES
LFT-6 TO LFT-9

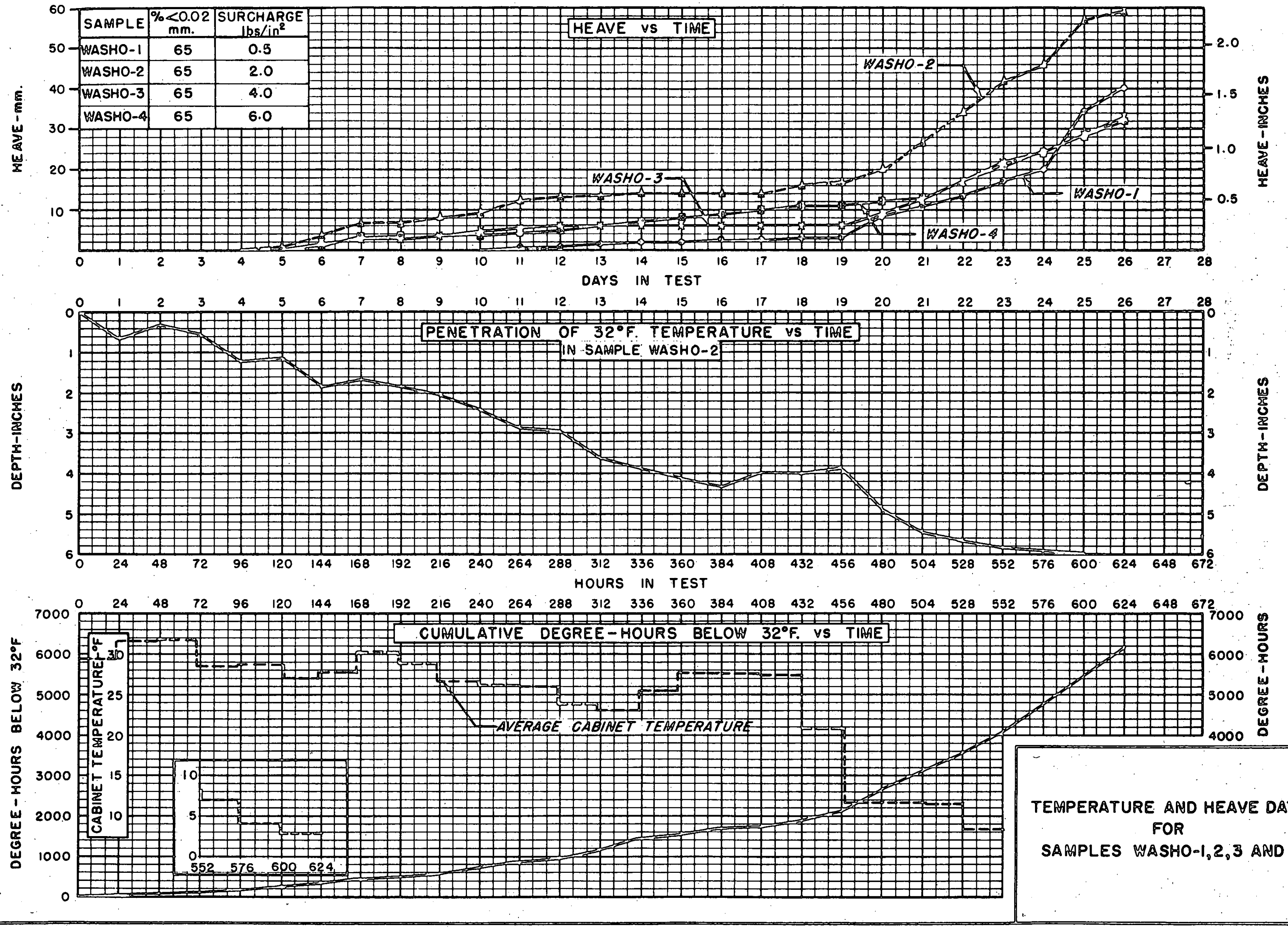
PLATE B5

PLATE B6



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES VIS-4, VIS-5 AND VIS-7

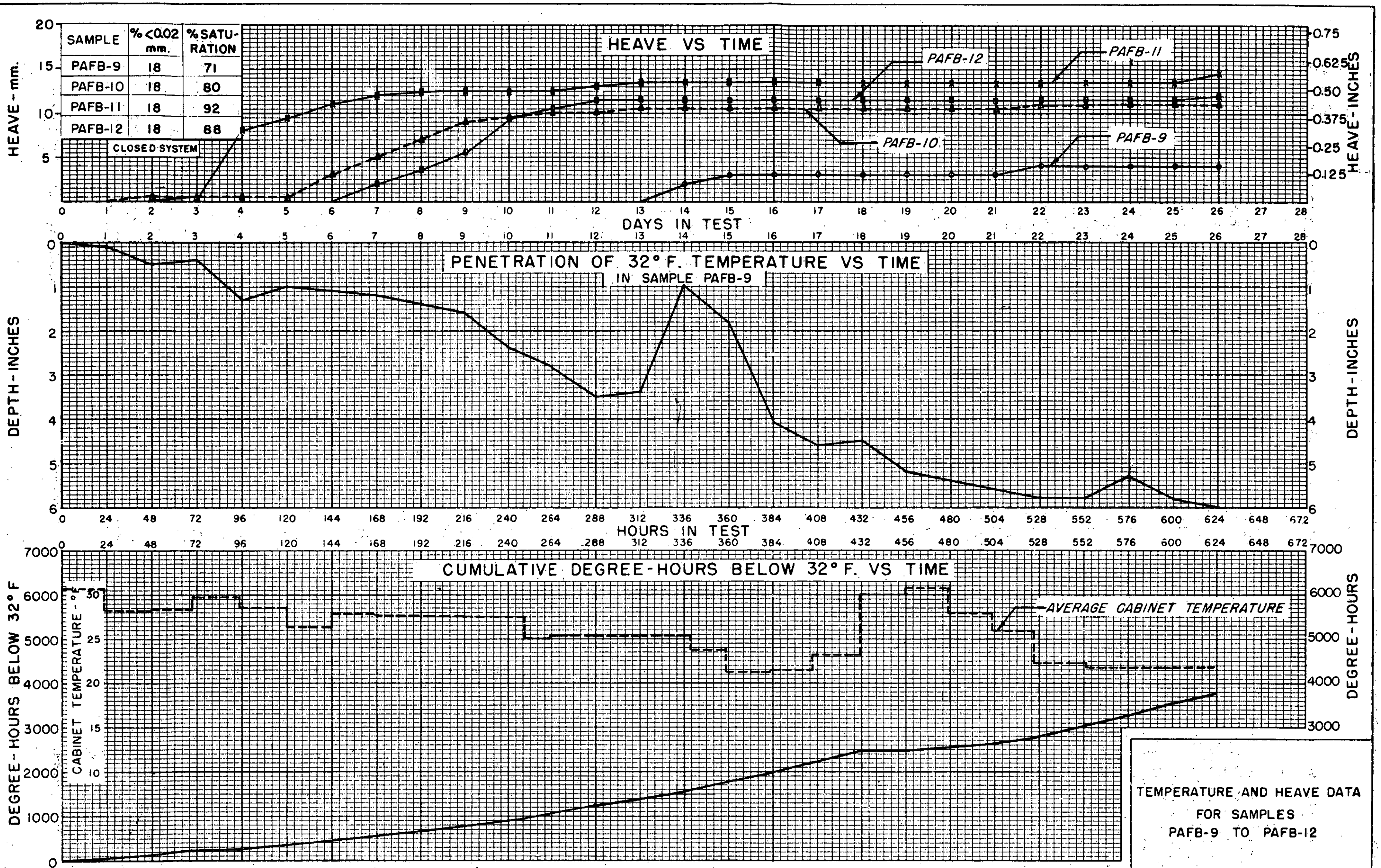
PLATE B7



SAMPLE	% < 0.02 mm.	SURCHARGE lbs/in²
WASHO-1	65	0.5
WASHO-2	65	2.0
WASHO-3	65	4.0
WASHO-4	65	6.0

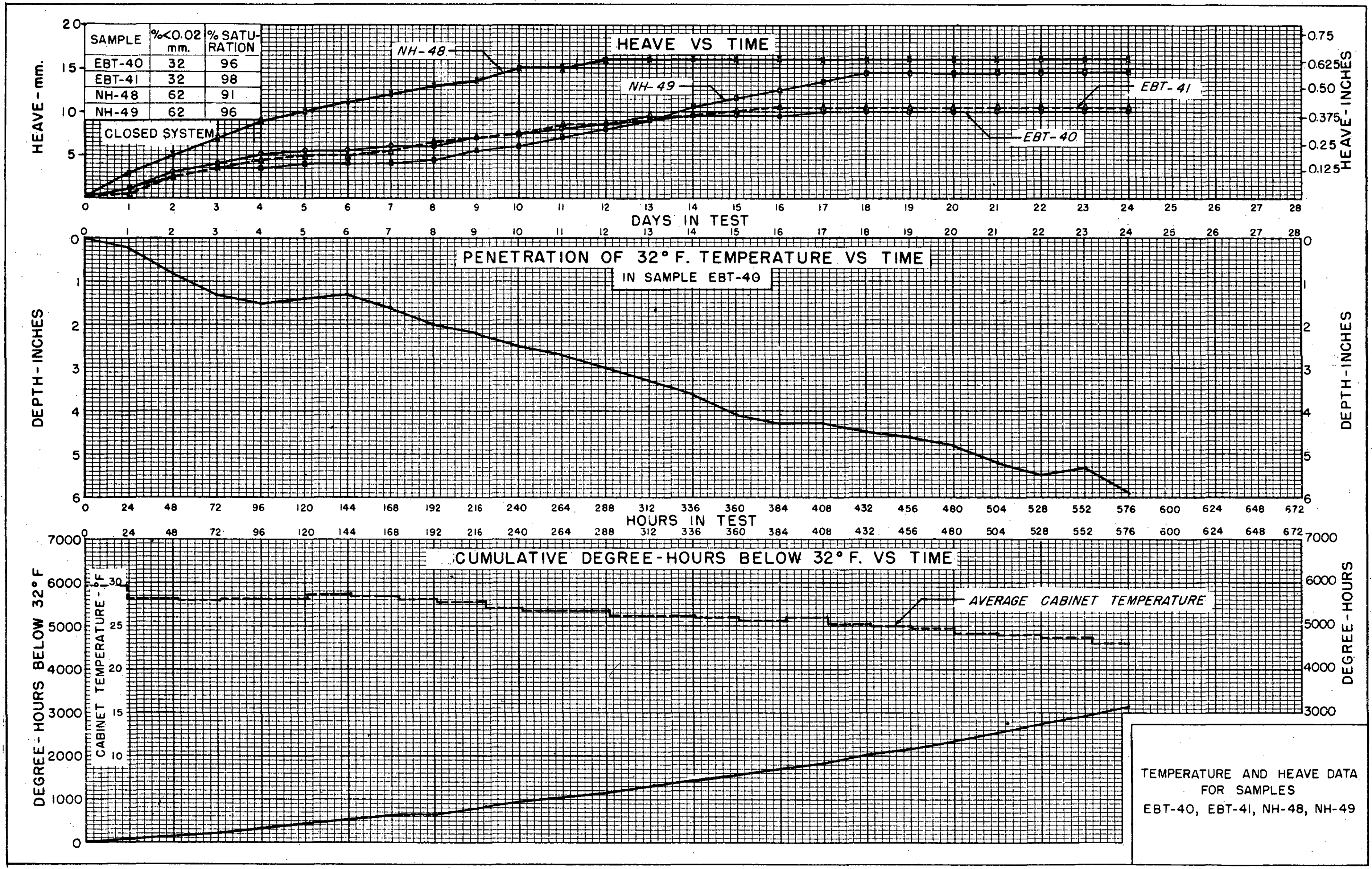
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES WASHO-1,2,3 AND 4

PLATE 88



SAMPLE	% < 0.02 mm.	% SATURATION
PAFB-9	18	71
PAFB-10	18	80
PAFB-11	18	92
PAFB-12	18	88

TEMPERATURE AND HEAVE DATA
FOR SAMPLES
PAFB-9 TO PAFB-12

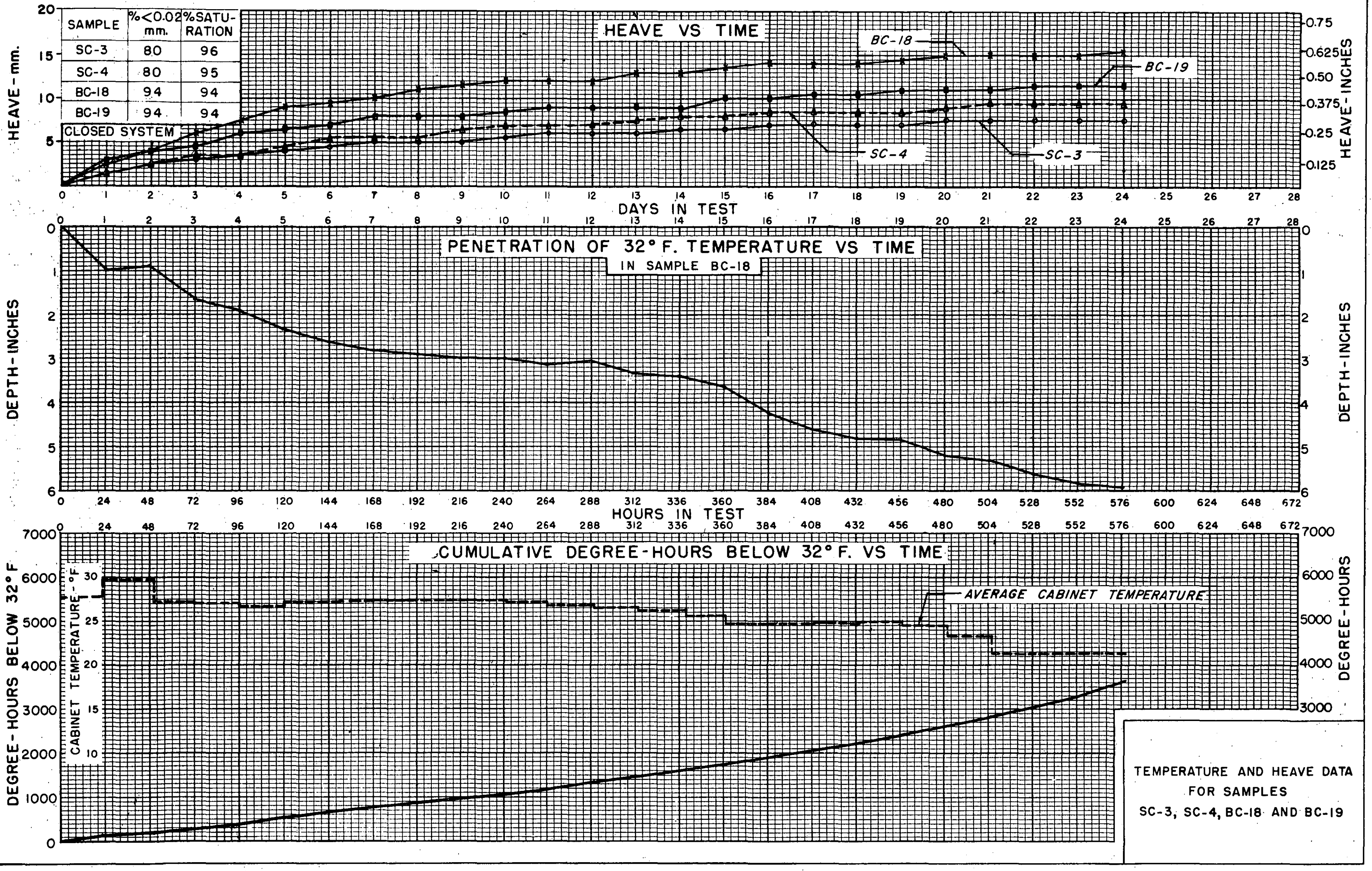


SAMPLE	%<0.02 mm.	% SATURATION
EBT-40	32	96
EBT-41	32	98
NH-48	62	91
NH-49	62	96

TEMPERATURE AND HEAVE DATA
FOR SAMPLES
EBT-40, EBT-41, NH-48, NH-49

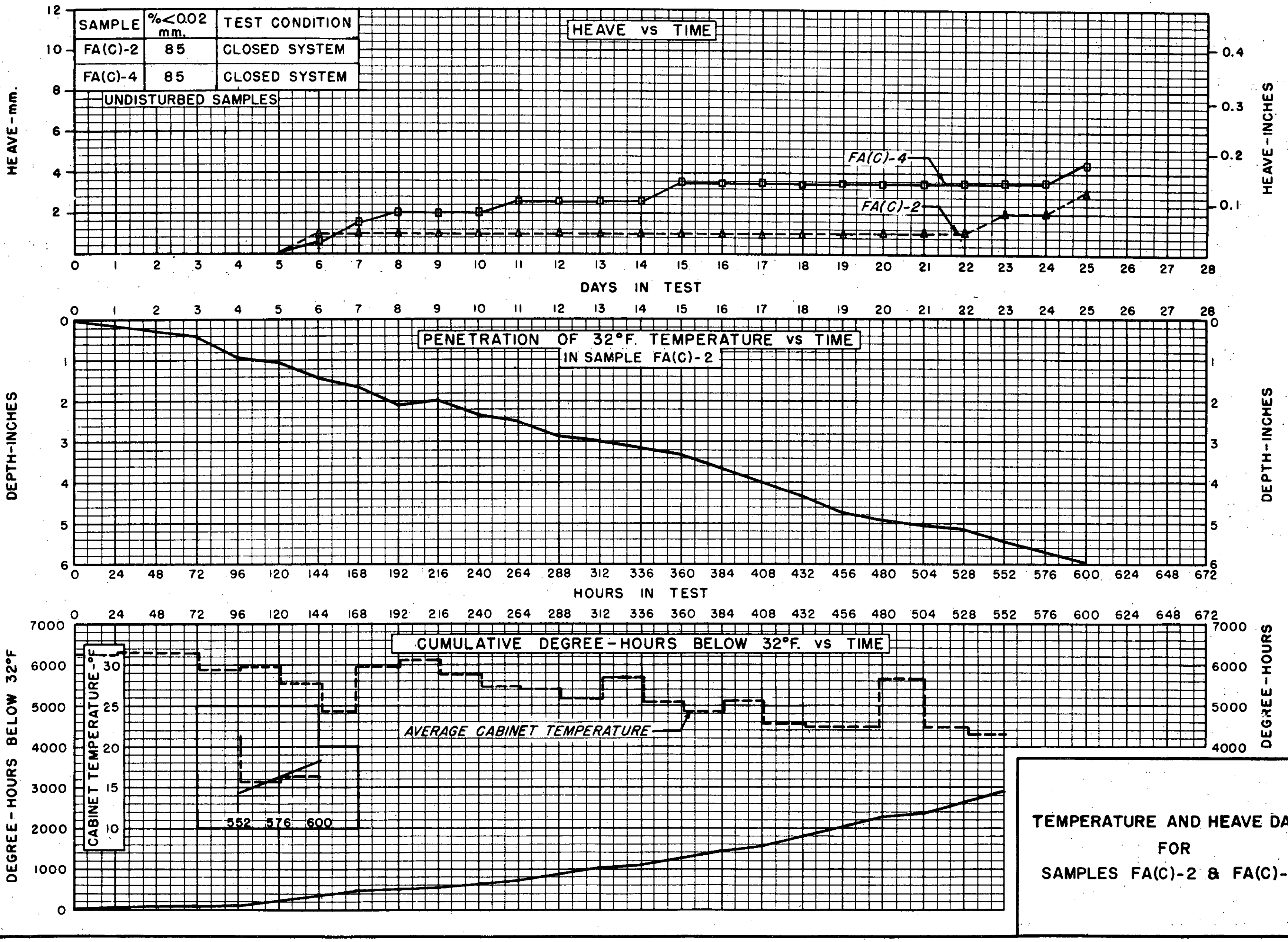
PLATE B9

PLATE B10



SAMPLE	% < 0.02 mm.	% SATURATION
SC-3	80	96
SC-4	80	95
BC-18	94	94
BC-19	94	94

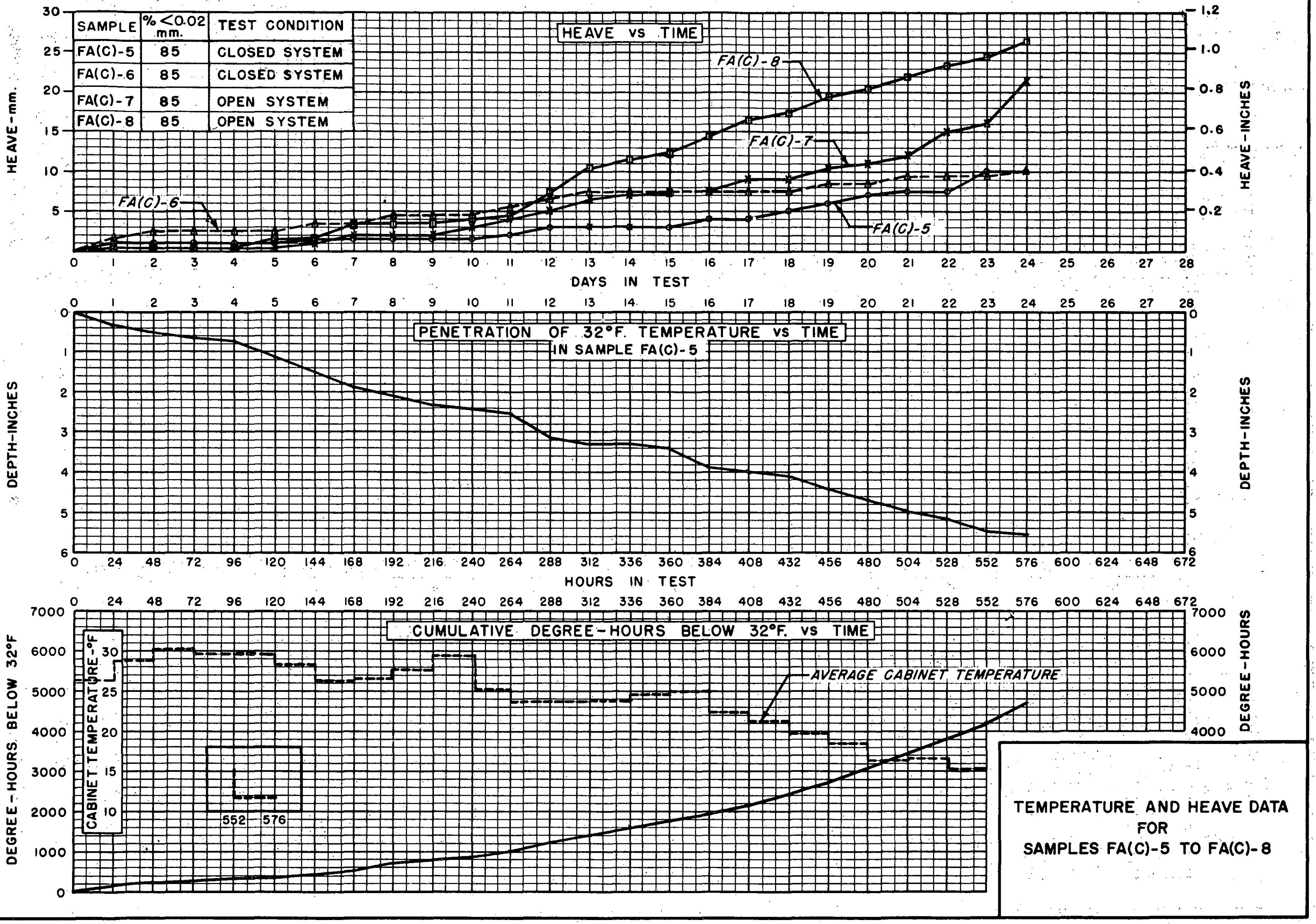
TEMPERATURE AND HEAVE DATA
FOR SAMPLES
SC-3, SC-4, BC-18 AND BC-19



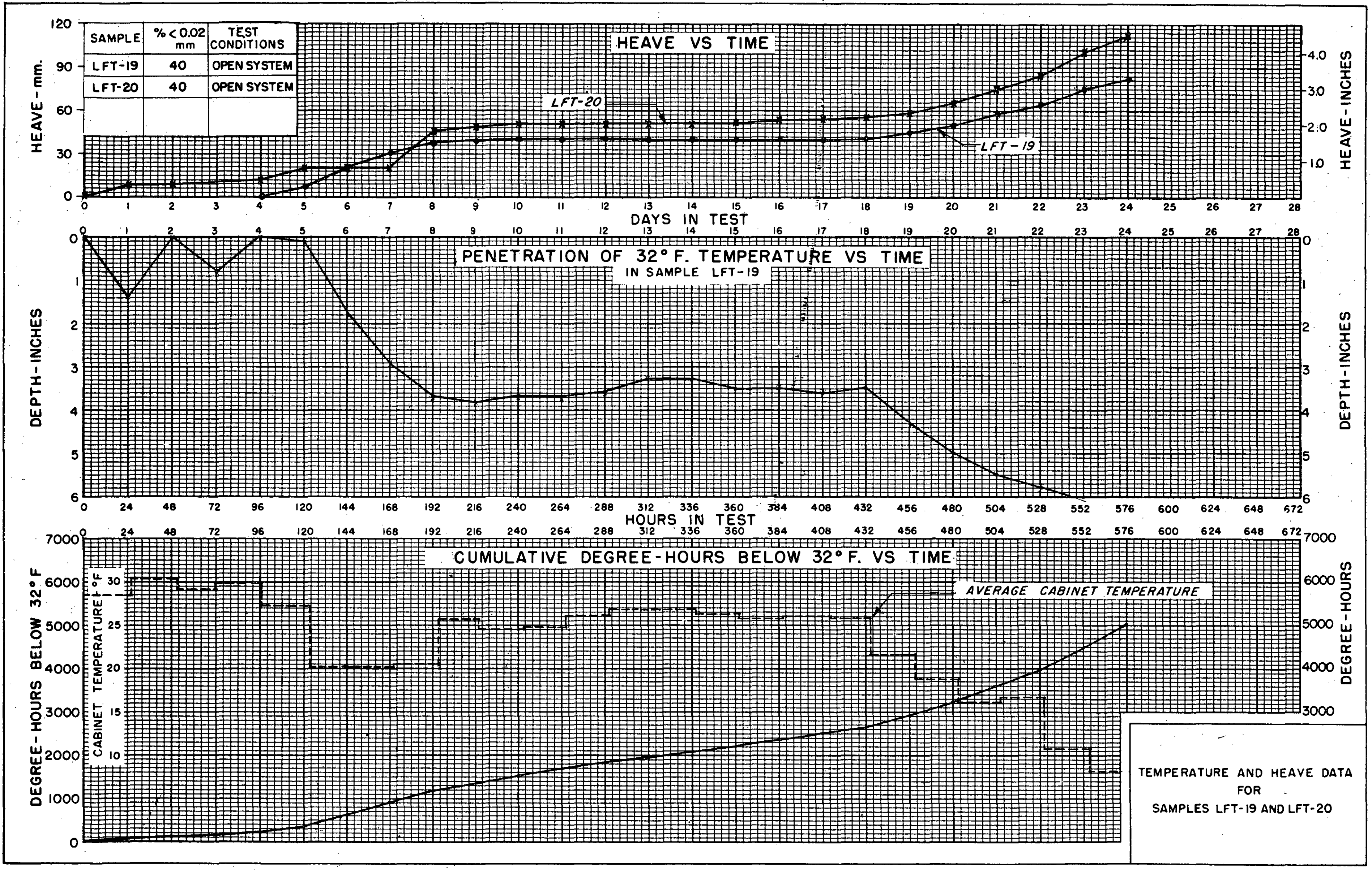
TEMPERATURE AND HEAVE DATA FOR SAMPLES FA(C)-2 & FA(C)-4

PLATE B11

PLATE B12



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES FA(C)-5 TO FA(C)-8

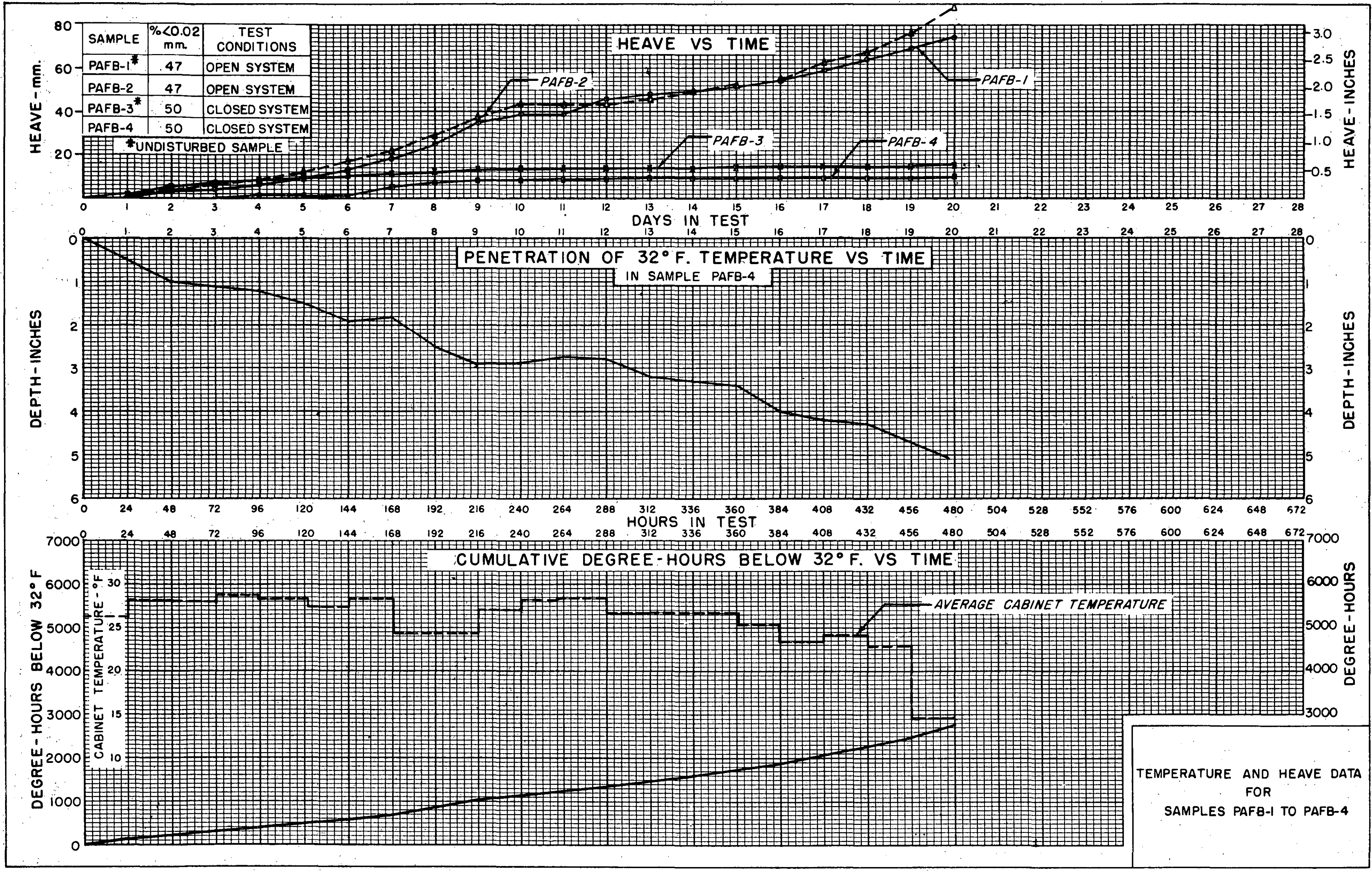


SAMPLE	% < 0.02 mm	TEST CONDITIONS
LFT-19	40	OPEN SYSTEM
LFT-20	40	OPEN SYSTEM

TEMPERATURE AND HEAVE DATA
FOR
SAMPLES LFT-19 AND LFT-20

PLATE B13

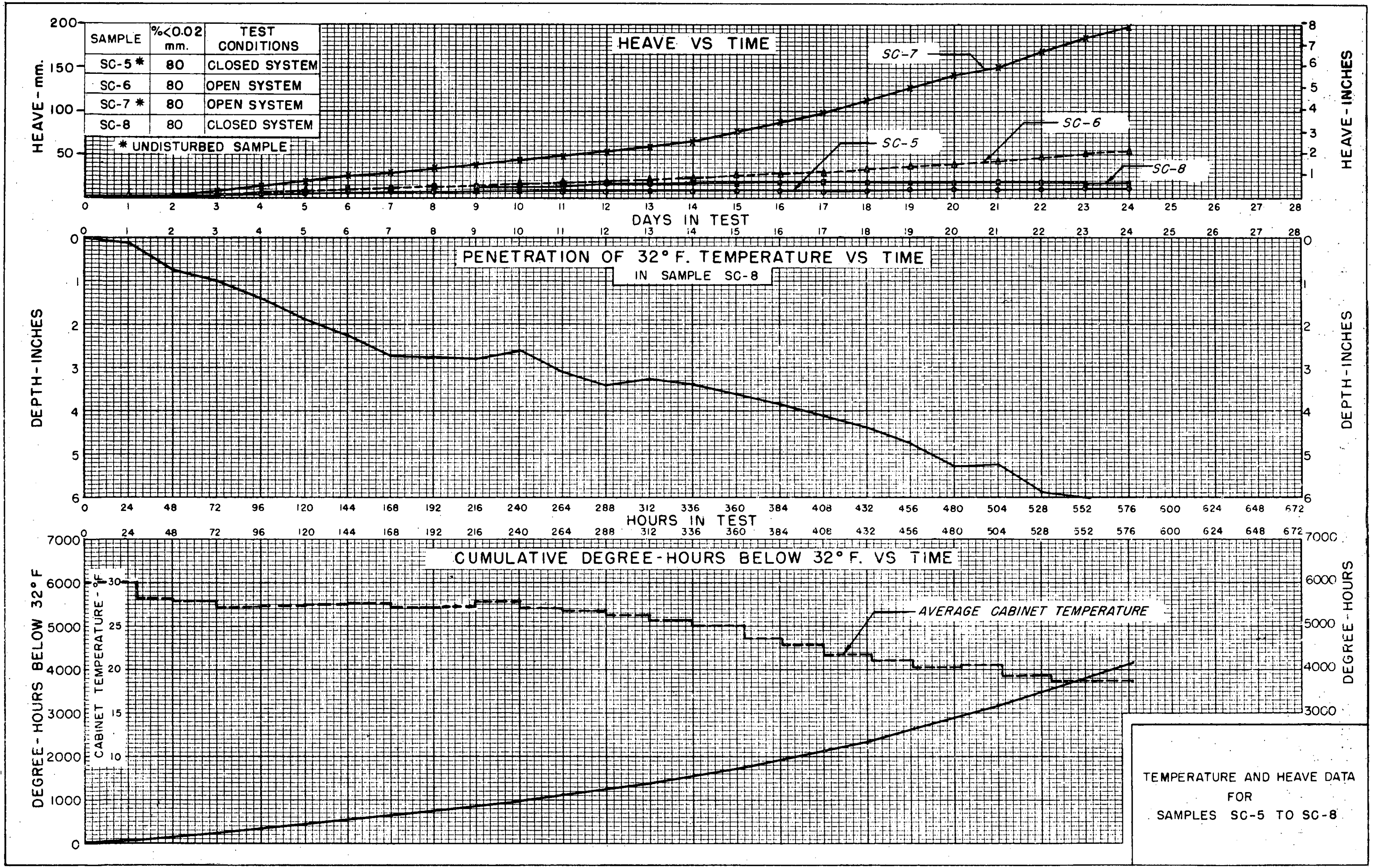
PLATE B14



SAMPLE	%<0.02 mm.	TEST CONDITIONS
PAFB-1*	47	OPEN SYSTEM
PAFB-2	47	OPEN SYSTEM
PAFB-3*	50	CLOSED SYSTEM
PAFB-4	50	CLOSED SYSTEM

*UNDISTURBED SAMPLE

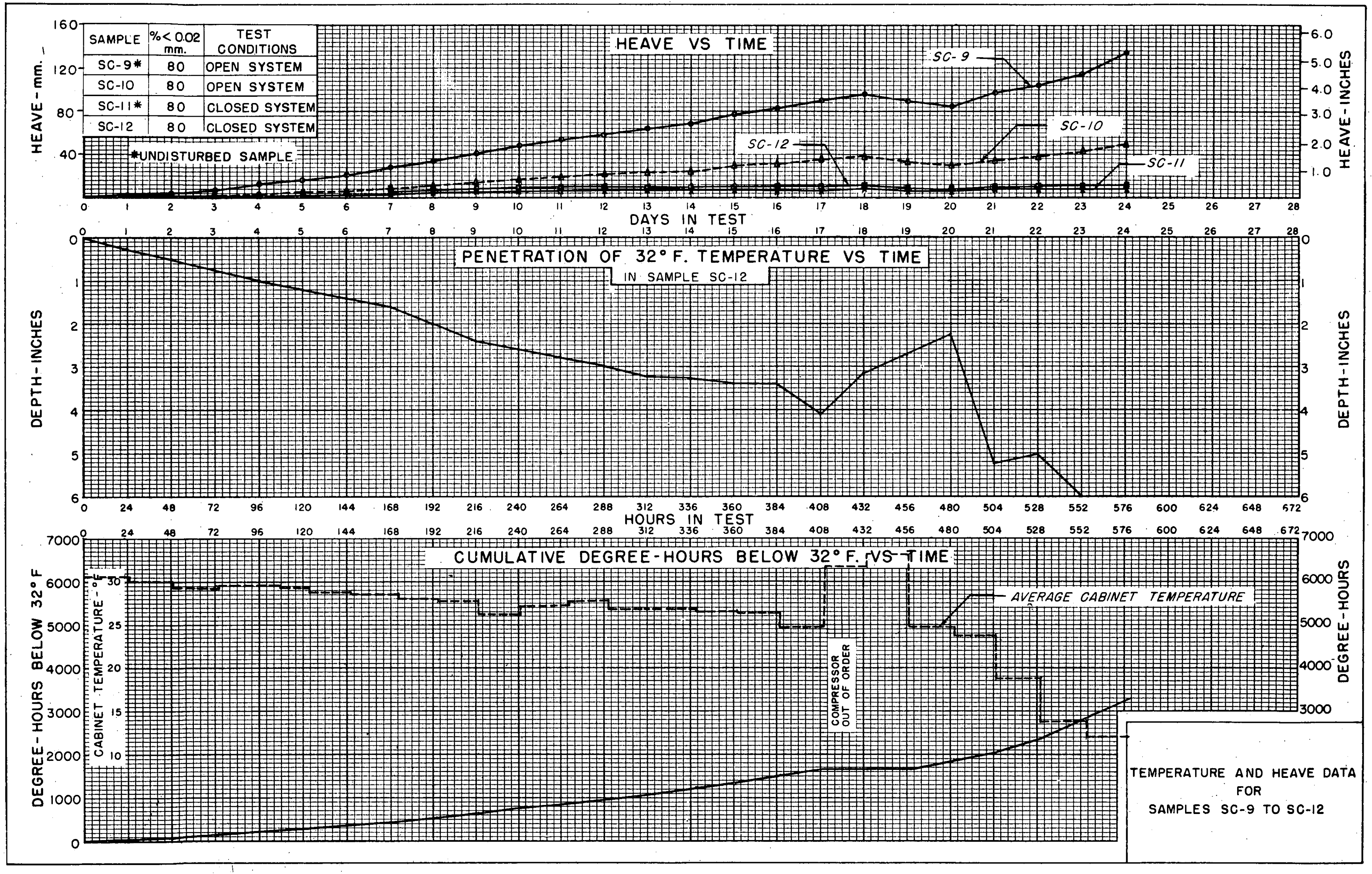
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES PAFB-1 TO PAFB-4



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES SC-5 TO SC-8

PLATE B15

PLATE B16

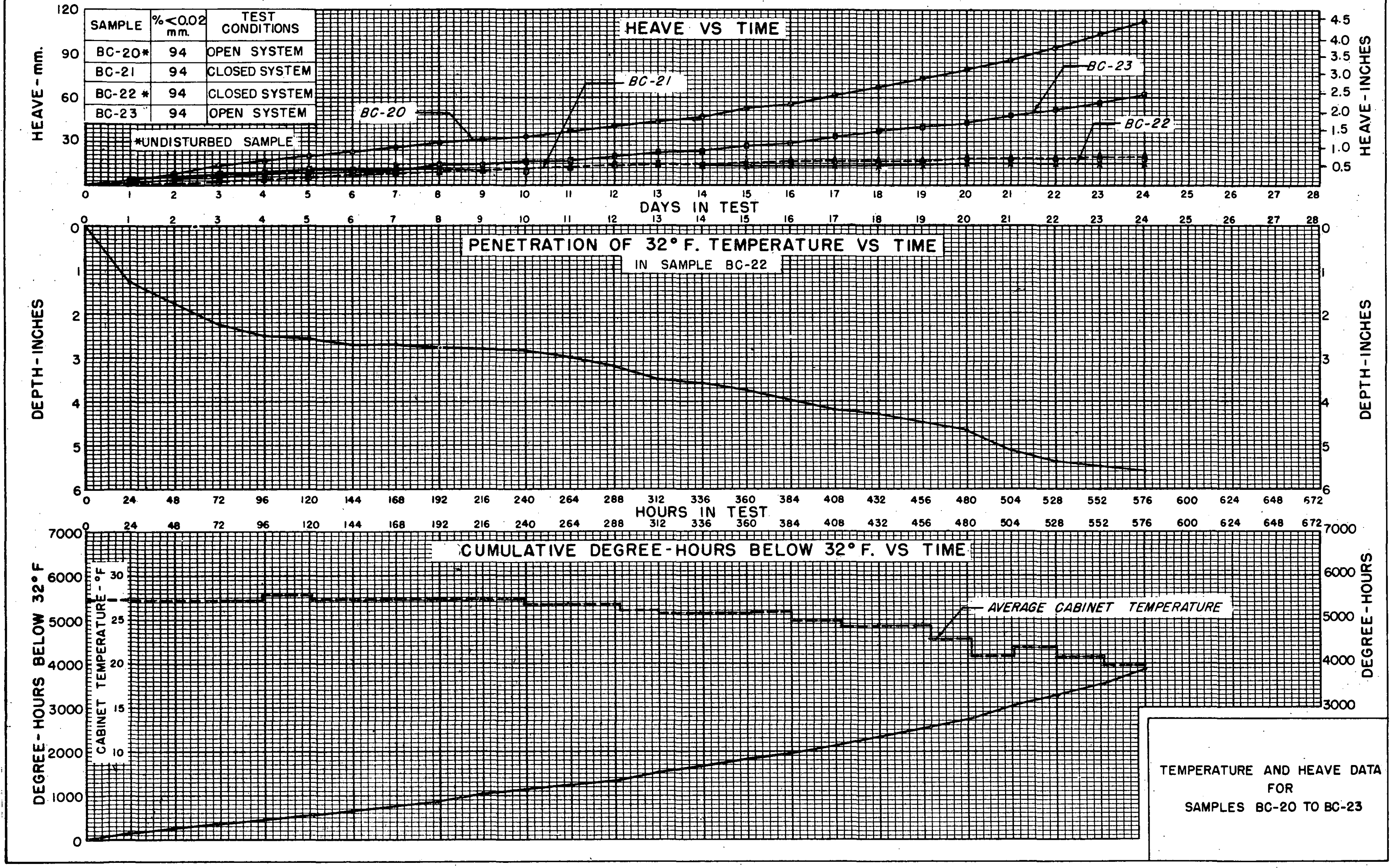


SAMPLE	%< 0.02 mm.	TEST CONDITIONS
SC-9*	80	OPEN SYSTEM
SC-10	80	OPEN SYSTEM
SC-11*	80	CLOSED SYSTEM
SC-12	80	CLOSED SYSTEM

*UNDISTURBED SAMPLE

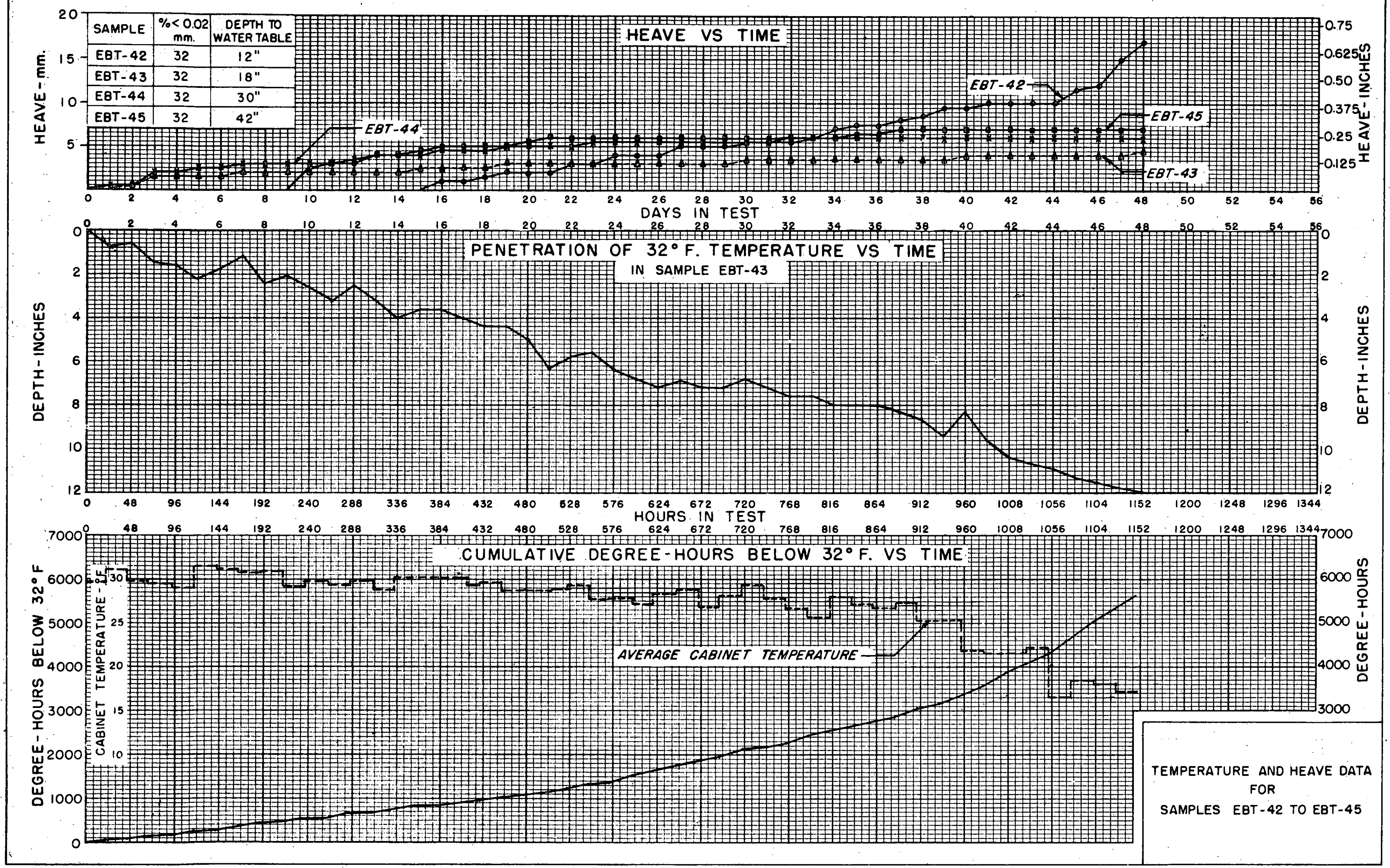
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES SC-9 TO SC-12

PLATE B17



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES BC-20 TO BC-23

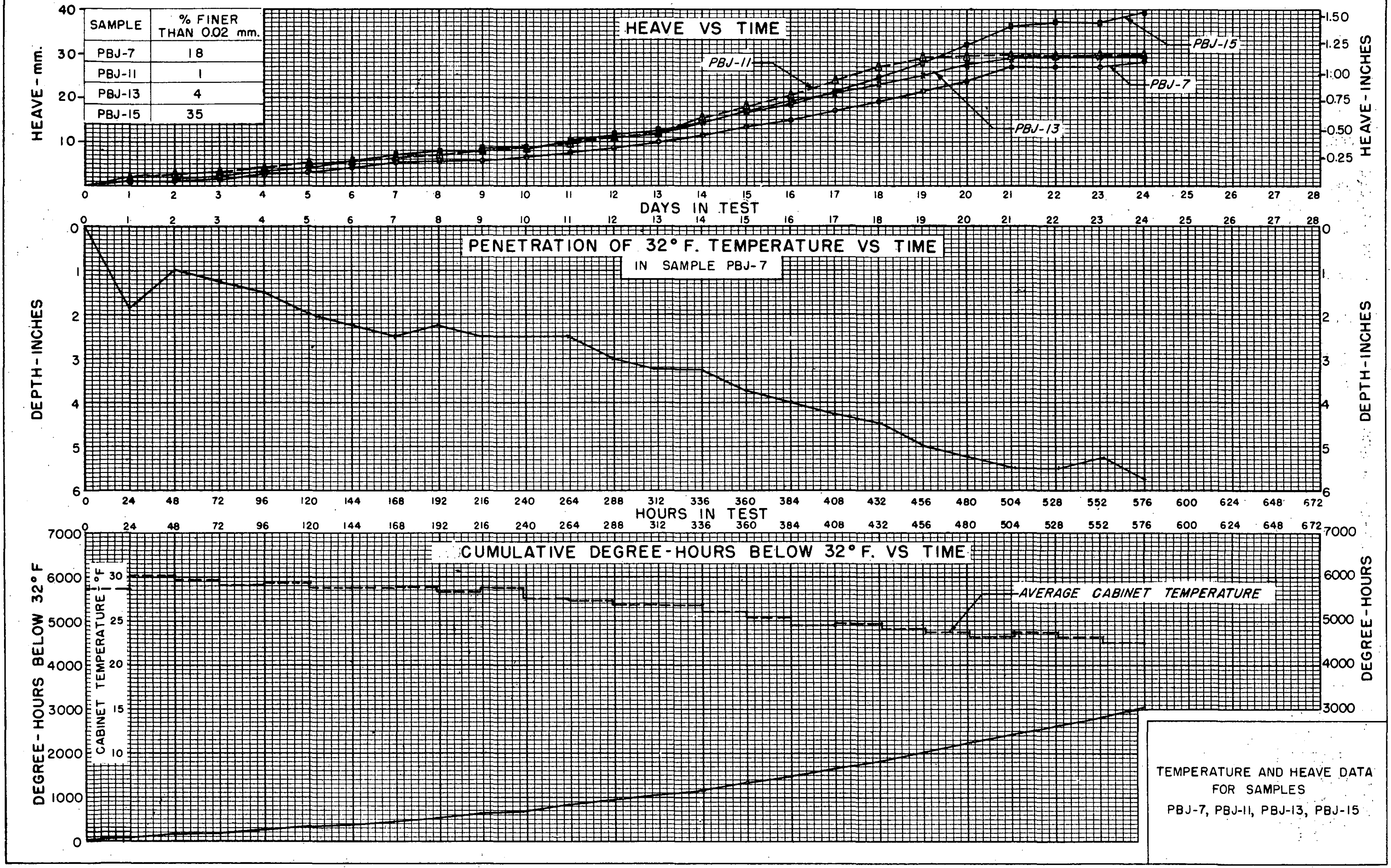
PLATE B18



SAMPLE	%< 0.02 mm.	DEPTH TO WATER TABLE
EBT-42	32	12"
EBT-43	32	18"
EBT-44	32	30"
EBT-45	32	42"

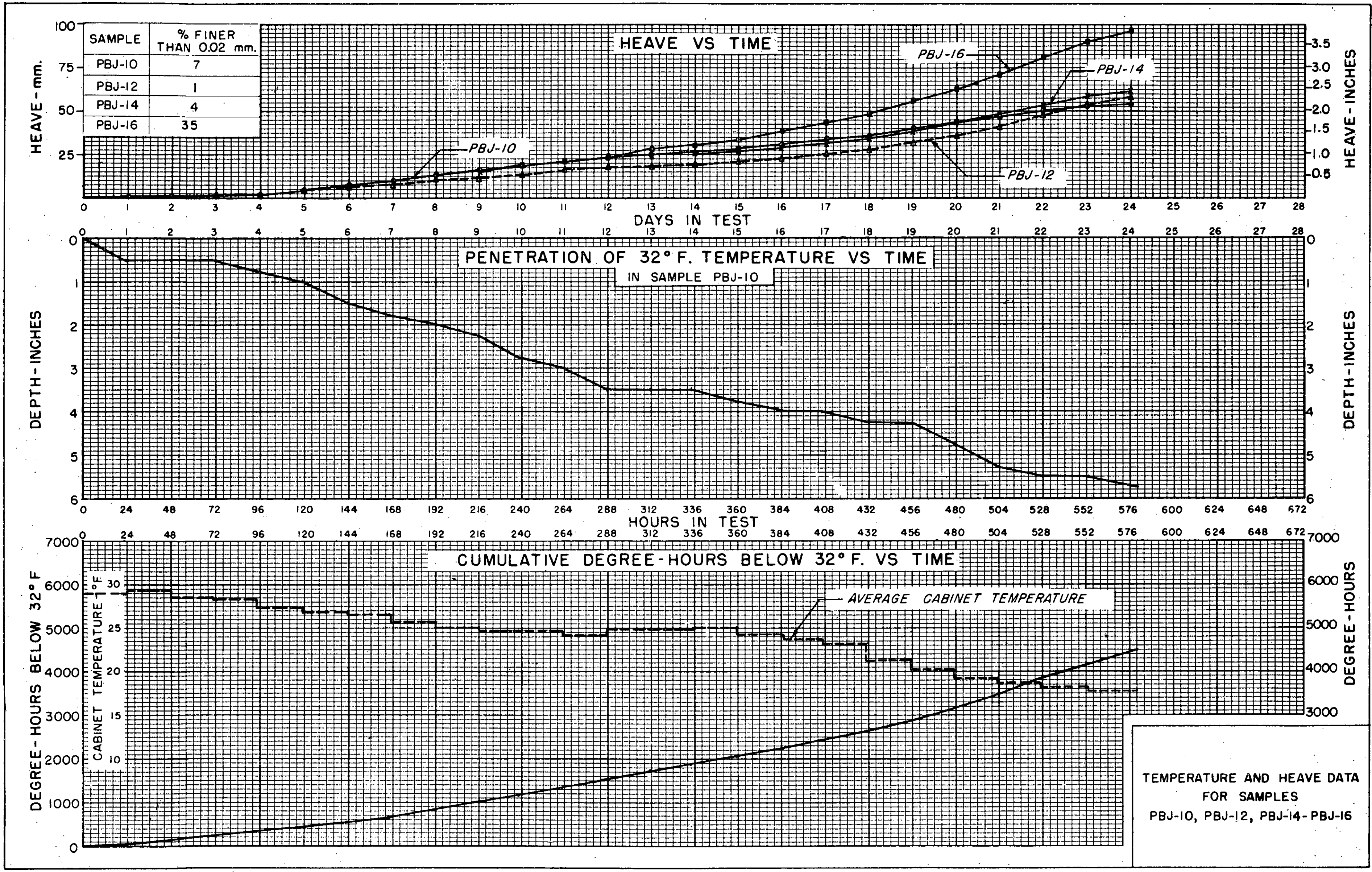
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES EBT-42 TO EBT-45

PLATE B19



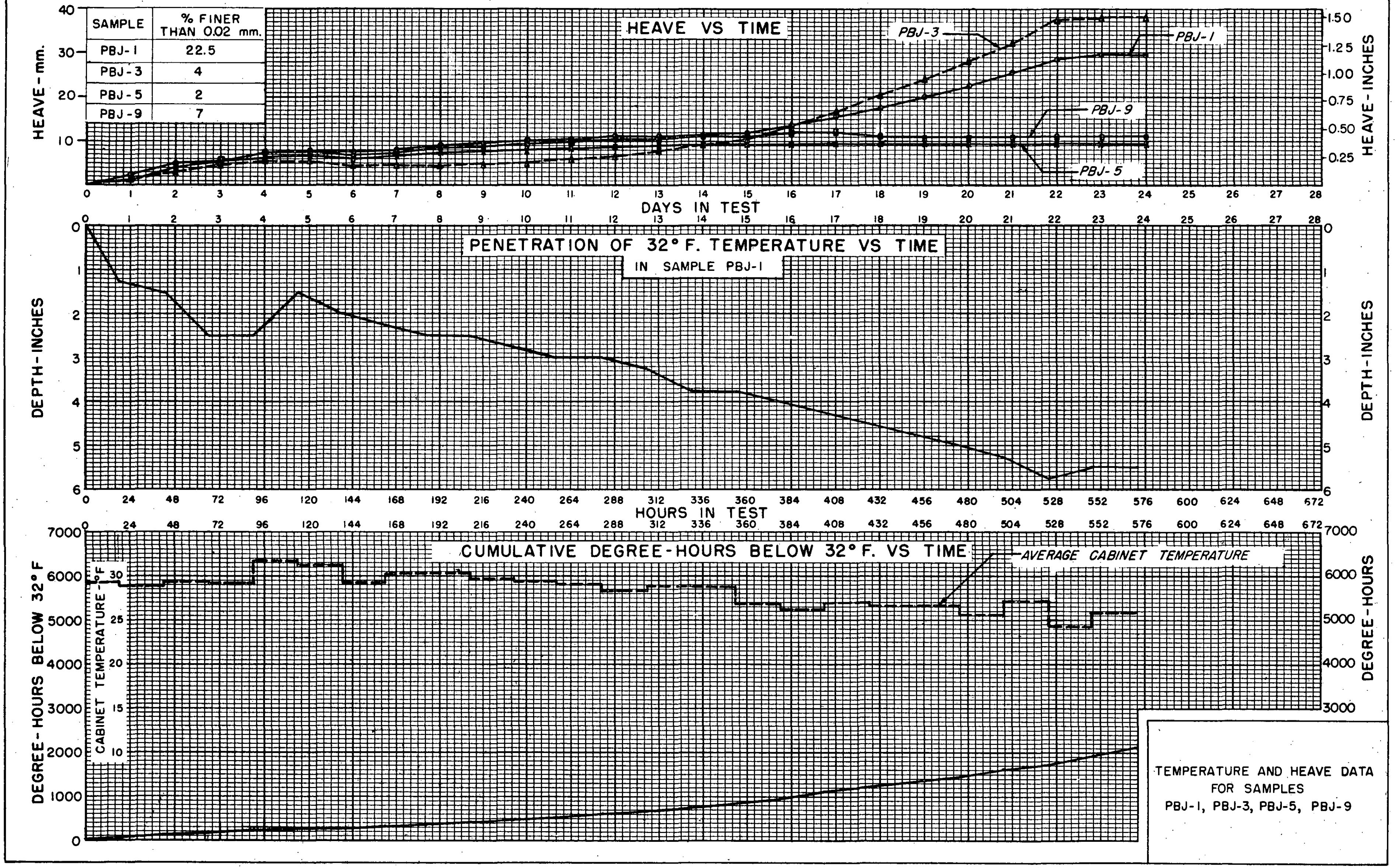
TEMPERATURE AND HEAVE DATA
FOR SAMPLES
PBJ-7, PBJ-11, PBJ-13, PBJ-15

PLATE B 20



SAMPLE	% FINER THAN 0.02 mm.
PBJ-10	7
PBJ-12	1
PBJ-14	4
PBJ-16	35

TEMPERATURE AND HEAVE DATA
FOR SAMPLES
PBJ-10, PBJ-12, PBJ-14 - PBJ-16

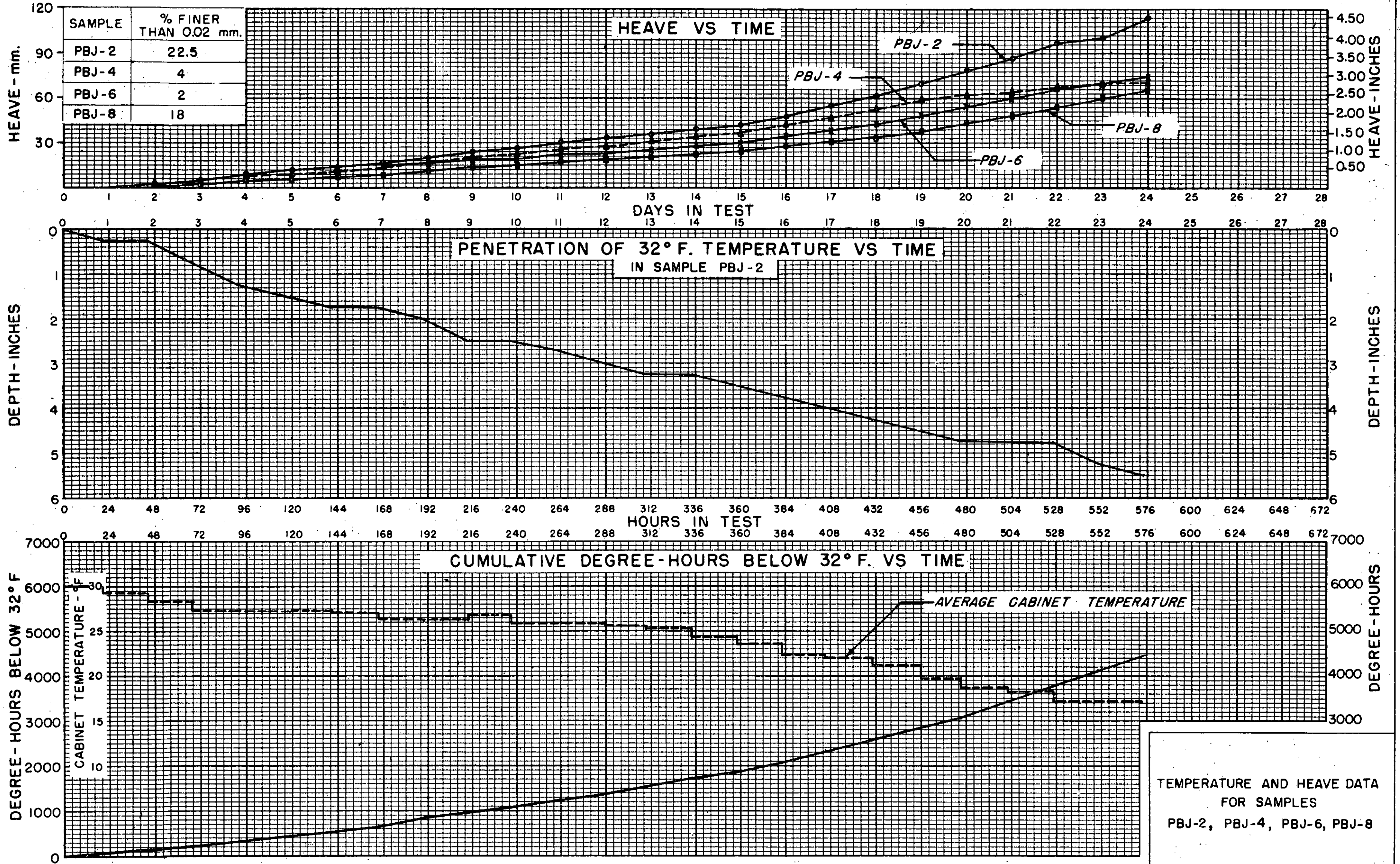


SAMPLE	% FINER THAN 0.02 mm.
PBJ-1	22.5
PBJ-3	4
PBJ-5	2
PBJ-9	7

TEMPERATURE AND HEAVE DATA
FOR SAMPLES
PBJ-1, PBJ-3, PBJ-5, PBJ-9

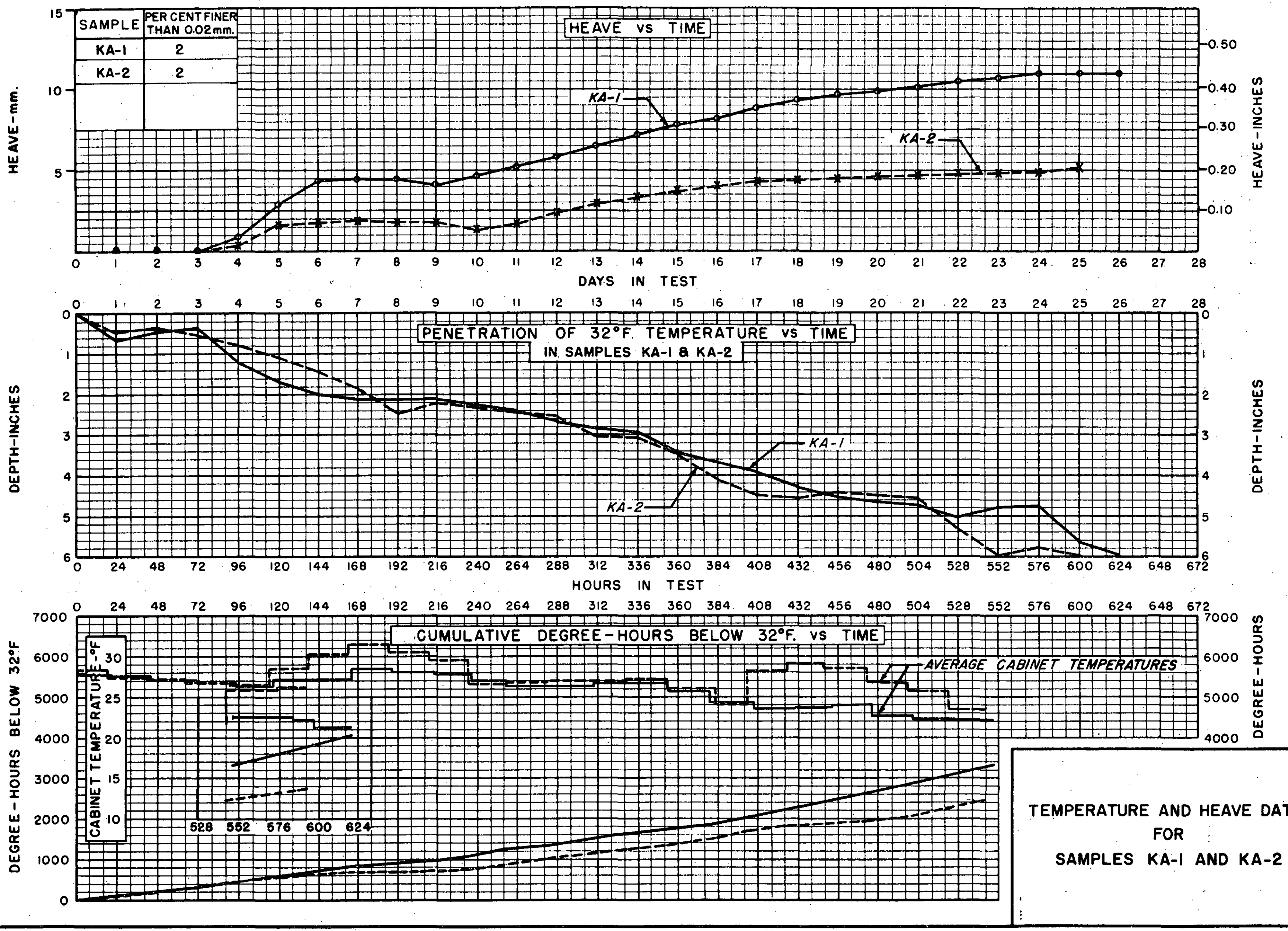
PLATE B 21

PLATE B 22



SAMPLE	% FINER THAN 0.02 mm.
PBJ-2	22.5
PBJ-4	4
PBJ-6	2
PBJ-8	18

TEMPERATURE AND HEAVE DATA
FOR SAMPLES
PBJ-2, PBJ-4, PBJ-6, PBJ-8

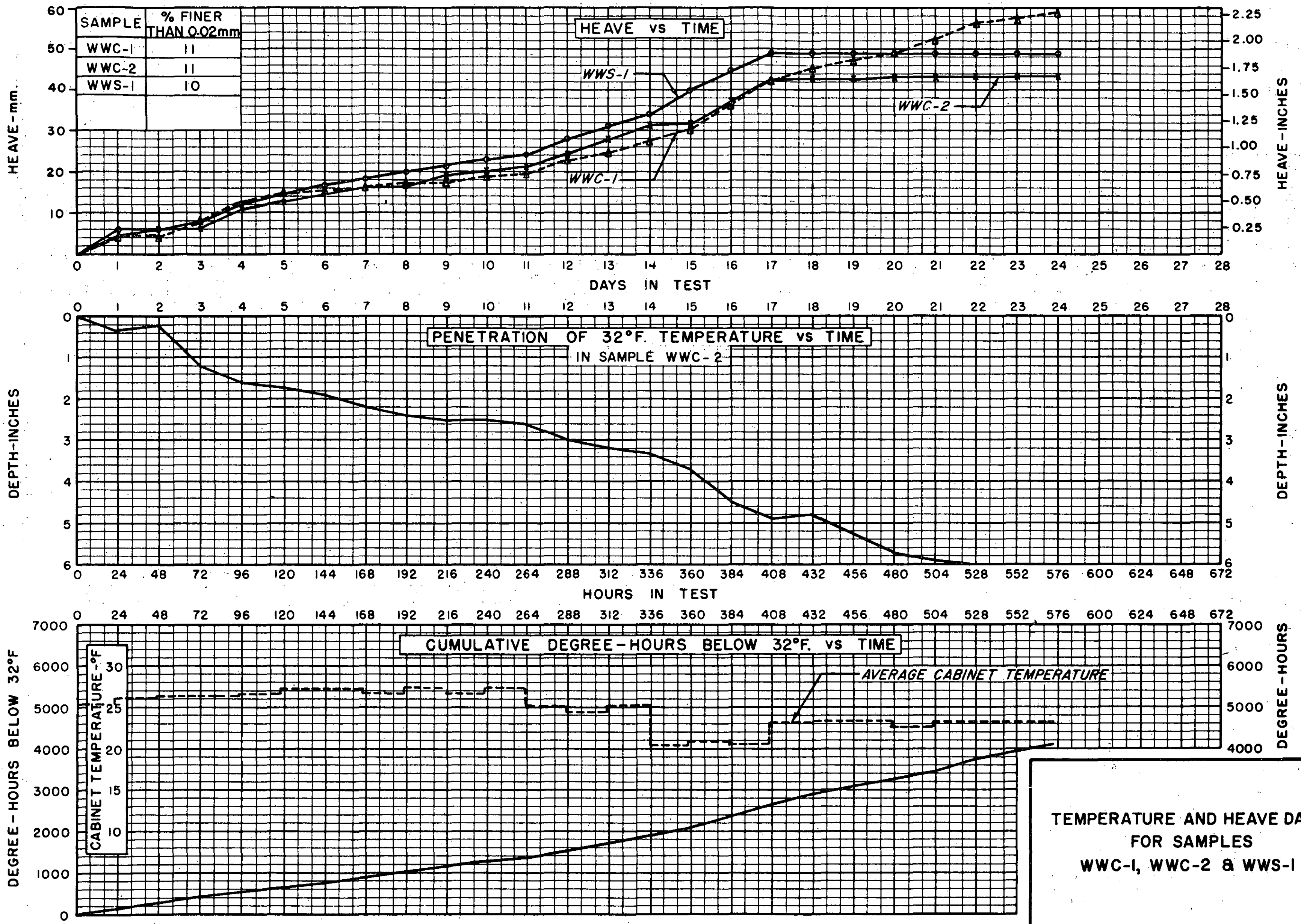


SAMPLE	PER CENT FINER THAN 0.02 mm.
KA-1	2
KA-2	2

TEMPERATURE AND HEAVE DATA
FOR
SAMPLES KA-1 AND KA-2

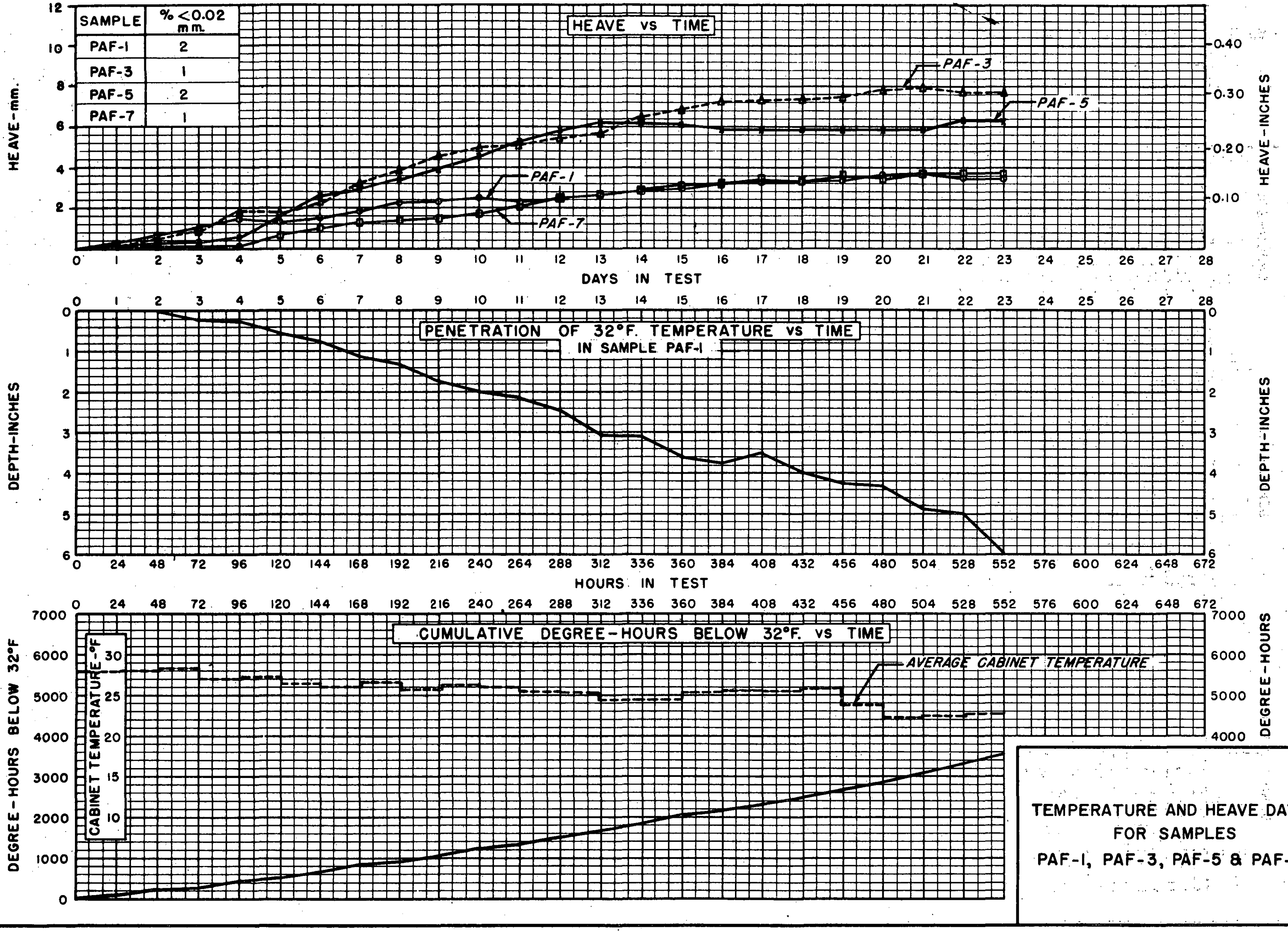
PLATE B23

PLATE B24



SAMPLE	% FINER THAN 0.02mm
WWC-1	11
WWC-2	11
WWS-1	10

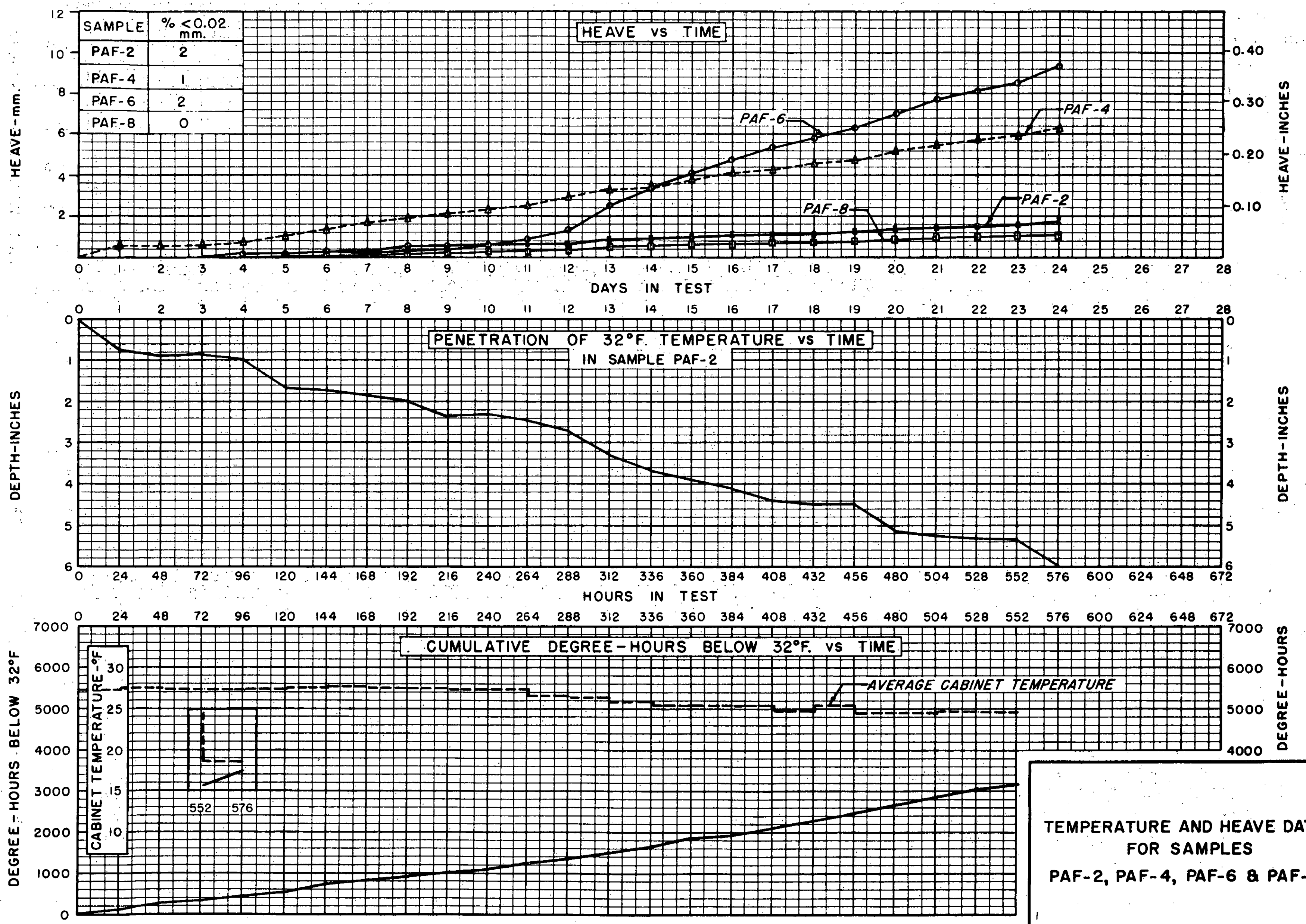
TEMPERATURE AND HEAVE DATA
FOR SAMPLES
WWC-1, WWC-2 & WWS-1



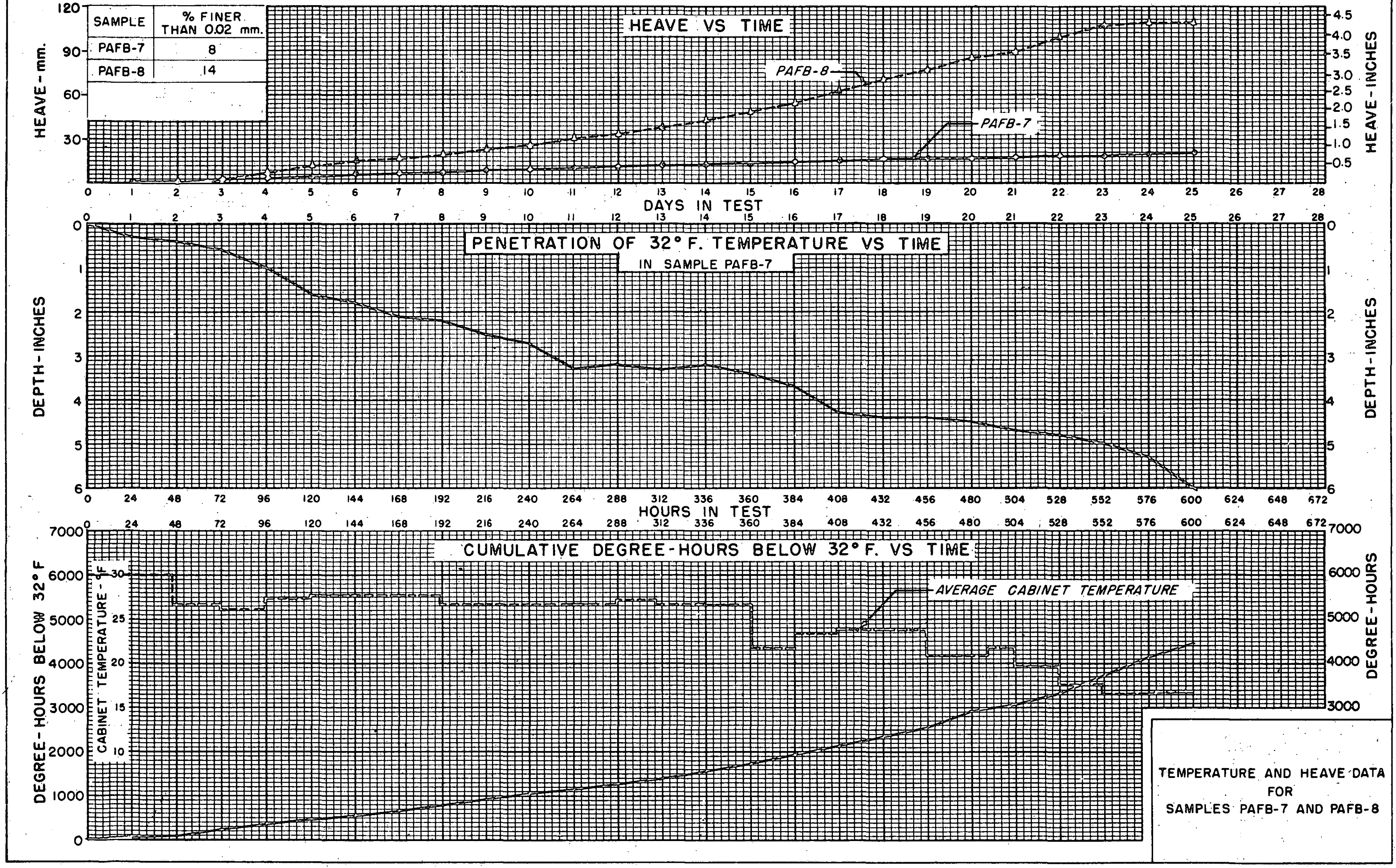
TEMPERATURE AND HEAVE DATA FOR SAMPLES PAF-1, PAF-3, PAF-5 & PAF-7

PLATE B25

PLATE B 26

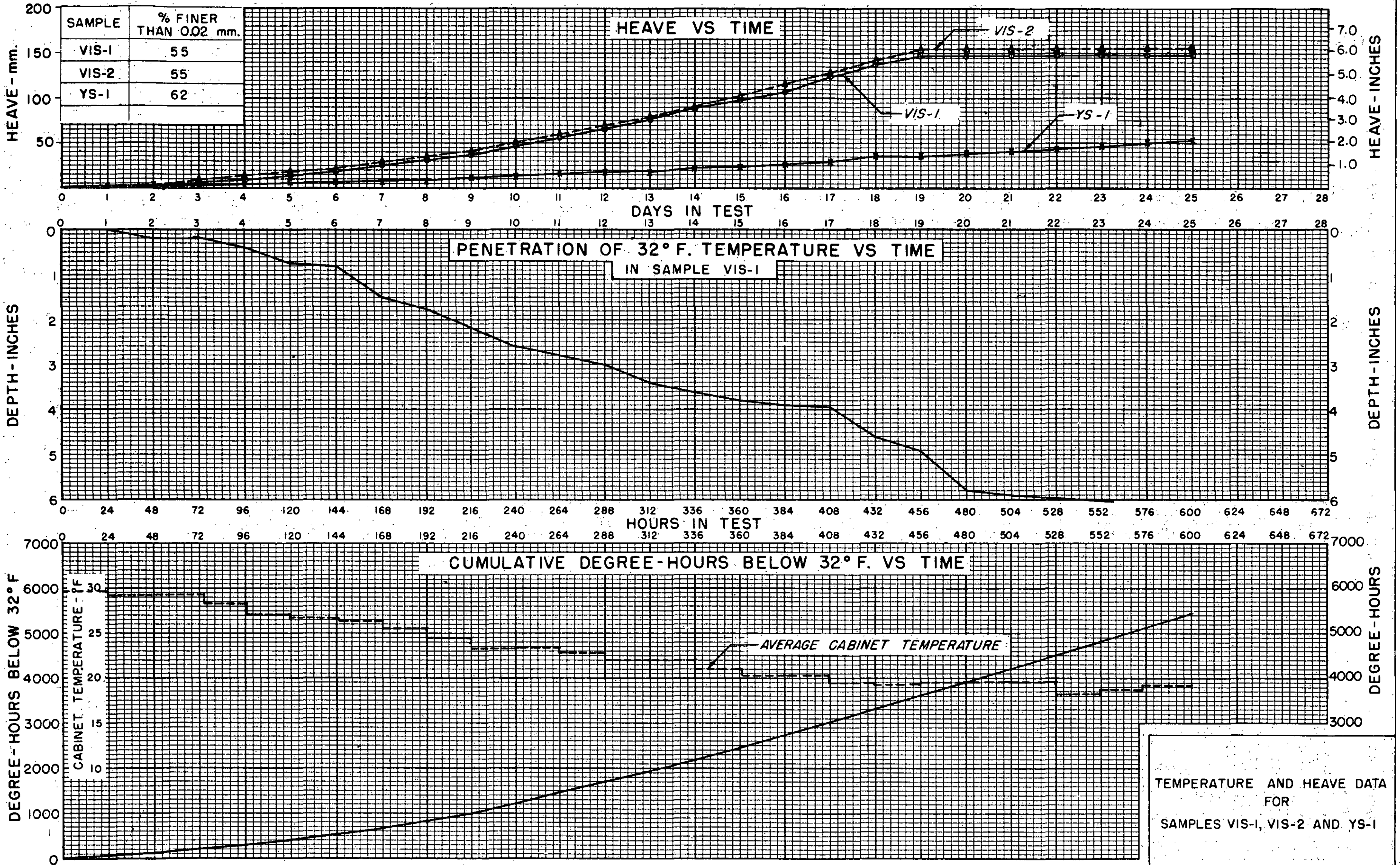


TEMPERATURE AND HEAVE DATA FOR SAMPLES PAF-2, PAF-4, PAF-6 & PAF-8



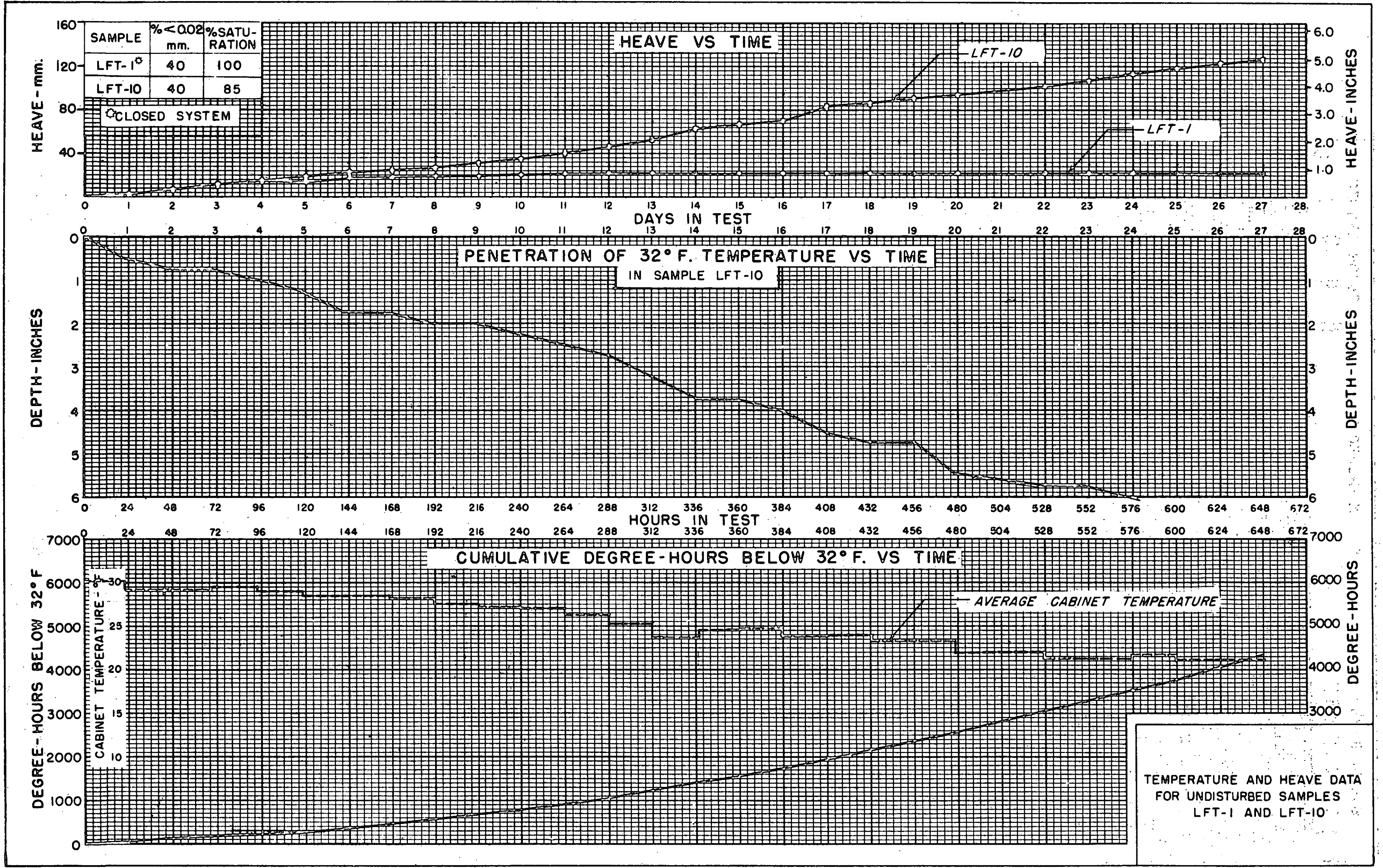
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES PAFB-7 AND PAFB-8

PLATE B 27



SAMPLE	% FINER THAN 0.02 mm.
VIS-1	55
VIS-2	55
YS-1	62

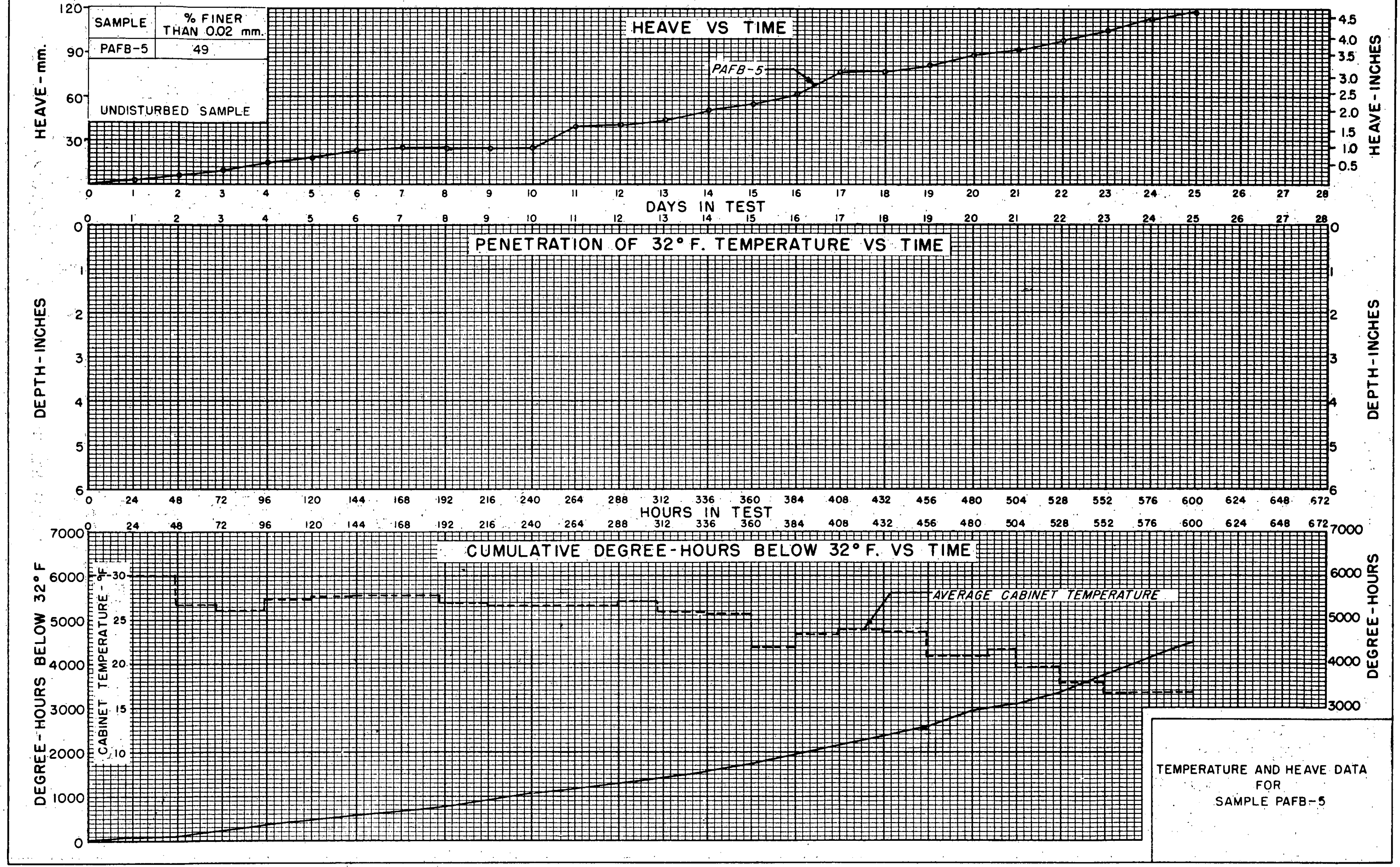
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES VIS-1, VIS-2 AND YS-1



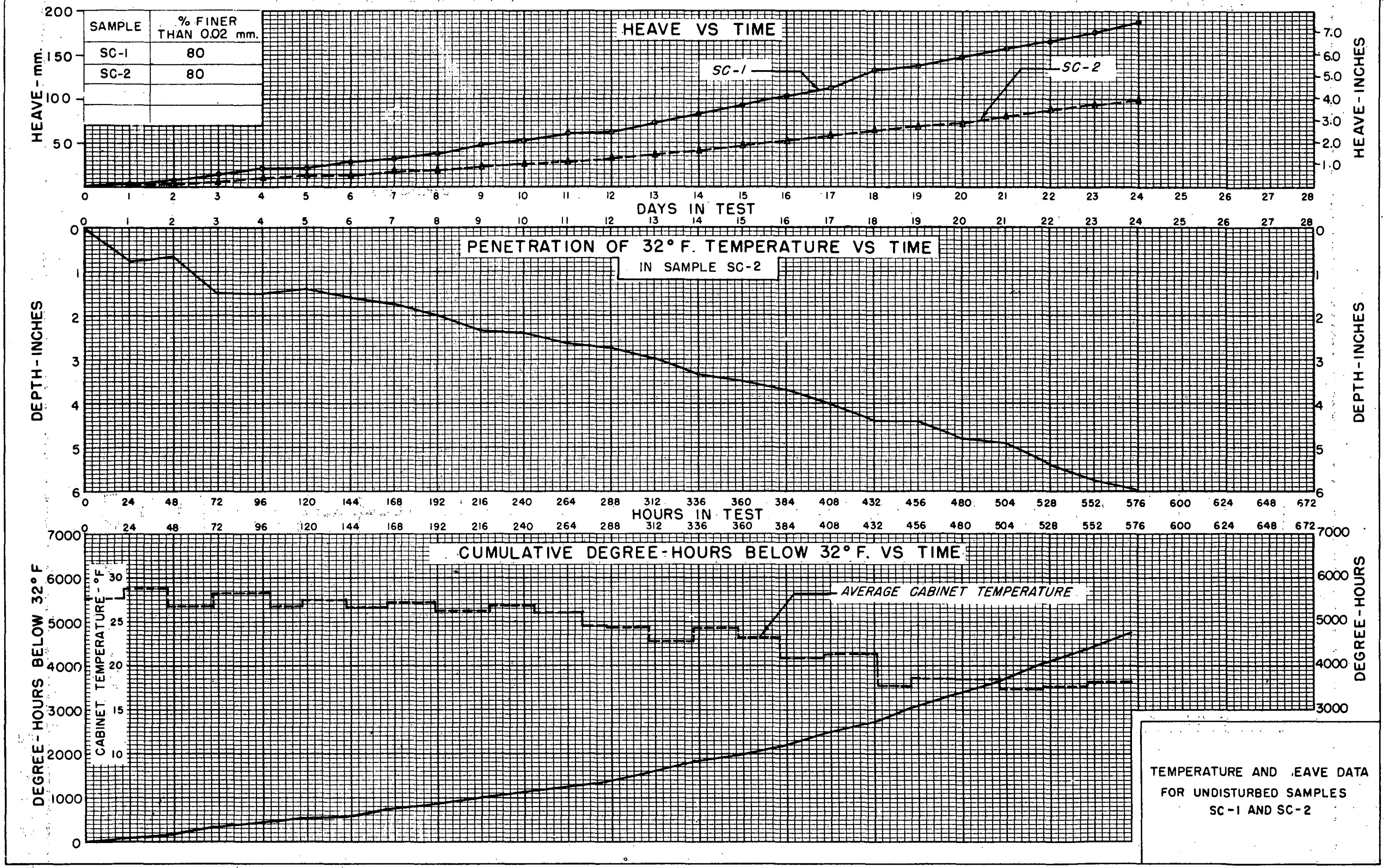
TEMPERATURE AND HEAVE DATA
FOR UNDISTURBED SAMPLES
LFT-1 AND LFT-10

PLATE B29

PLATE B 30



TEMPERATURE AND HEAVE DATA
FOR
SAMPLE PAFB-5

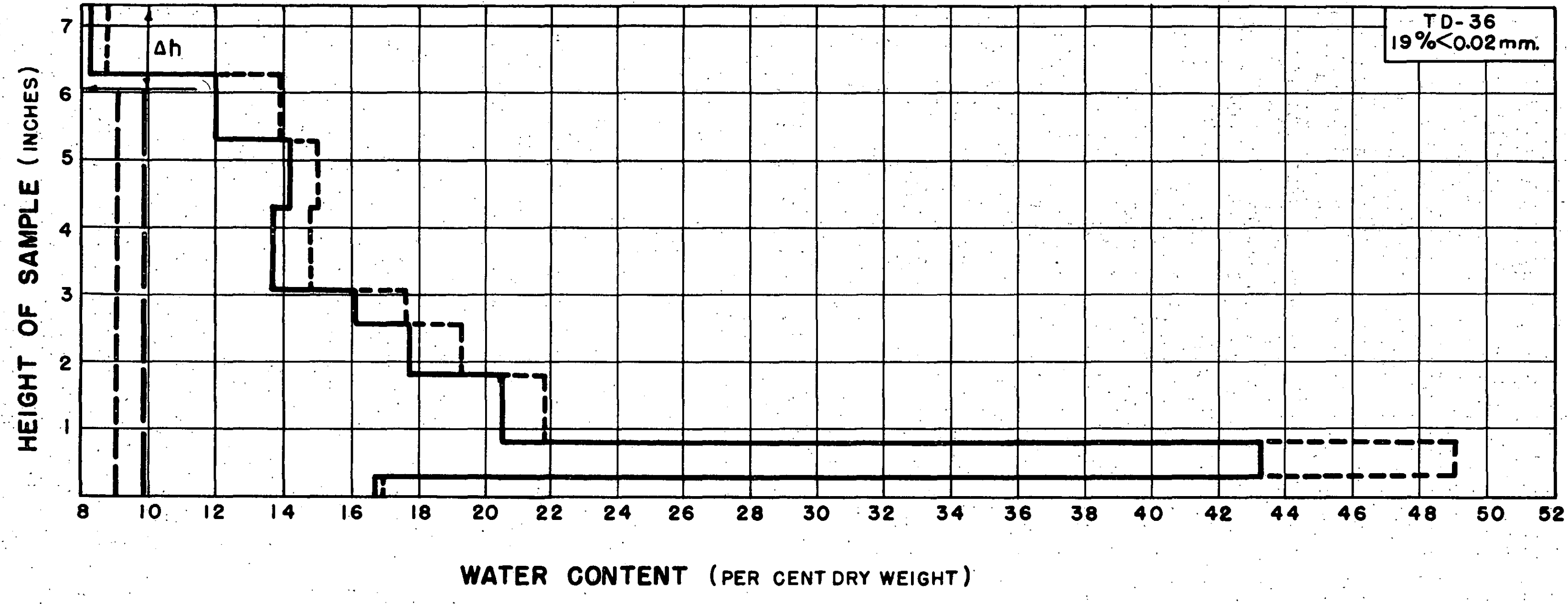


SAMPLE	% FINER THAN 0.02 mm.
SC-1	80
SC-2	80

TEMPERATURE AND HEAVE DATA
FOR UNDISTURBED SAMPLES
SC - 1 AND SC - 2

PLATE B 31

PLATE B32



LEGEND

— — — ORIGINAL WATER CONTENT OF TOTAL SAMPLE BEFORE TEST.

——— WATER CONTENT OF TOTAL SAMPLE AFTER TEST.

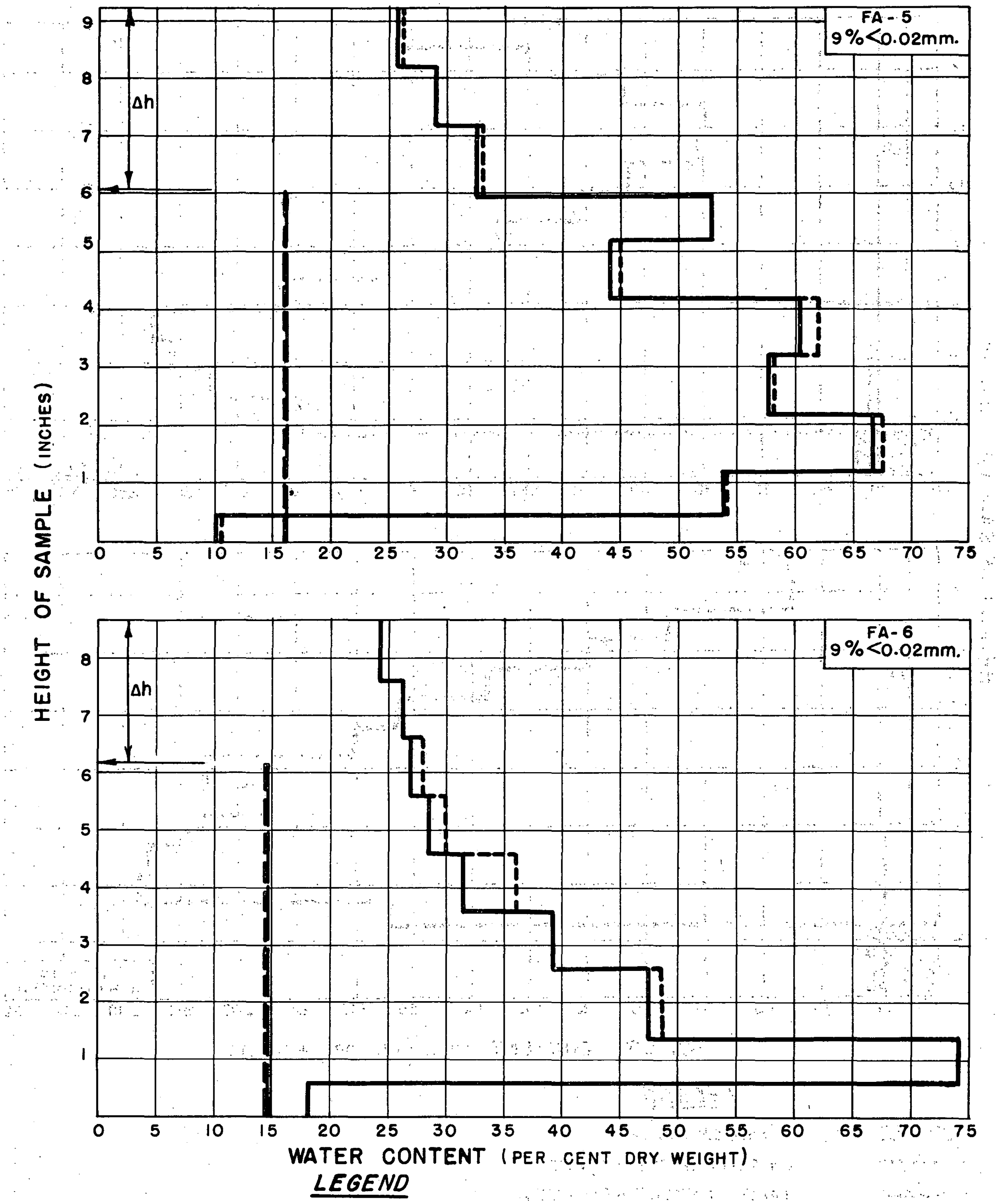
—— —— ORIGINAL WATER CONTENT OF MINUS $\frac{1''}{4}$ MATERIAL BEFORE TEST.

- - - - - WATER CONTENT OF MINUS $\frac{1''}{4}$ MATERIAL AFTER TEST.

◄—— ORIGINAL HEIGHT OF SAMPLE.

Δh INCREMENT OF HEAVE.

WATER CONTENT
VS
DEPTH



LEGEND

— — — ORIGINAL WATER CONTENT OF TOTAL SAMPLE BEFORE TEST.

——— WATER CONTENT OF TOTAL SAMPLE AFTER TEST.

—— —— ORIGINAL WATER CONTENT OF MINUS $\frac{1''}{4}$ MATERIAL BEFORE TEST.

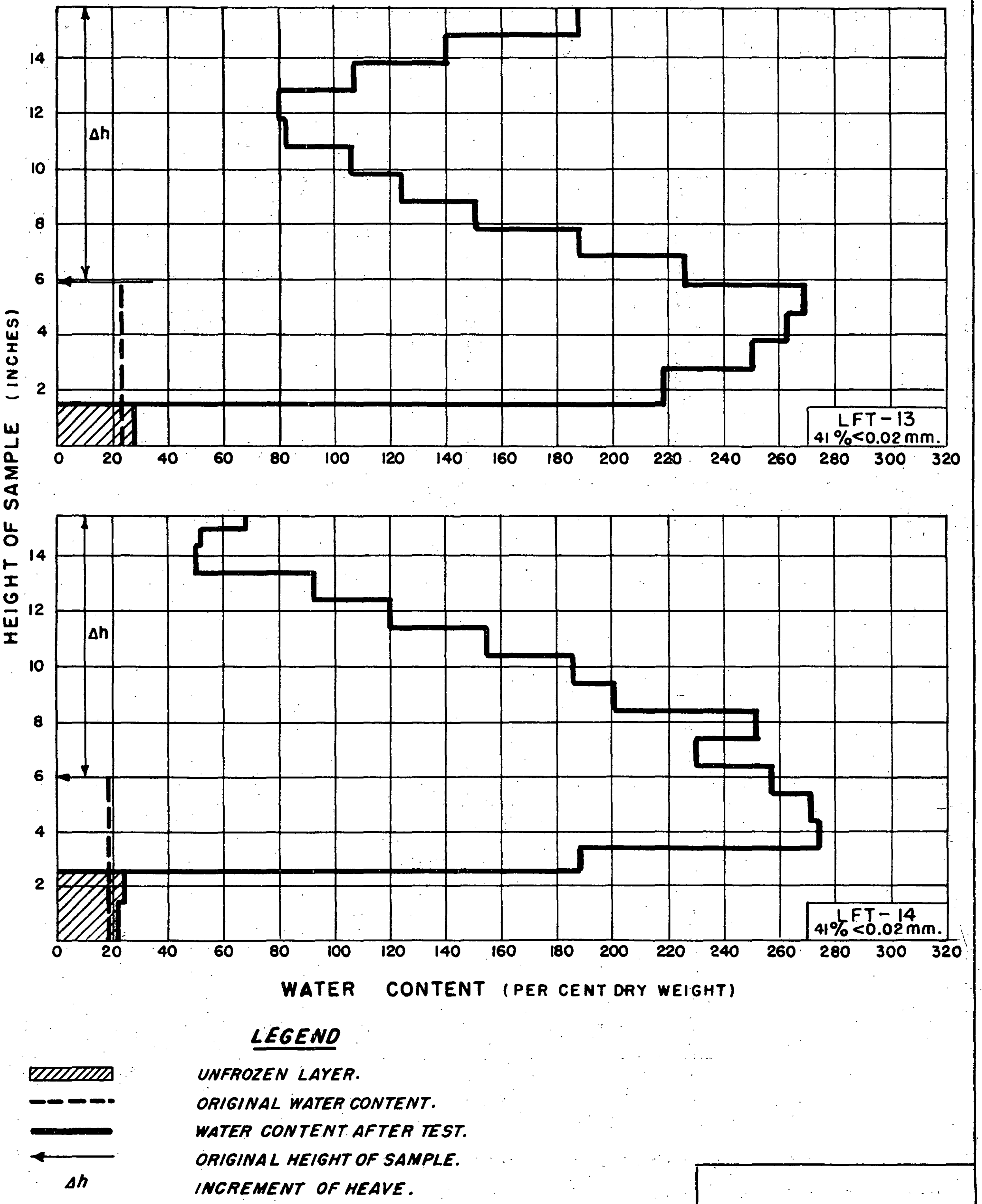
- - - WATER CONTENT OF MINUS $\frac{1''}{4}$ MATERIAL AFTER TEST.

←—— ORIGINAL HEIGHT OF SAMPLE.

Δh INCREMENT OF HEAVE.

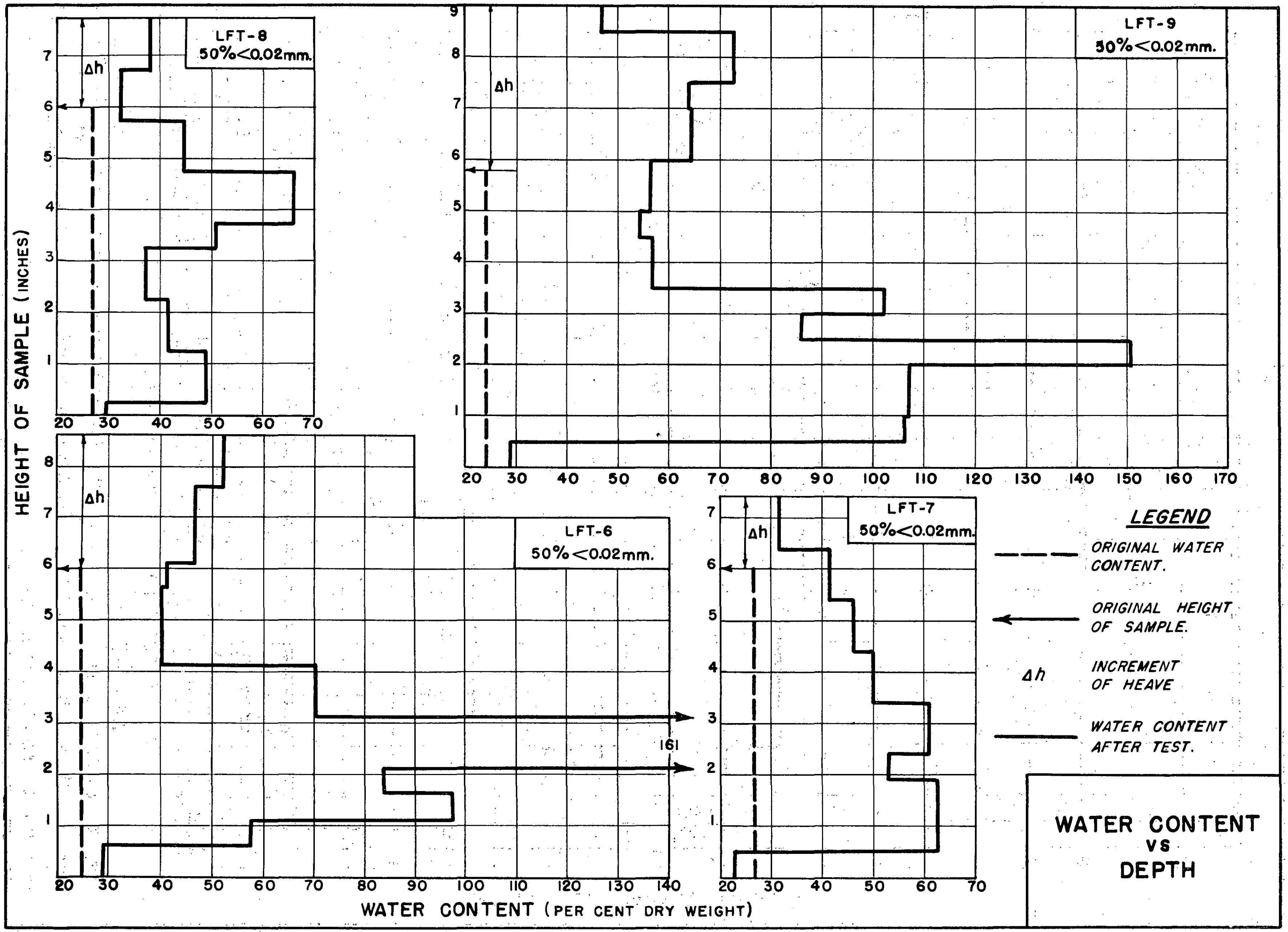
WATER CONTENT
VS
DEPTH

PLATE B33



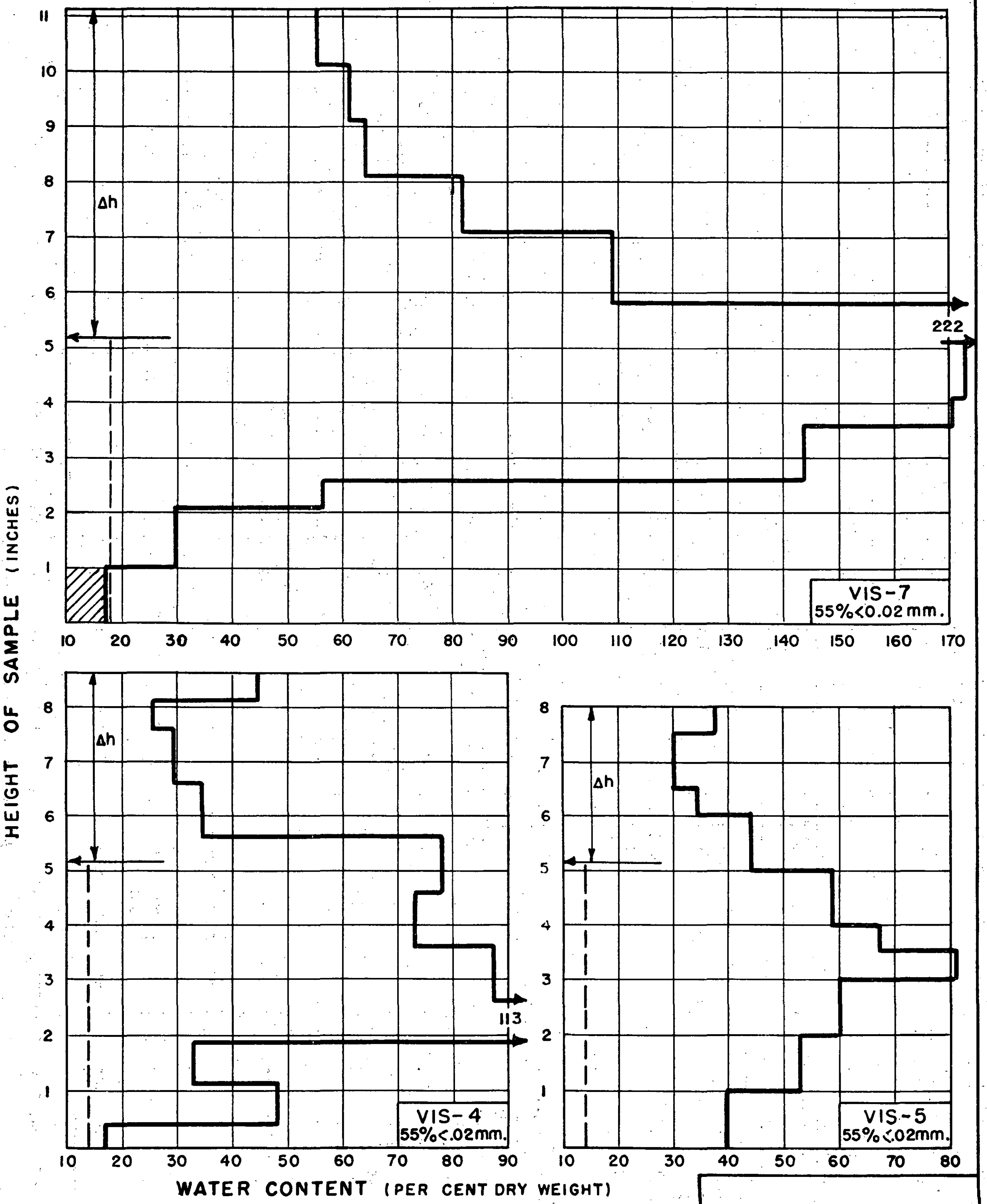
WATER CONTENT
VS
DEPTH

PLATE B34



WATER CONTENT
VS
DEPTH

PLATE B35



LEGEND

▨ *UNFROZEN LAYER.*

← *ORIGINAL HEIGHT OF SAMPLE.*

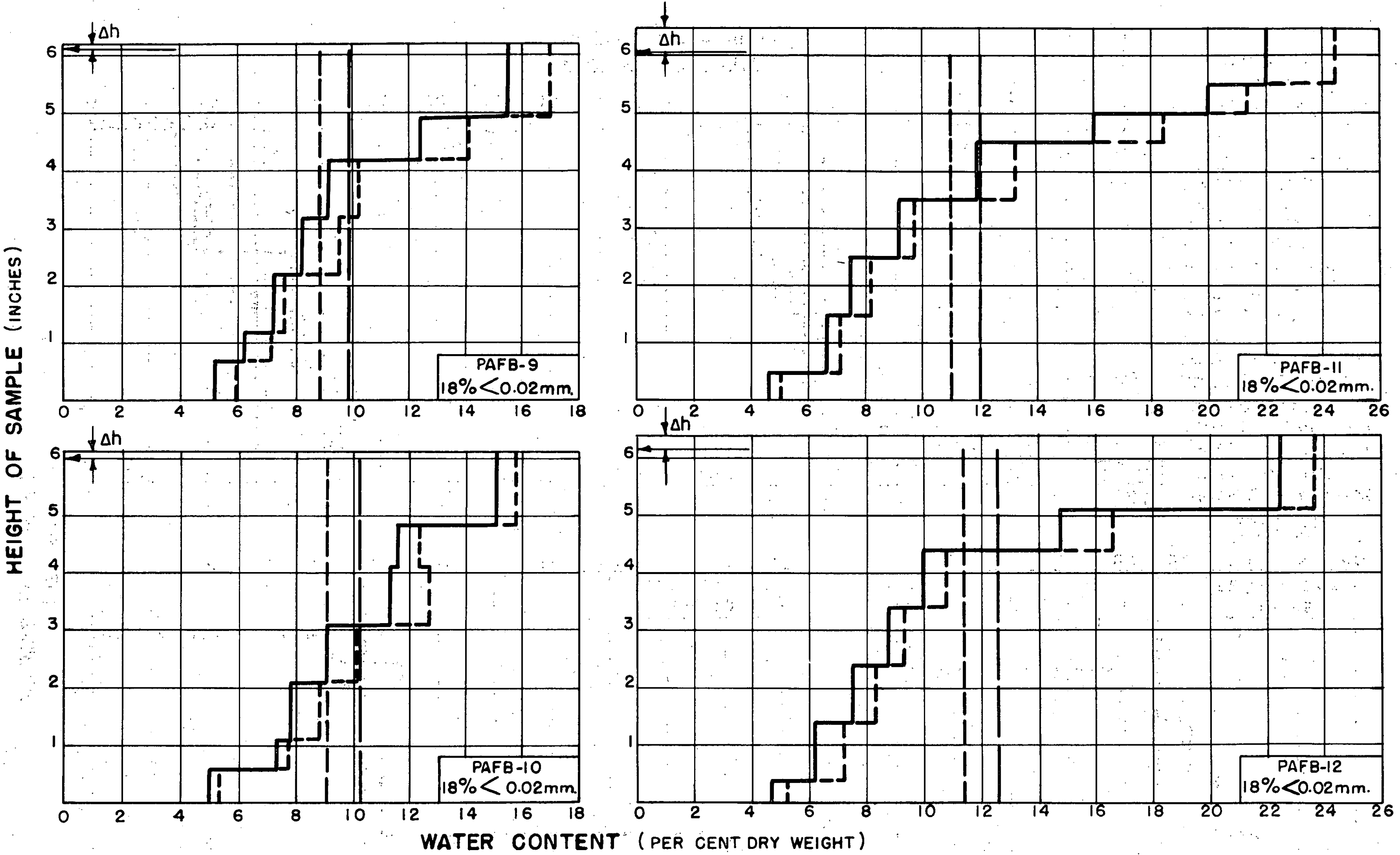
— — — *ORIGINAL WATER CONTENT.*

Δh INCREMENT OF HEAVE.

▬ *WATER CONTENT AFTER TEST.*

WATER CONTENT
VS
DEPTH

PLATE B 36



LEGEND

– – – ORIGINAL WATER CONTENT OF TOTAL SAMPLE BEFORE TEST.

——— WATER CONTENT OF TOTAL SAMPLE AFTER TEST.

—— —— ORIGINAL WATER CONTENT OF MINUS $\frac{1}{4}$" MATERIAL BEFORE TEST.

- - - - WATER CONTENT OF MINUS $\frac{1}{4}$" MATERIAL AFTER TEST.

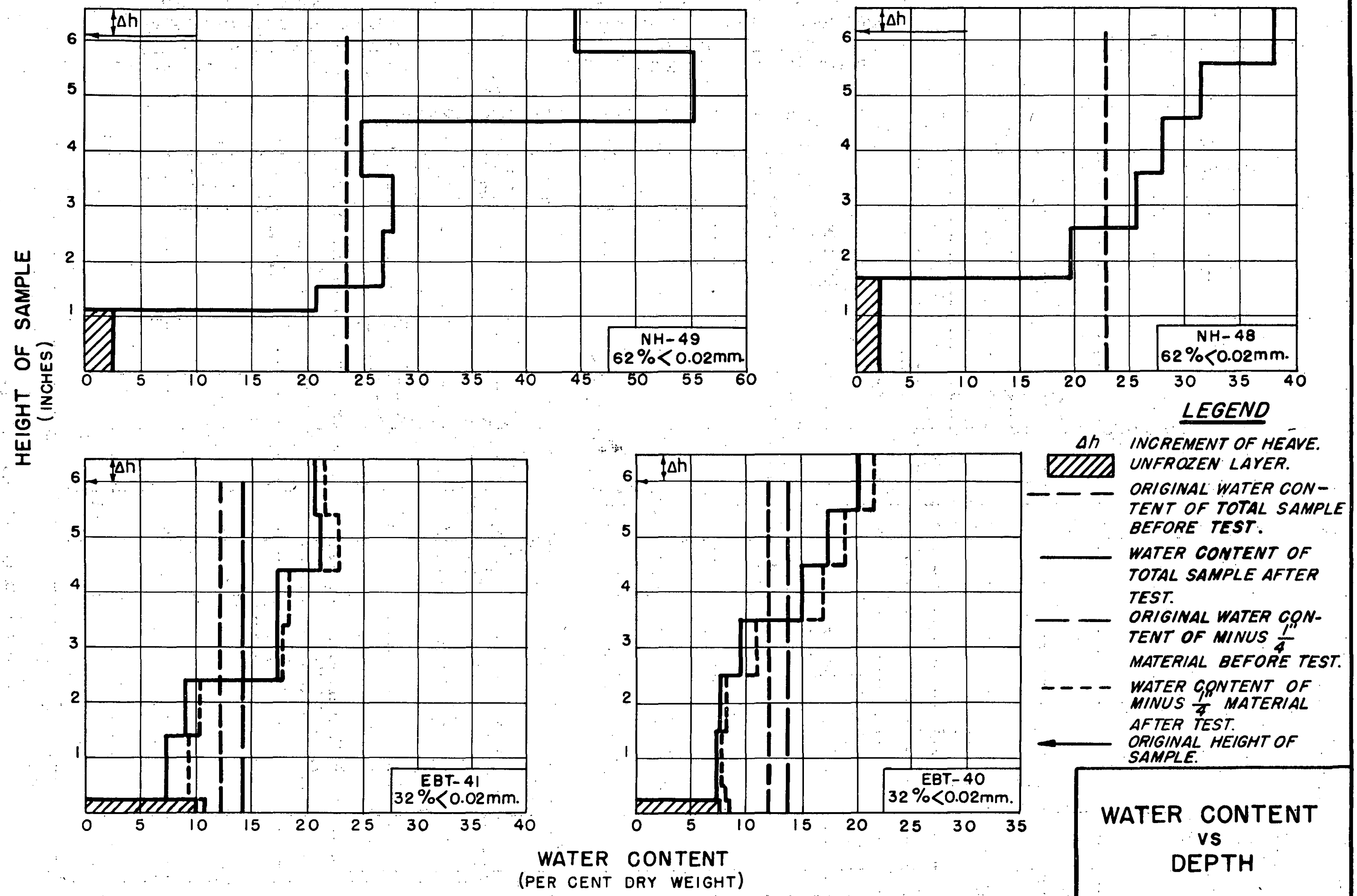
← ORIGINAL HEIGHT OF SAMPLE.

Δh INCREMENT OF HEAVE.

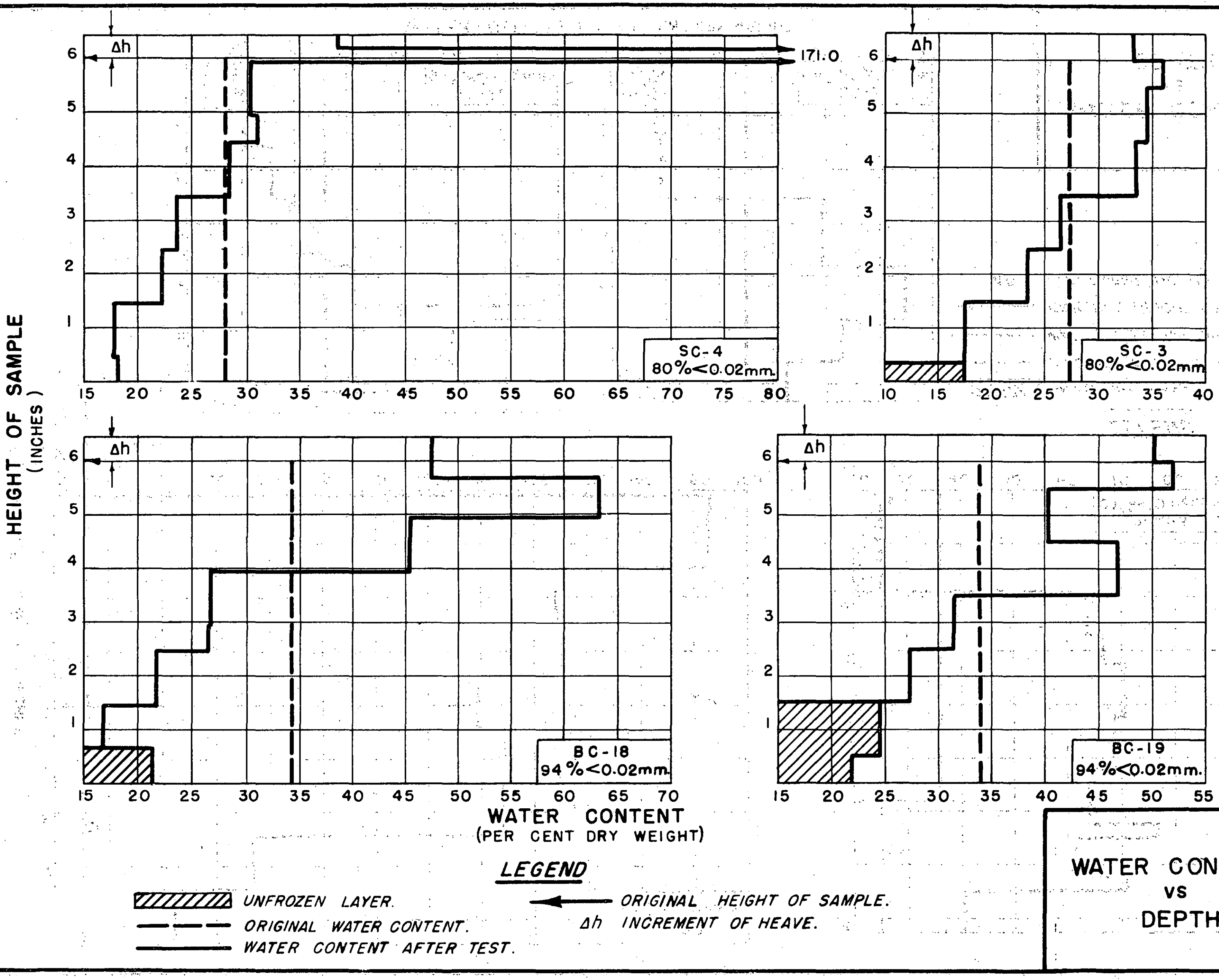
WATER CONTENT
vs
DEPTH

PLATE B37

PLATE B38



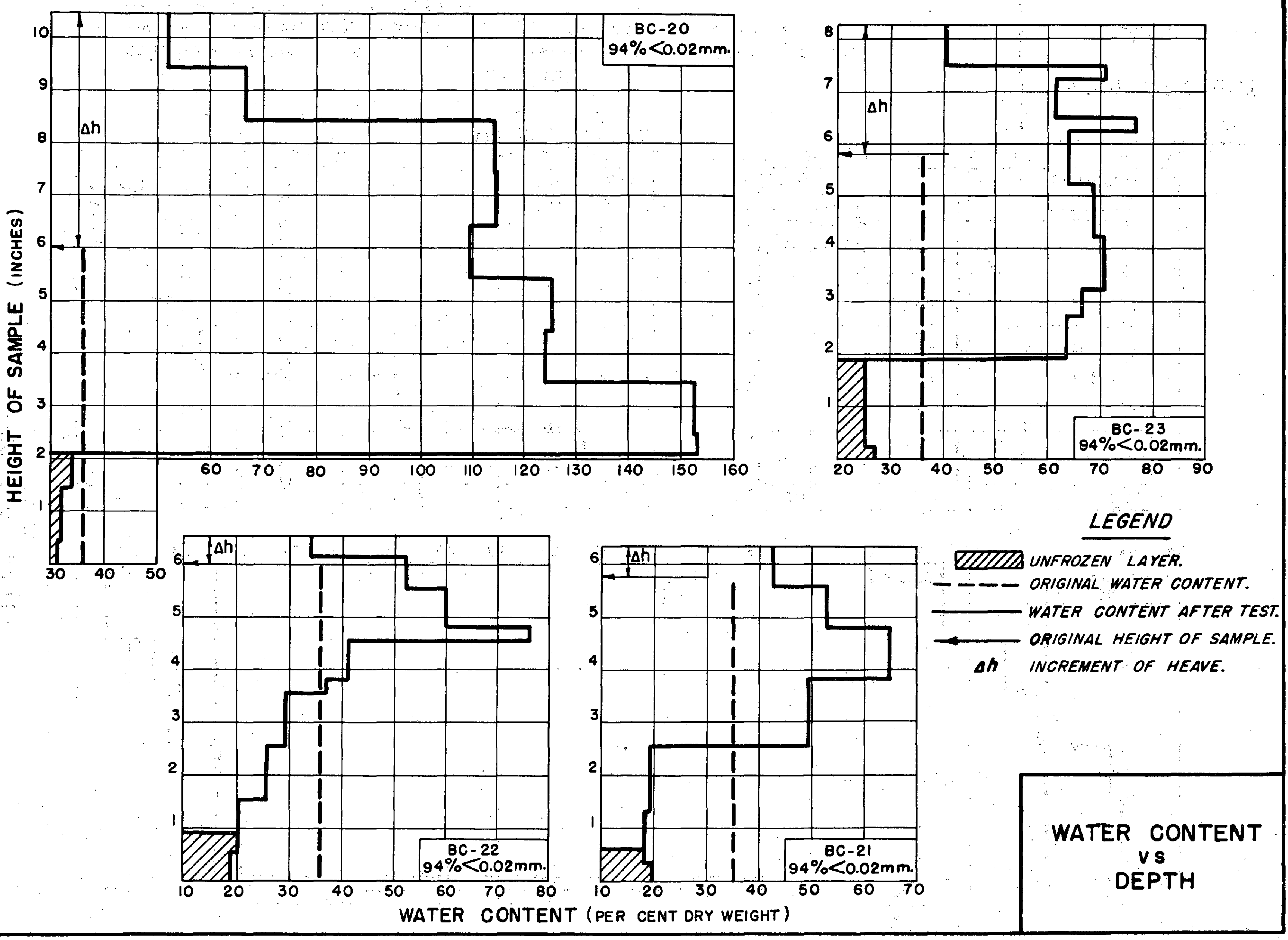
WATER CONTENT
VS
DEPTH



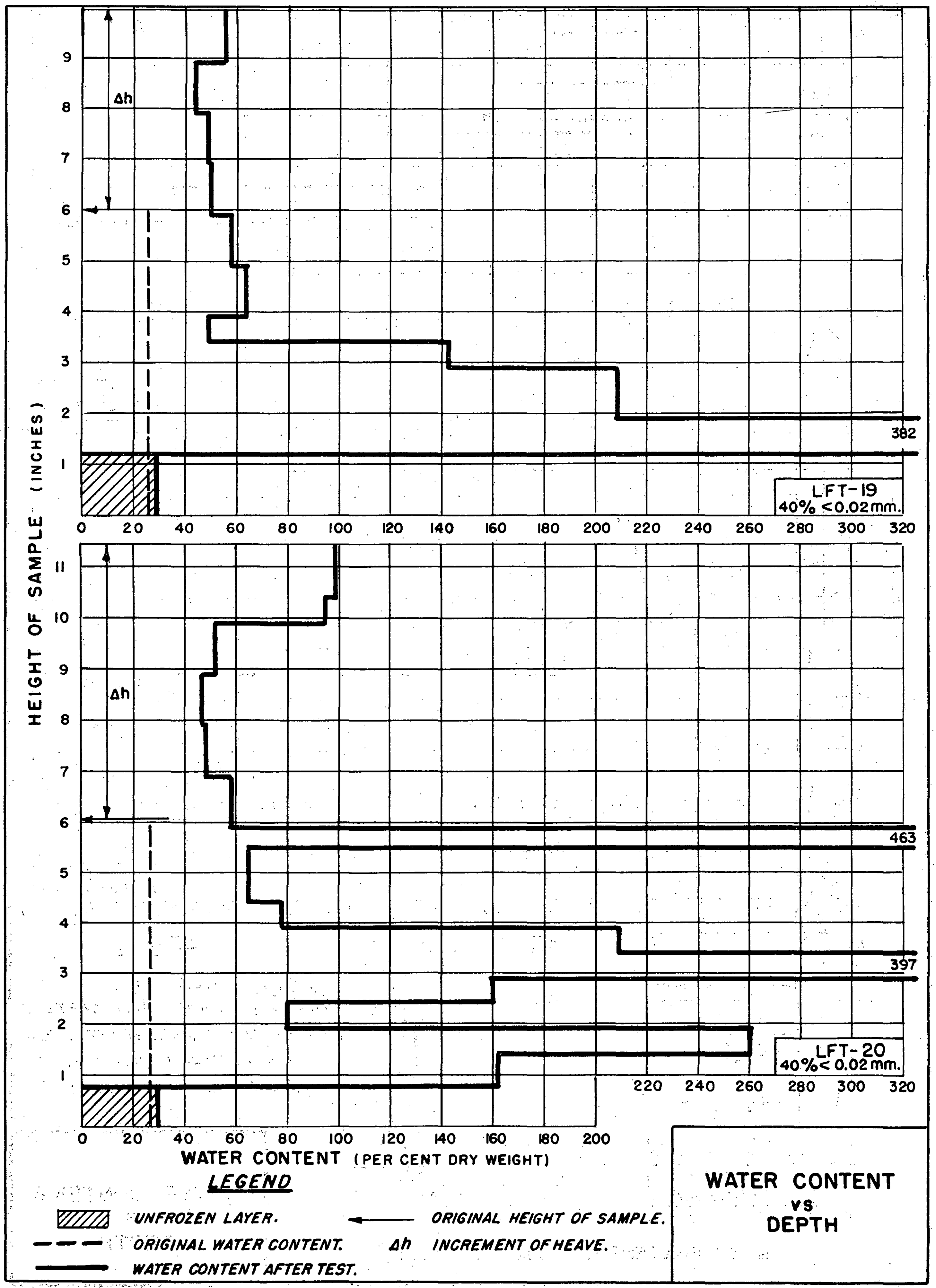
WATER CONTENT
VS
DEPTH

PLATE B39

PLATE B 40

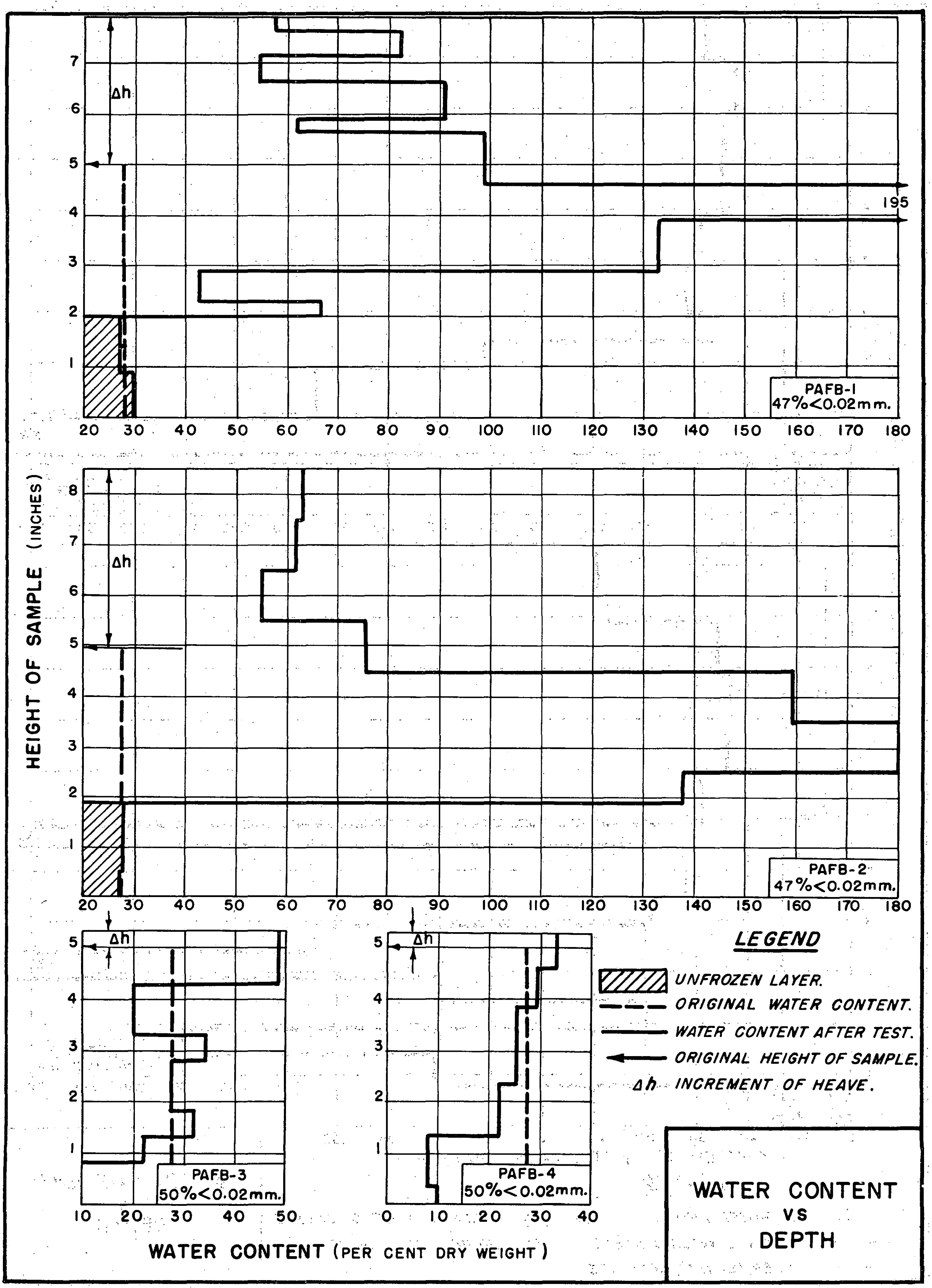


WATER CONTENT VS DEPTH



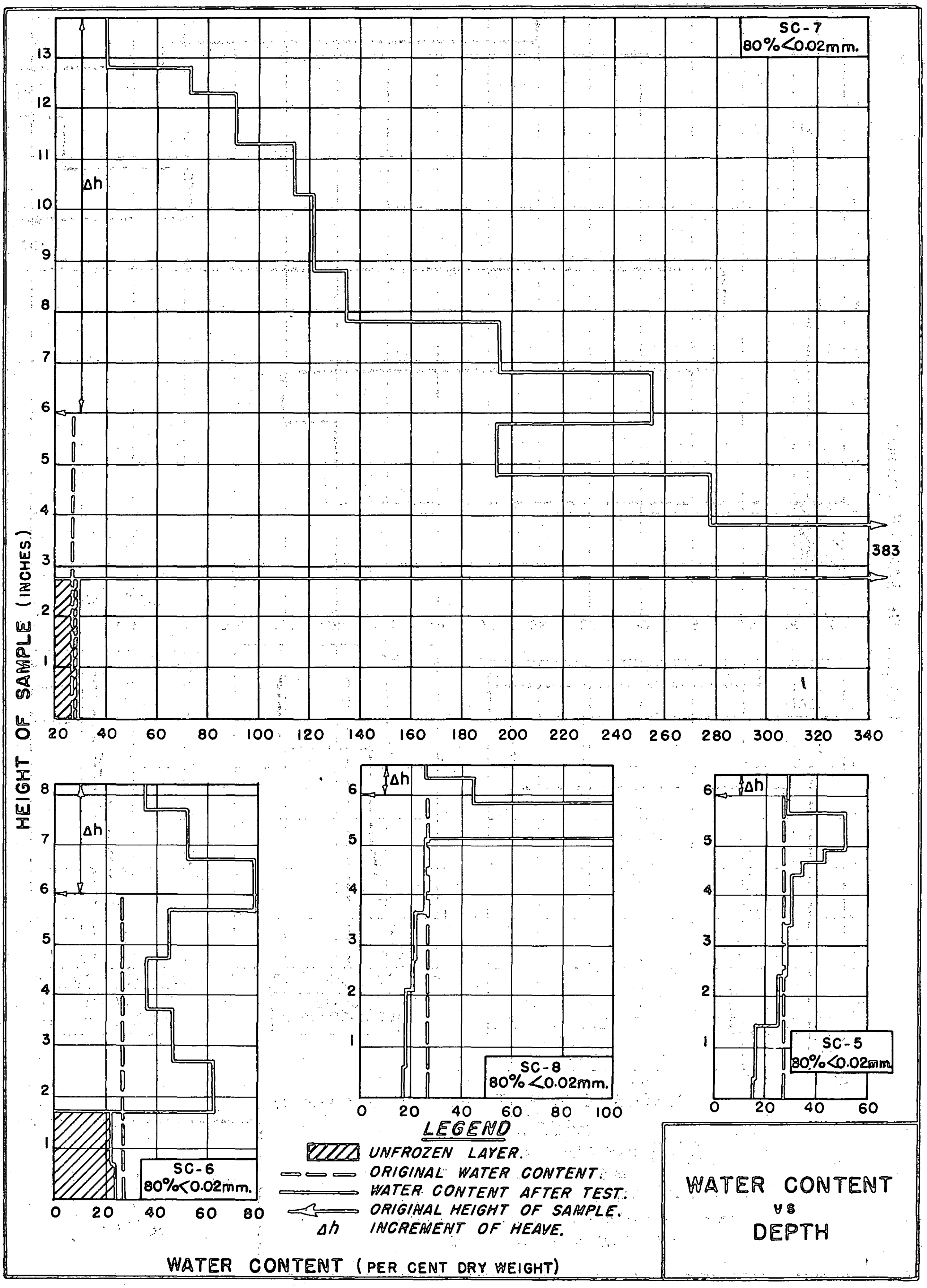
WATER CONTENT
VS
DEPTH

PLATE B41



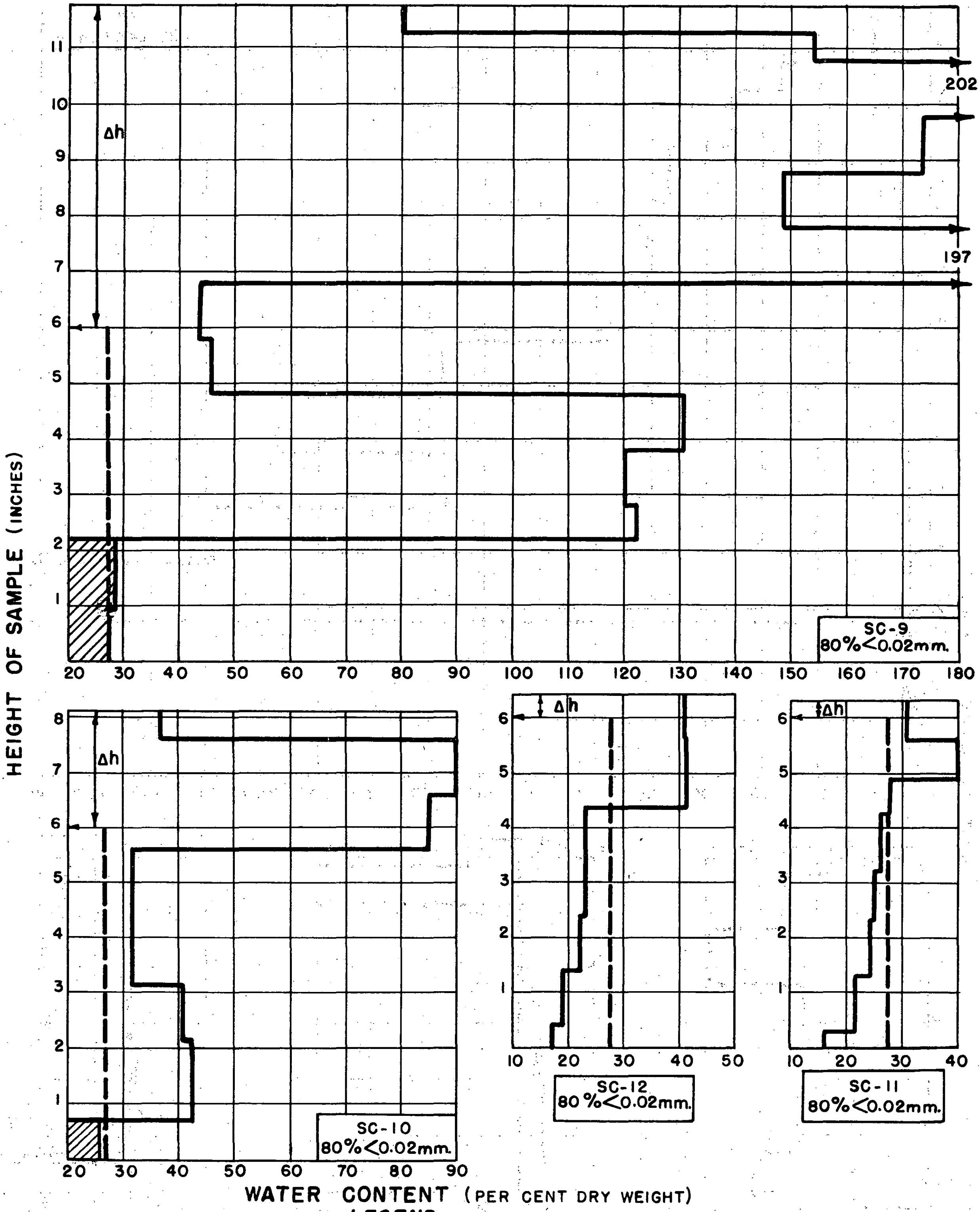
WATER CONTENT
VS
DEPTH

PLATE B42



WATER CONTENT
vs
DEPTH

PLATE B 43

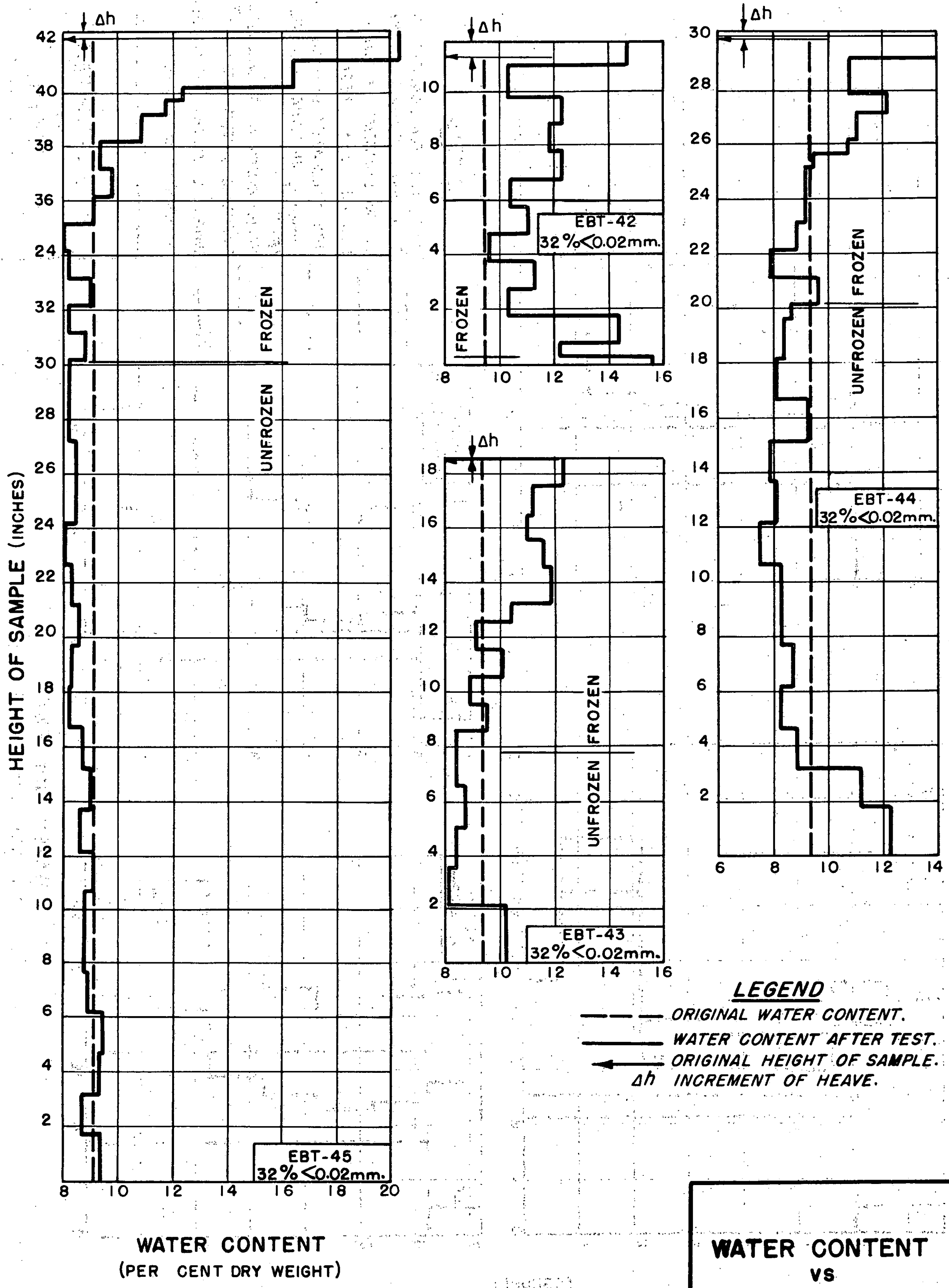


LEGEND

- ▨ *UNFROZEN LAYER.*
- — — — *ORIGINAL WATER CONTENT.*
- ——— *WATER CONTENT AFTER TEST.*
- ←—— *ORIGINAL HEIGHT OF SAMPLE.*
- *Δh INCREMENT OF HEAVE.*

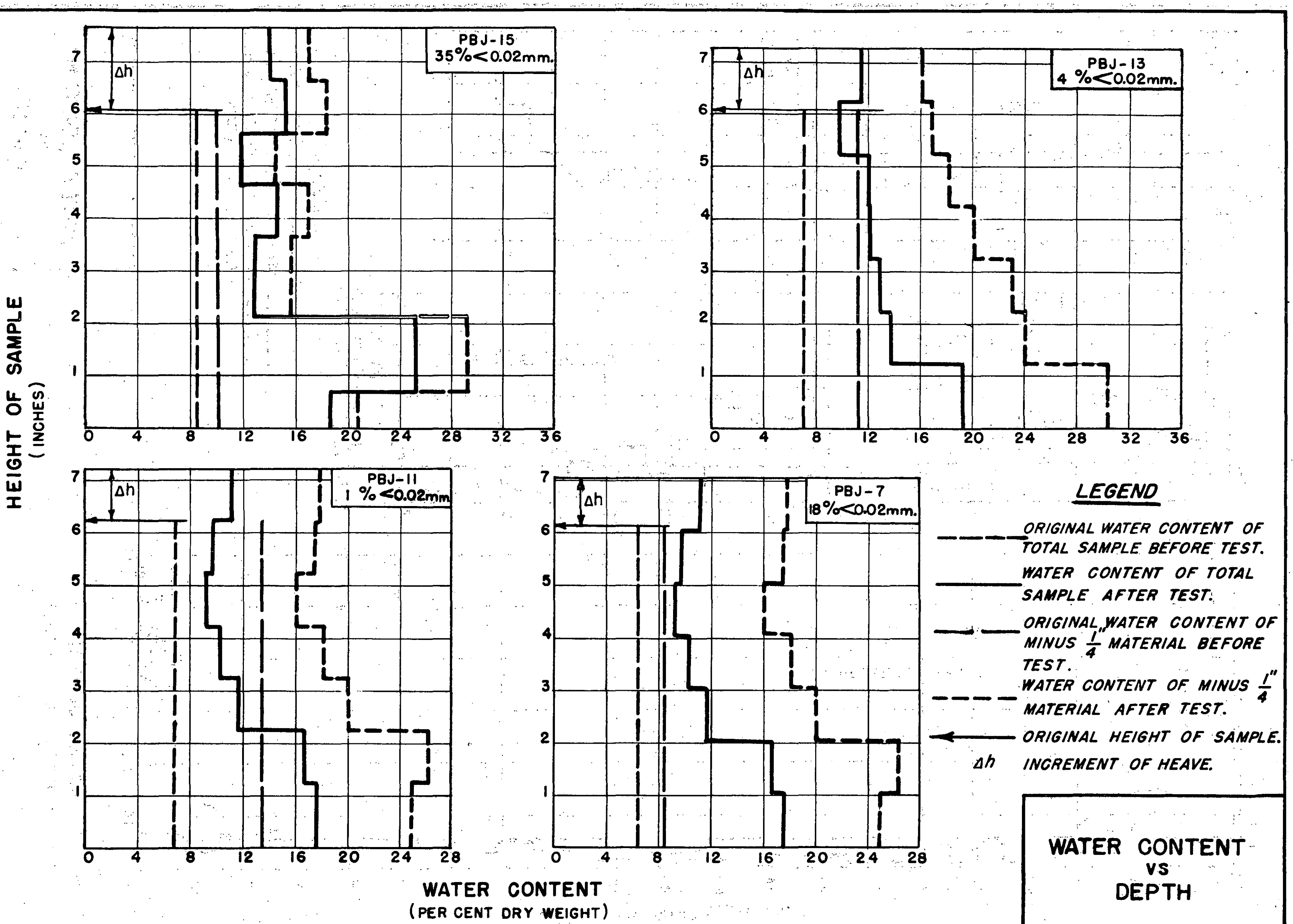
WATER CONTENT
VS
DEPTH

PLATE B 44

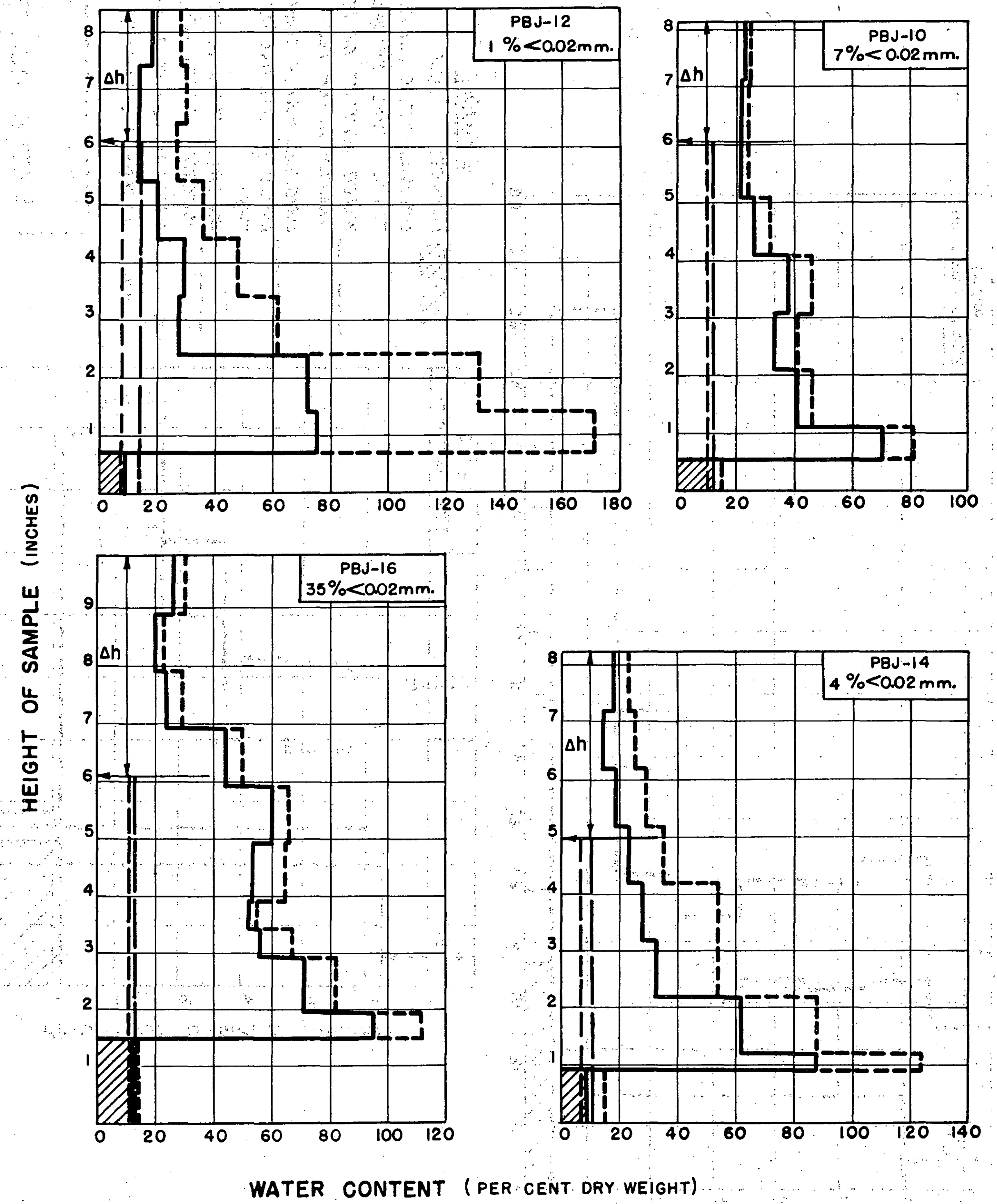


WATER CONTENT
VS
DEPTH

PLATE B45



WATER CONTENT
VS
DEPTH



LEGEND

▨ *UNFROZEN LAYER.*

– – – *ORIGINAL WATER CONTENT OF TOTAL SAMPLE BEFORE TEST.*

—— *WATER CONTENT OF TOTAL SAMPLE AFTER TEST.*

—— —— *ORIGINAL WATER CONTENT OF MINUS $\frac{1}{4}''$ MATERIAL BEFORE TEST.*

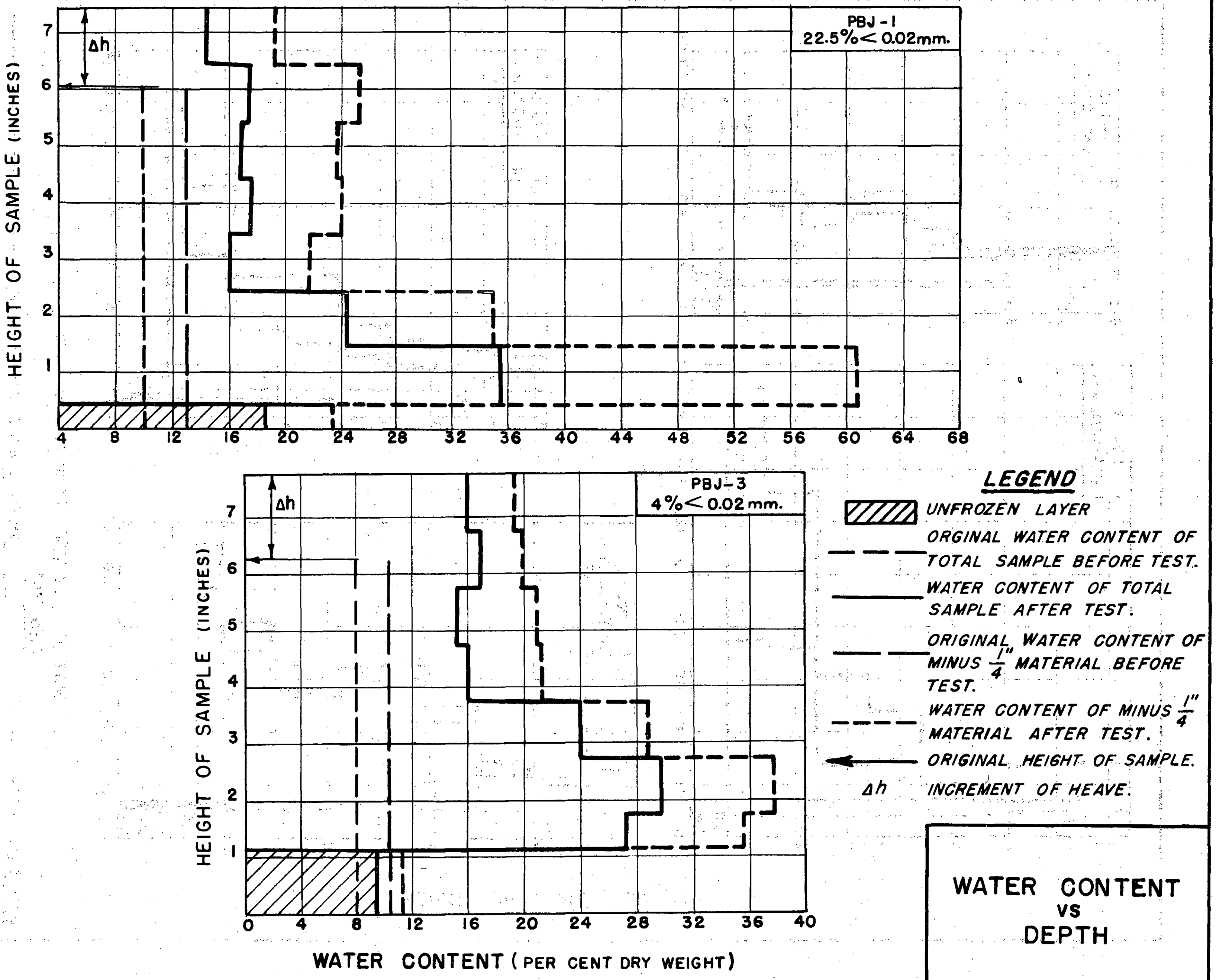
- - - - *WATER CONTENT OF MINUS $\frac{1}{4}''$ MATERIAL AFTER TEST.*

← *ORIGINAL HEIGHT OF SAMPLE.*

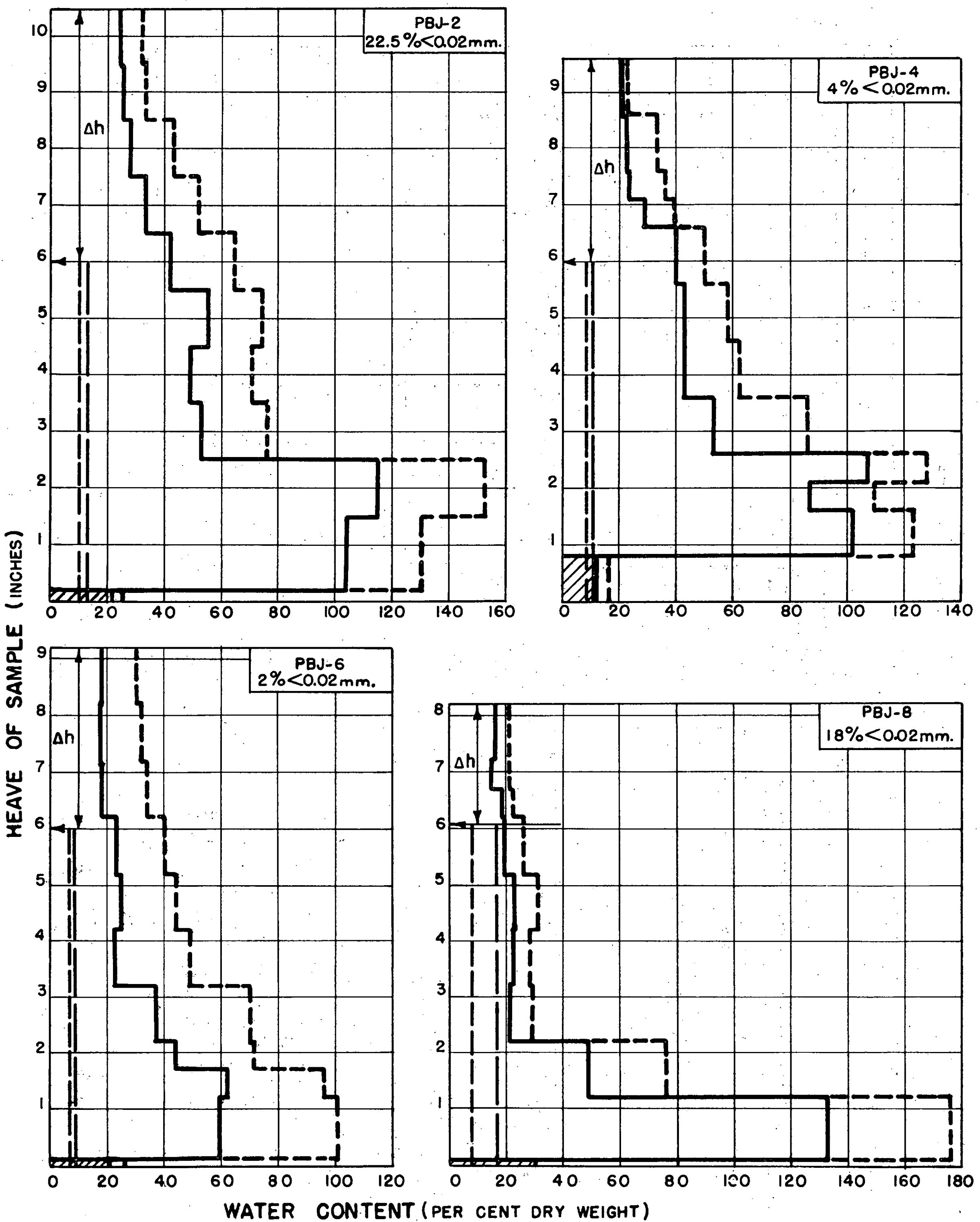
Δh INCREMENT OF HEAVE.

WATER CONTENT
VS
DEPTH

PLATE B48



WATER CONTENT
VS
DEPTH



LEGEND

▨ UNFROZEN LAYER.

– – – – ORIGINAL WATER CONTENT OF TOTAL SAMPLE BEFORE TEST.

——— WATER CONTENT OF TOTAL SAMPLE AFTER TEST.

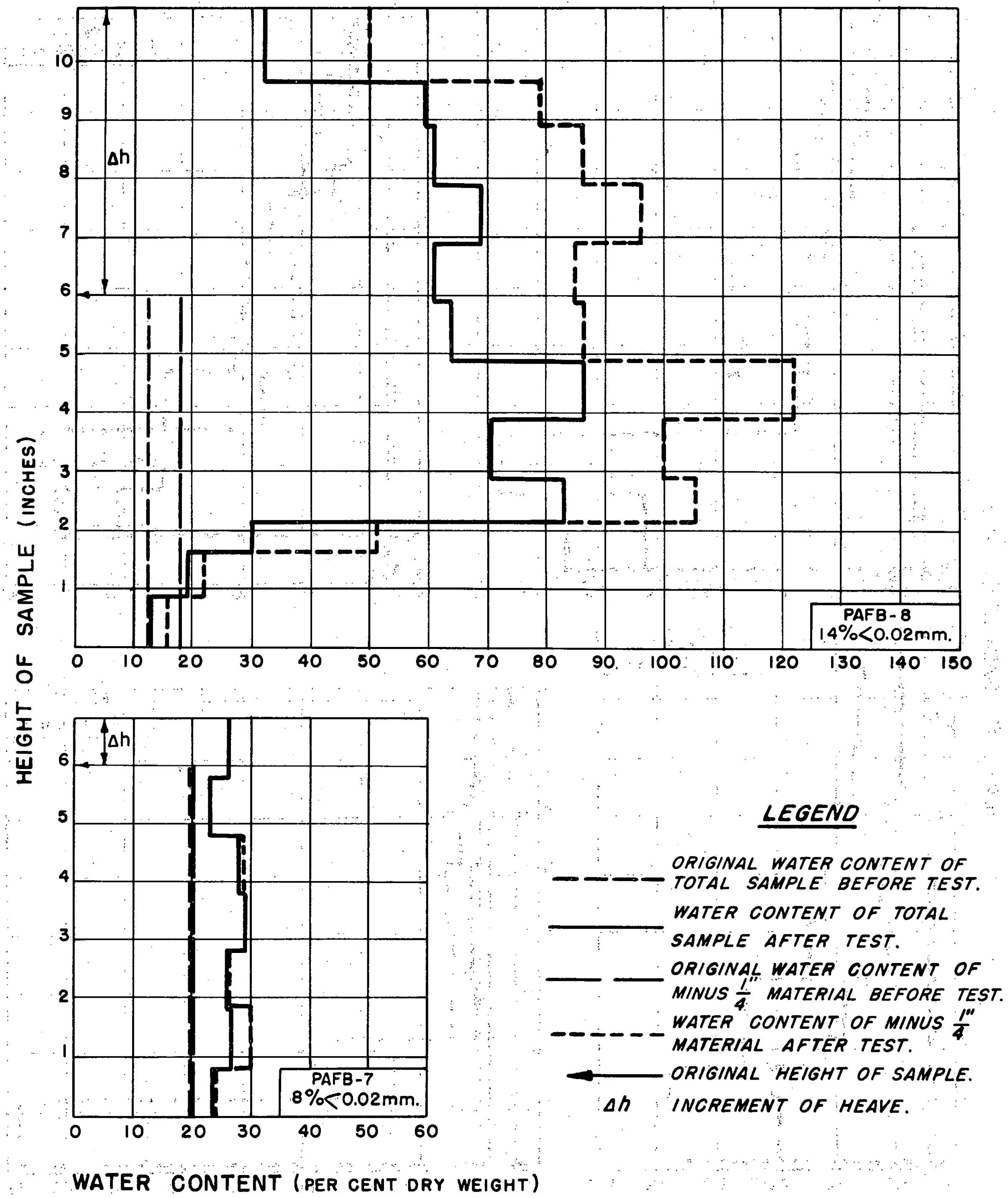
—— —— ORIGINAL WATER CONTENT OF MINUS $\frac{1}{4}$" MATERIAL BEFORE TEST.

- - - - - WATER CONTENT OF MINUS $\frac{1}{4}$" MATERIAL AFTER TEST.

◄—— ORIGINAL HEIGHT OF SAMPLE.

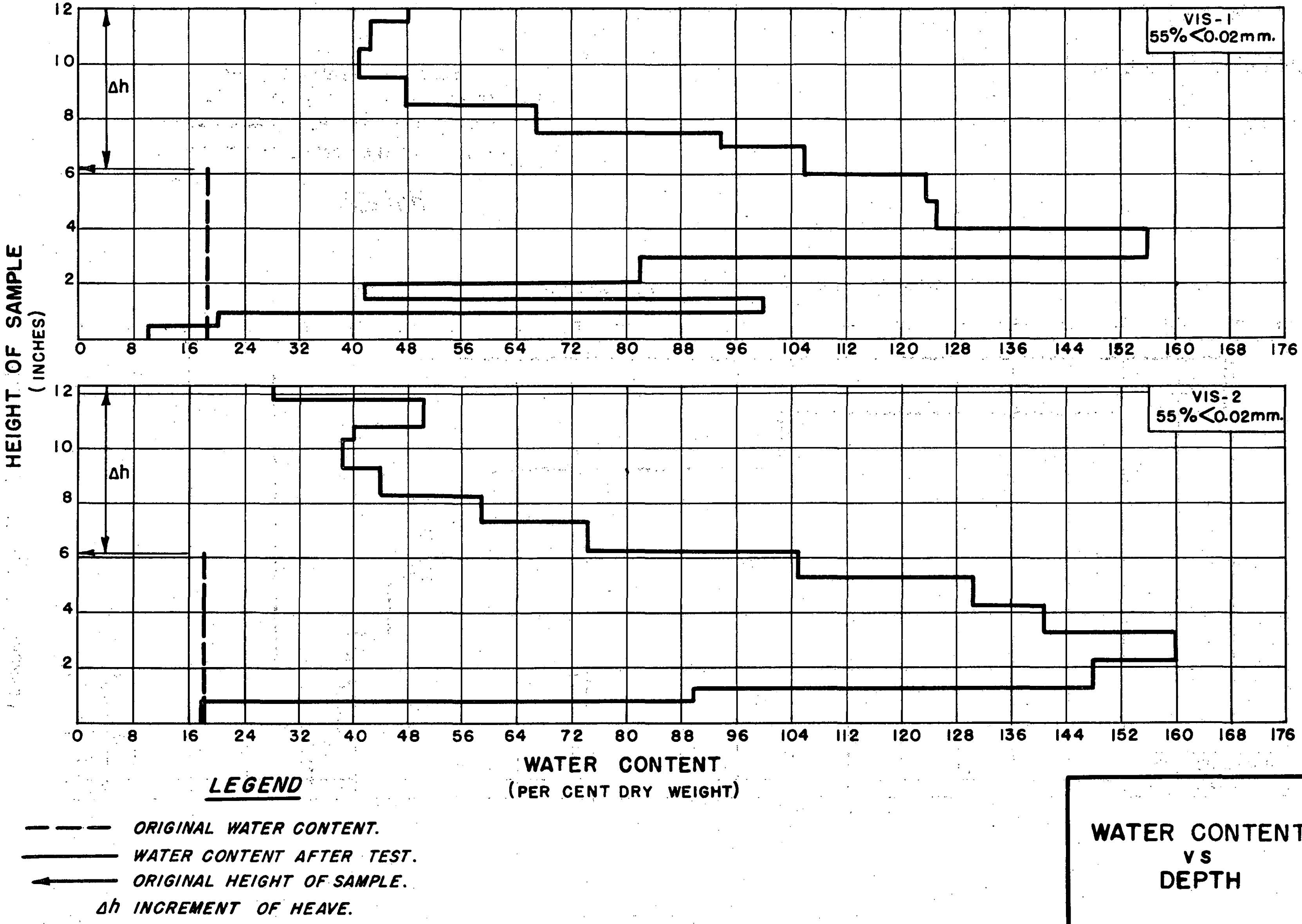
Δh INCREMENT OF HEAVE.

WATER CONTENT
VS
DEPTH



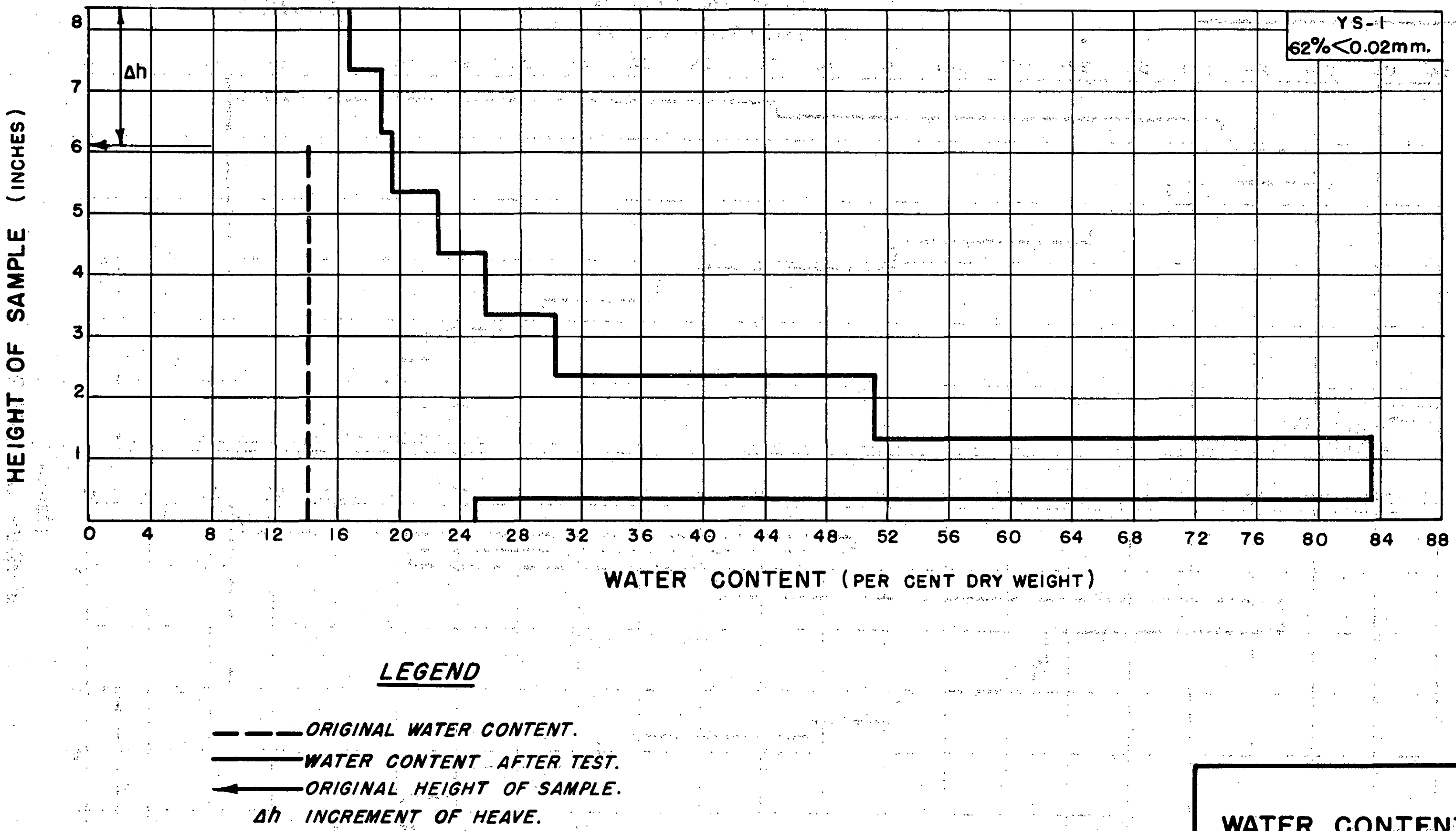
WATER CONTENT
VS
DEPTH

PLATE B50

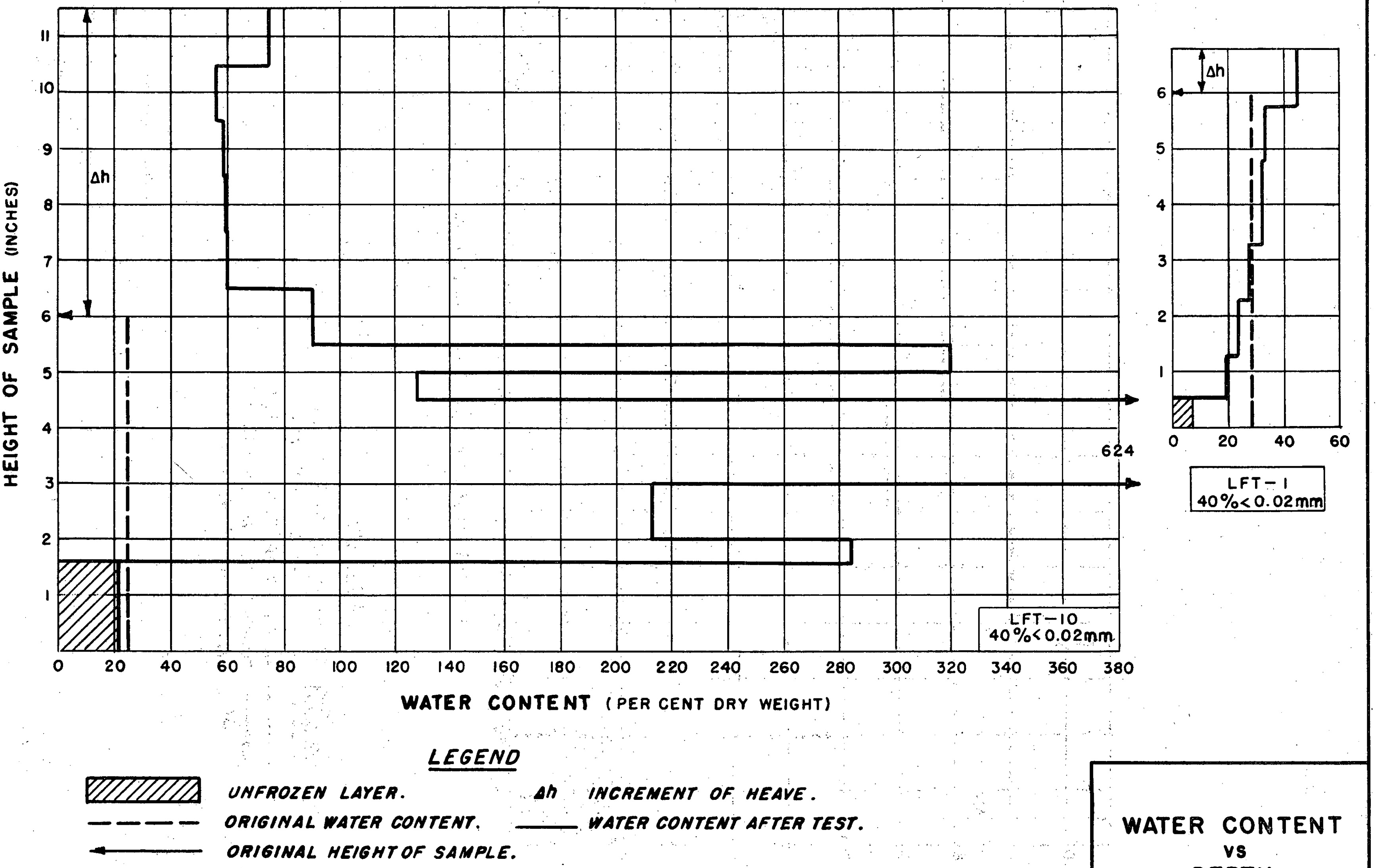


WATER CONTENT
VS
DEPTH

PLATE B-52

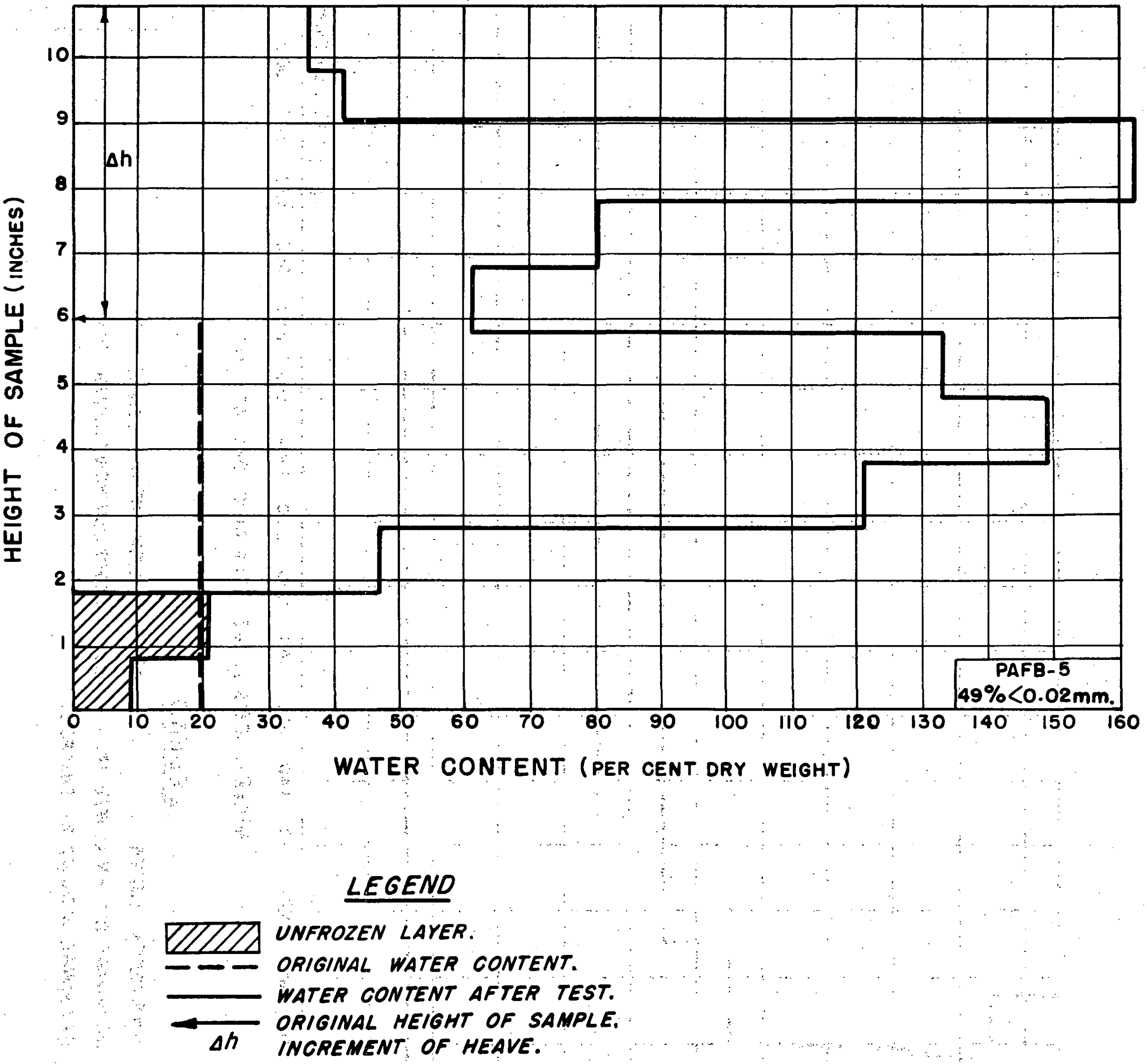


WATER CONTENT
VS
DEPTH



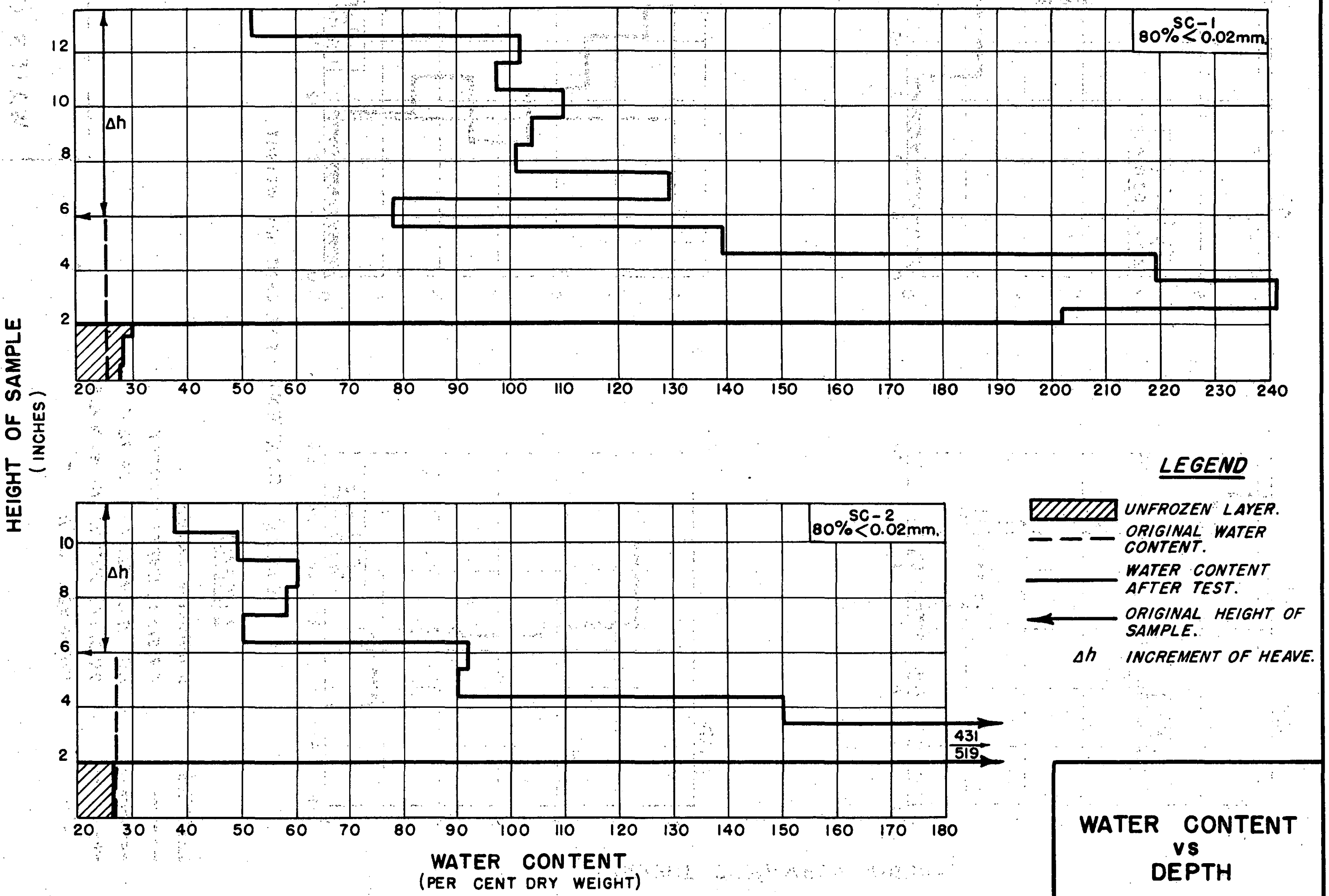
WATER CONTENT
VS
DEPTH

PLATE B 53



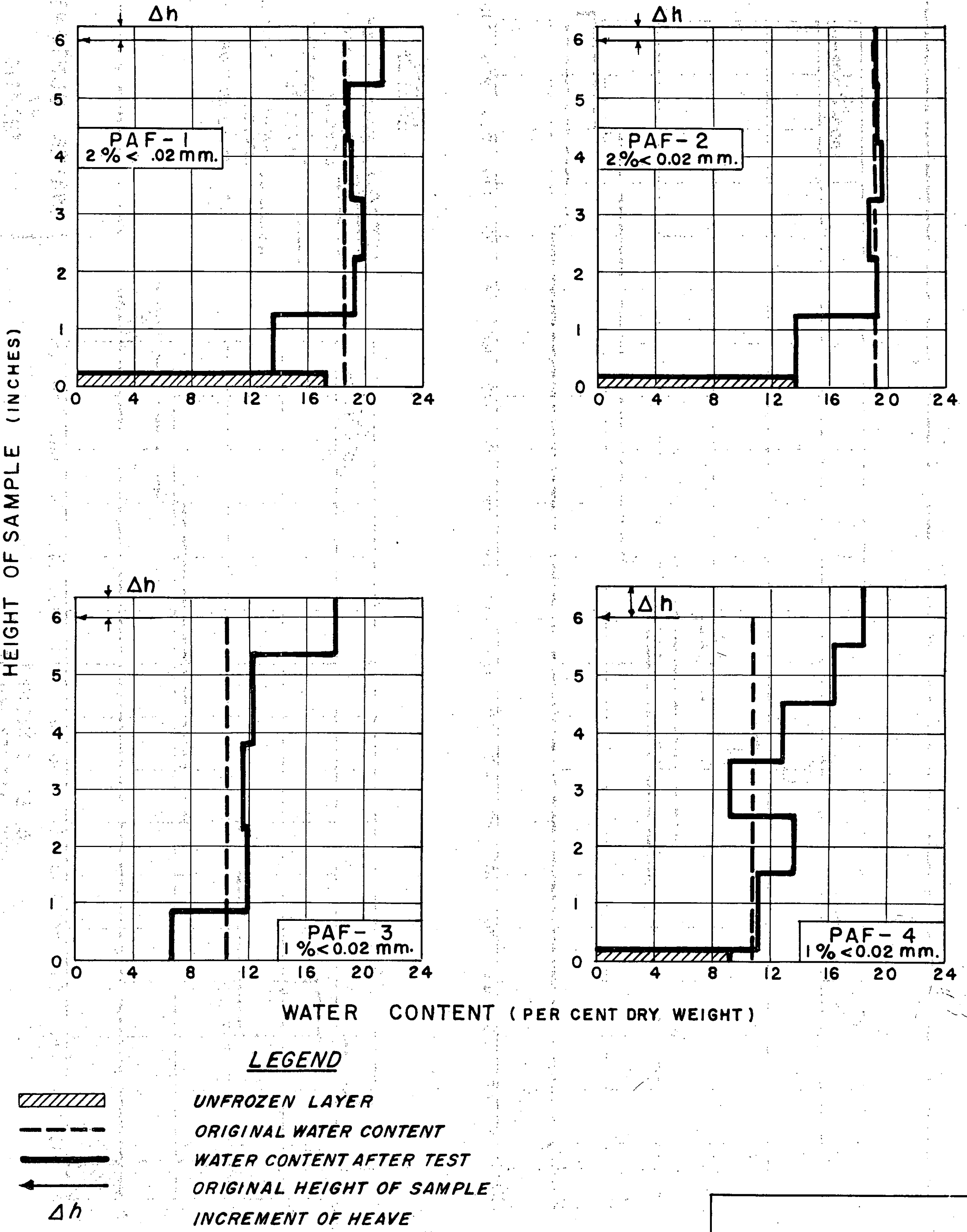
WATER CONTENT
VS
DEPTH

PLATE B54



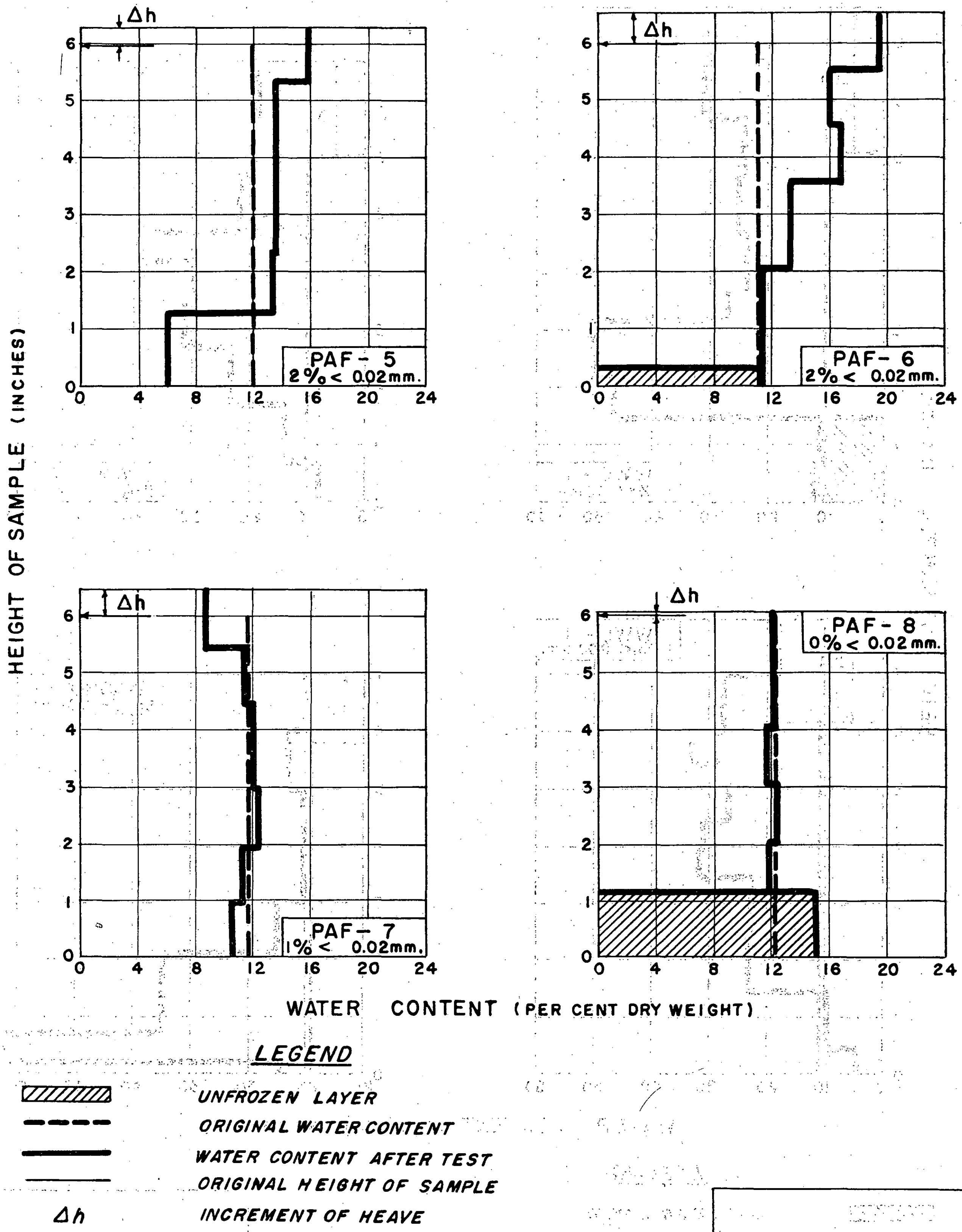
WATER CONTENT
vs
DEPTH

PLATE B 55



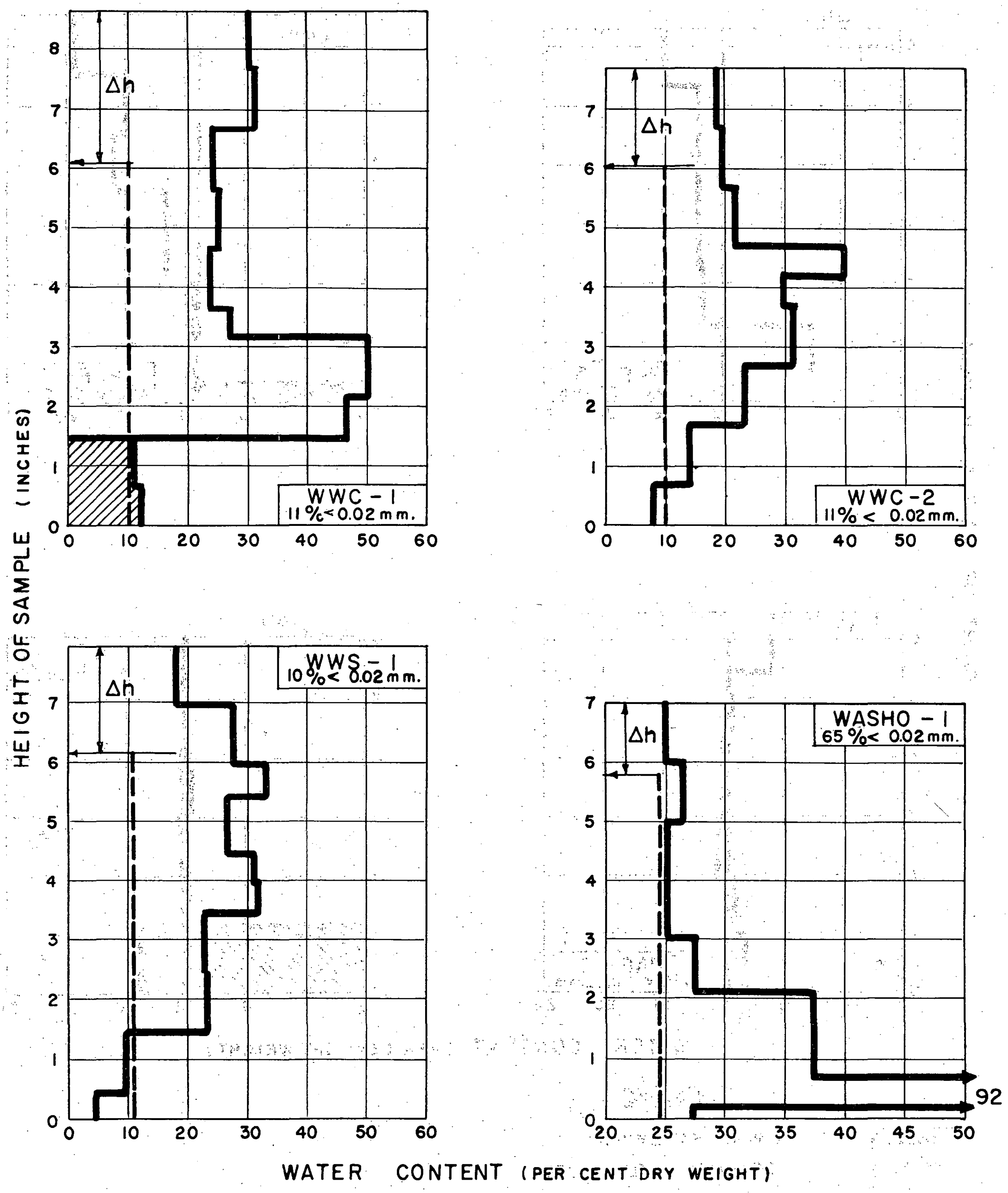
WATER CONTENT
VS
DEPTH

PLATE B56



WATER CONTENT
VS
DEPTH

PLATE B 57

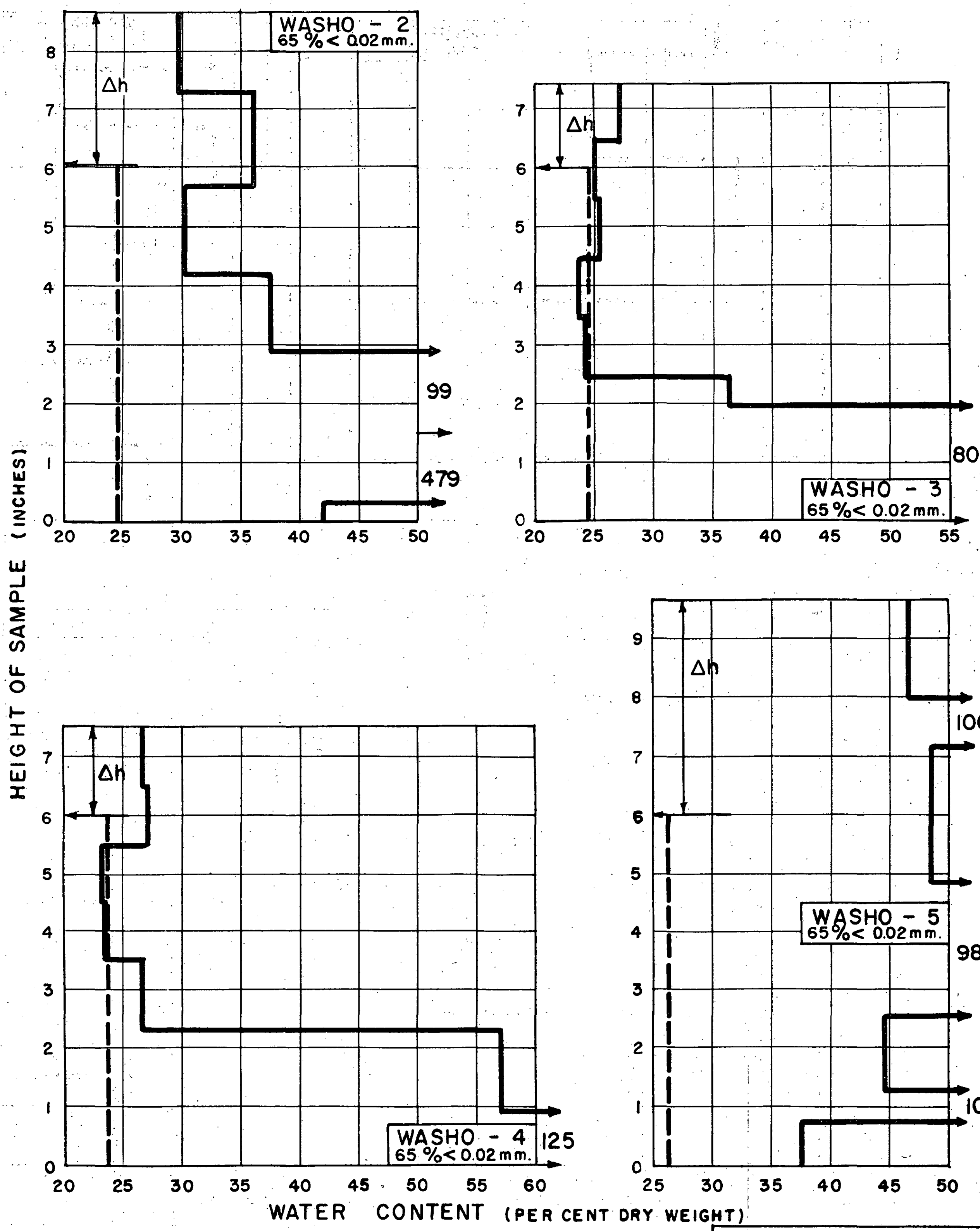


LEGEND

▨	*UNFROZEN LAYER*
- - -	*ORIGINAL WATER CONTENT*
━	*WATER CONTENT AFTER TEST*
←	*ORIGINAL HEIGHT OF SAMPLE*
Δh	*INCREMENT OF HEAVE*

WATER CONTENT
VS
DEPTH

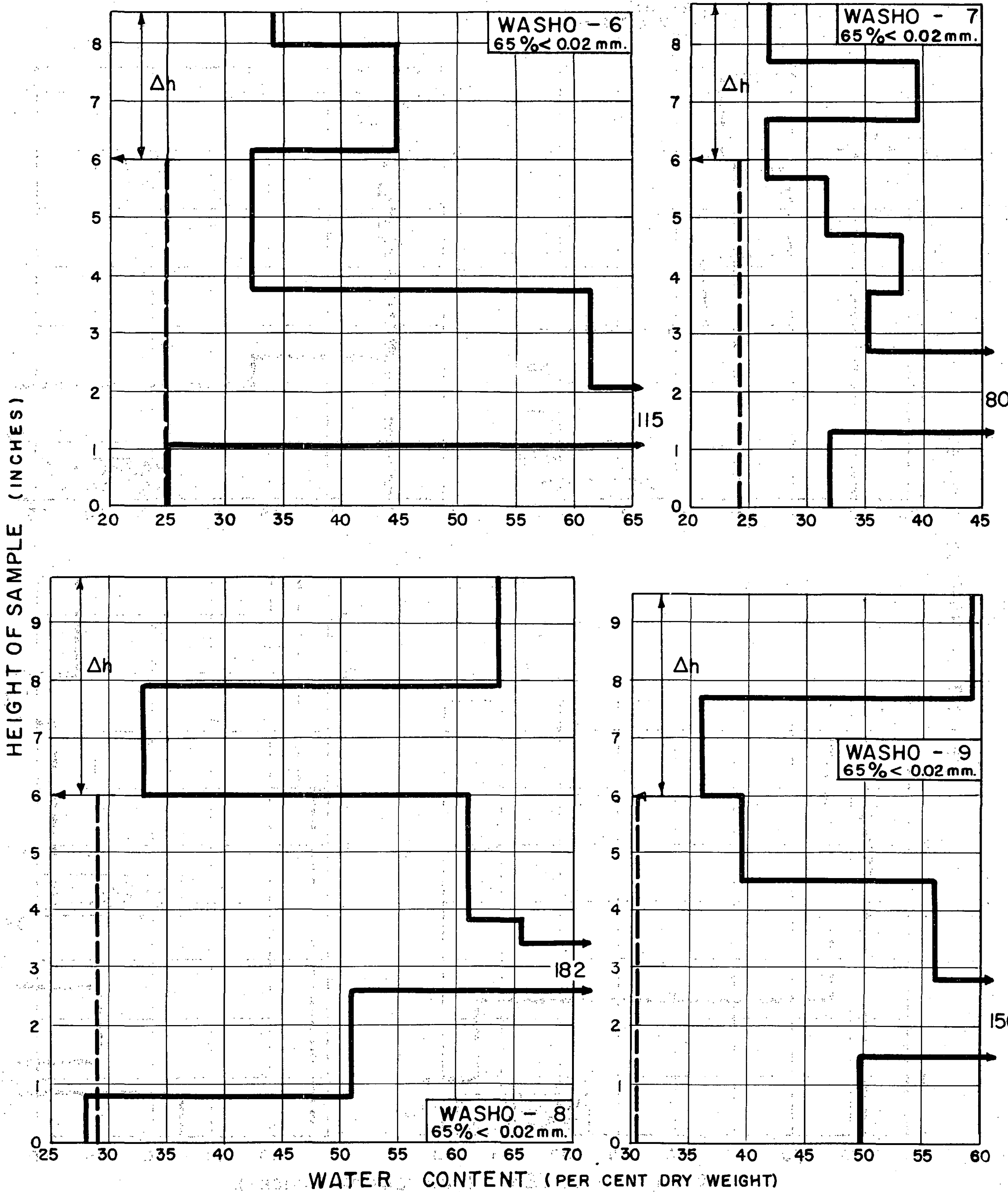
PLATE B58



LEGEND

— — —	*ORIGINAL WATER CONTENT*
▬▬▬	*WATER CONTENT AFTER TEST*
←——	*ORIGINAL HEIGHT OF SAMPLE*
Δh	*INCREMENT OF HEAVE*

WATER CONTENT
VS
DEPTH



LEGEND

- - - *ORIGINAL WATER CONTENT*

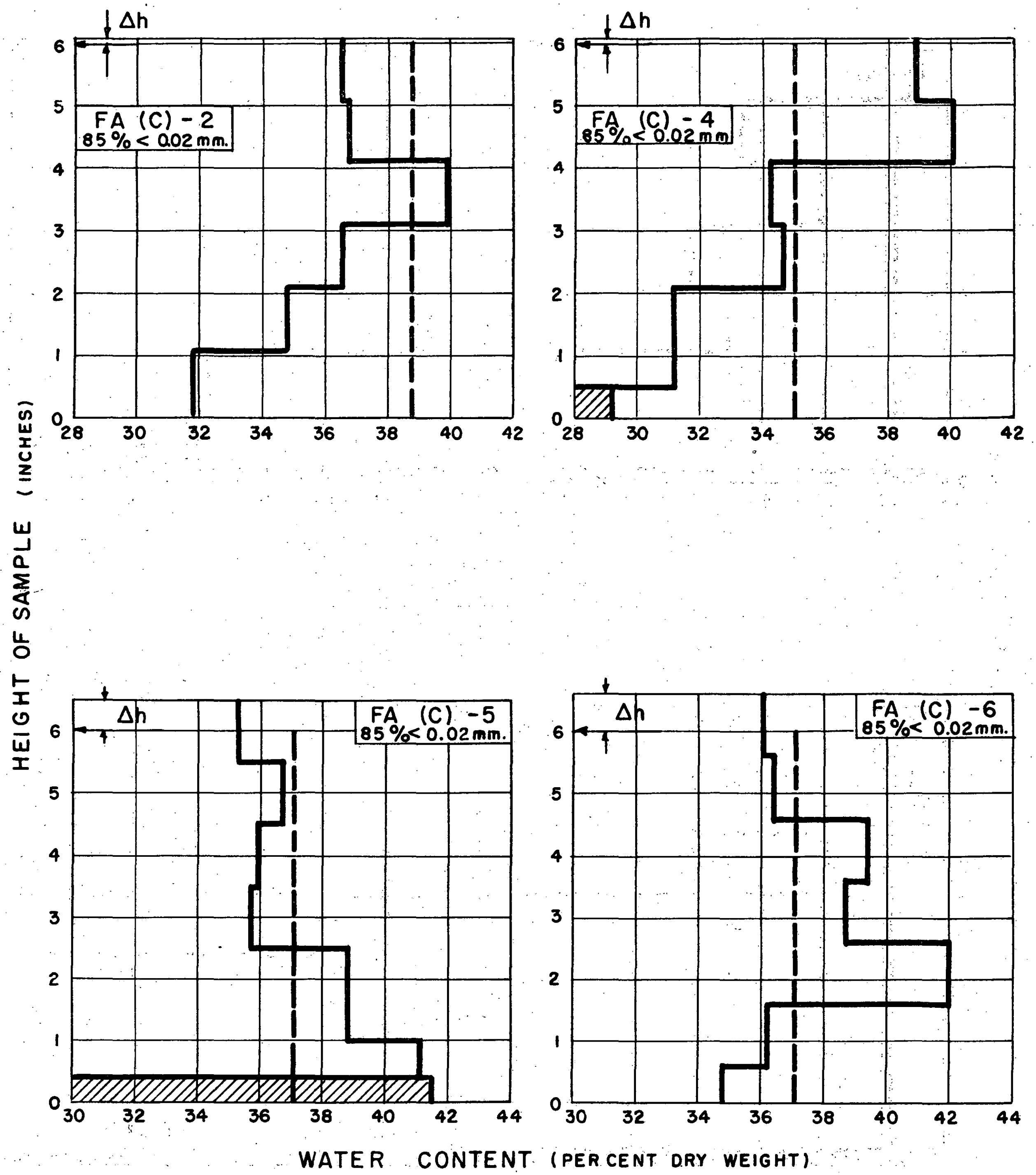
━ *WATER CONTENT AFTER TEST*

← *ORIGINAL HEIGHT OF SAMPLE*

Δh *INCREMENT OF HEAVE*

WATER CONTENT
VS
DEPTH

PLATE B60



LEGEND

▨ *UNFROZEN LAYER*

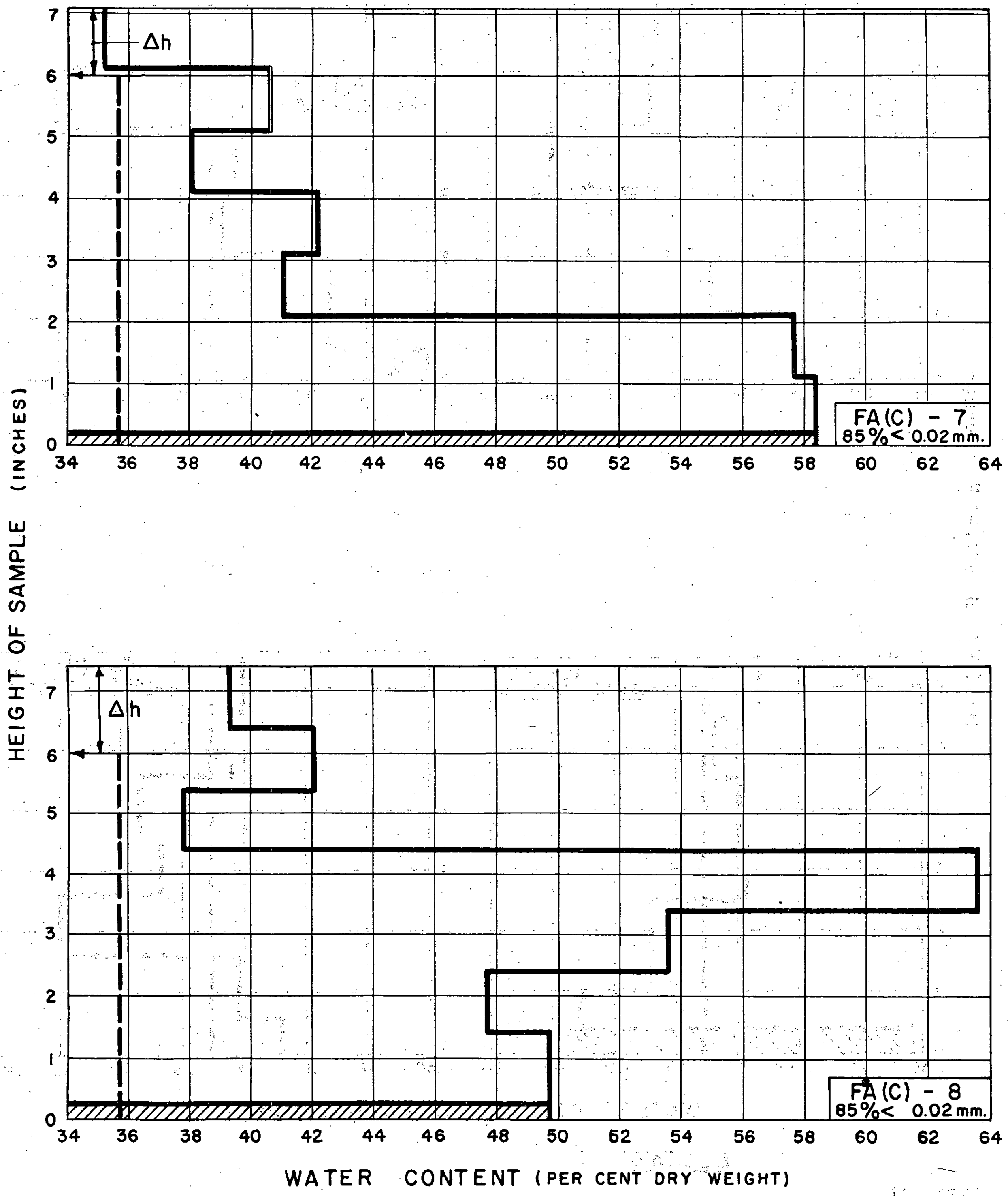
– – – *ORIGINAL WATER CONTENT*

━ *WATER CONTENT AFTER TEST*

← *ORIGINAL HEIGHT OF SAMPLE*

Δh *INCREMENT OF HEAVE*

WATER CONTENT
VS
DEPTH



LEGEND

▨ *UNFROZEN LAYER*

— — — *ORIGINAL WATER CONTENT*

━━━ *WATER CONTENT AFTER TEST*

← *ORIGINAL HEIGHT OF SAMPLE*

Δh *INCREMENT OF HEAVE*

WATER CONTENT
VS
DEPTH

PLATE B62