CORPS OF ENGINEERS, U. S. ARMY

FROST INVESTIGATIONS

COLD ROOM STUDIES

MINERAL AND CHEMICAL STUDIES

by

T. William Lambe

APPENDIX A: ACFEL INVESTIGATIONAL DATA

Contract No. DA-19-016-eng-2640

TECHNICAL REPORT NO. 53

UNDER CONTRACT WITH

ARCTIC CONSTRUCTION AND FROST EFFECTS LABORATORY
U. S. ARMY ENGINEER DIVISION, NEW ENGLAND
WALTHAM, MASSACHUSETTS

FOR

OFFICE OF THE CHIEF OF ENGINEERS
AIRFIELDS BRANCH
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Revised April 1959

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FOREWORD

The following interim report presents the results of continuing studies to determine the effect of the mineral composition of soil fines and investigations of admixtures to prevent or minimize frost action in frost-susceptible subgrade soils and base course material.

The studies reported herein were carried out in Fiscal Year 1954 under a contractural agreement with Dr. T. William Lambe of the Massachusetts Institute of Technology, Cambridge, Massachusetts. They are a continuation of the work performed in Fiscal Years 1952 and 1953 as reported in Volume II of the Frost Investigations, Cold Room Studies, Third Interim Report of Investigations, October 1958, entitled, "Appendix C: Mineral and Chemical Studies".

The contractor obtained, prepared and furnished the Arctic Construction and Frost Effects Laboratory (ACFEL) the fines, chemicals and other admixtures for cold room tests and also performed necessary chemical and mineralogical tests for the studies. The results of the freezing tests were summarized and submitted to the contractor by the Laboratory for interpretation and recommended additional tests. During the course of the studies, frequent conferences were held between Dr. Lambe and personnel of the Laboratory at which agreements were reached concerning the direction of the continuing studies.

This report was written by Dr. T. William Lambe in fulfillment of the Fiscal Year 1954 contract and was reviewed and processed for reproduction by the Laboratory. The investigations are being continued by Dr. Lambe.

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SYNOPSIS

This report describes the research conducted during the Fiscal Year 1954. It is a continuation of work done during Fiscal Years 1952 and 1953 which was presented in Appendixes C and D, Volume 2, of the report by the Arctic Construction and Frost Effects Laboratory[10]*

The immediate objectives were: (1) to correlate the composition of fines and the rate of frost heave of soil and (2) to find additives which in trace quantities can reduce the frost susceptibility of soil.

The addition of sodium montmorillonite and of peat fines to a sandy clay, a silt and a clay soil generally resulted in a decrease in rate of frost heave. Both the hydrated and dehydrated forms of a natural halloysite when frozen with water available for ice segregation were found to be highly frost-susceptible, with the hydrated form more susceptible.

A number of chemical additives were effective as frost modifiers, with dispersants showing the most promise. Some dispersants, at a material cost as low as of about 1 to 3 cents per cubic foot of soil, reduced the rate of heave of a sandy clay and a silt to less than half of the values of the untreated soils. Frost tests were performed and reported on 32 additives; 12 of these are listed which will reduce the rate of heave by 50 percent or more when one percent or less of additive is used.

Ten specific conclusions are given. Continuation of the research work is recommended and eleven specific investigations are proposed. A reference bibliography is included.

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

PART I - INTRODUCTION

1-01. Background and Purpose. Experience has shown that both the formation of ice lenses in a soil on freezing and the reduction of soil strength on thawing are dependent on the presence of small-sized particles in the soil. Tests have shown that the frost susceptibility of a soil is related not only to the size and amount of soil fines but also to the composition of these fines. The Arctic Construction and Frost Effects Laboratory[9] began a study on the relationships of frost behavior and soil composition in 1951. This research was continued by the Arctic Construction and Frost Effects Laboratory in conjunction with the contractor during the Fiscal Years 1952 and 1953[10].

In this report the terms "additive" and "frost modifier" are used to describe materials added to soils for the purpose of reducing the heaving of the soil on freezing and/or the loss of strength of the frozen soil on thawing. In general, such materials are used in a relatively small percentage of the soil weight.

For a number of years the search for additives which will reduce the susceptibility of soil to frost action has been conducted by various investigators. While materials such as asphalt and portland cement will prevent frost heave, the level of treatment required is of the order of magnitude normally used in a pavement. The cost of the additive for such high-level treatments and the cost of incorporating these quantities in the field make the use of these materials to reduce frost heave generally uneconomical. In fact, any additive, even if effective in small quantities which would require drying of the soil before or after incorporation would be considered unfavorably. Recent advances in soil technology suggested that trace quantities, of additives which react with the soil components to alter their surface characteristics might significantly alter the frost characteristics of soils. Accordingly, the Arctic Construction and Frost Effects Laboratory, in conjunction with the contractor, conducted a laboratory investigation during the Fiscal Years 1952 and 1953 (ref. 10, Volume 2) on the effect of various trace chemicals on the frost characteristics of soil.

The present report for the Fiscal Year 1954 covers studies which are a continuation of the 1952-1953 work. The two purposes of these studies are:

(a) To develop correlations between the composition and frost behavior of soils, and

(b) To search for additives which, in trace quantities (one percent of the dry soil weight or less), will reduce the frost susceptibility of soils.

The development of correlations between composition and frost behavior of soils will not only permit better prediction of the frost behavior of natural soils, but will also aid in the delineation of the mechanism through which soils heave upon freezing and lose strength upon thawing. The value of economical treatments to reduce the frost susceptibility of soils is obvious. The contractor has never visualized the possible discovery of a magic chemical which, at low cost, will transform a highly frost-susceptible soil to one completely non-frost-susceptible. He has, however, set as a reasonable goal the discovery of a treatment which would reduce the frost heave of a soil to one-half, or less, of its untreated value at a reasonable cost. As the results presented in this report show, a treatment which fulfills this goal, at least on certain soils, has been developed.

The contractor is aware that some criticism may be levied relative to the scatter of the test results and scarcity of tests in some of the areas covered in this report. One can argue, with much justification, that in nearly all studies of soil strength, compressibility, permeability, density, etc. should involve statistical analyses. Early in the planning stage, it was decided to run few specimens of each treatment and to use miniature-sized specimens, and thus possibly be exposed to criticism. The use of laboratory freezing tests, as a measure of frost susceptibility, is also open to criticism. In setting up these investigations, a several-step program was envisaged: (1) an extensive laboratory screening evaluation of additives; (2) additional laboratory evaluation, employing several specimens treated with each promising additive; (3) careful theoretical and laboratory study of the additives which were still shown to be promising to determine if they had any deleterious effects on other properties, such as compressibility and strength; (4) limited field tests; (5) carefully conducted field tests. The contractor believes that the ultimate answer lies in careful and thorough field testing of any soil inhibitor. The data in this and the preceding report[10] are on the first phase of the investigation. To run sufficent tests to permit statistical analysis in this first stage would be, in the contractor's opinion, unwise use of limited time and testing facilities. Although some scatter of test data is apparent in these tests, and would also, in all probability, occur in subsequent tests, it is felt that such scatter will not cause any really promising additive to be overlooked.

1-02. Authorization. The work performed by the contractor described in this report was authorized by Contract No. DA-19-016-ENG-2640 between the Arctic Construction and Frost Effects Laboratory and the contractor, T. William Lambe.

1-03. Scope of Studies. The scope of the studies covered by the contract mentioned above and described in this report was very extensive. Many materials have been studied with the primary objective of determining trends and thereby narrowing the limits of the future research. It is intended that in future work those additives which have shown promise will be studied in greater detail, in order to evaluate their effectiveness more completely, both in the laboratory and in the field.

As has been pointed out, this report describes work that is a continuation of past research, and which will also be continued during the next fiscal year; in other words, this is a progress report. Time and personnel limitations prevented the accumulation of all the data desired and, therefore, the conclusions drawn in this report are tentative pending the performance of additional tests.

1-04. Acknowledgments. The contractor (and writer of this report) obtained, prepared and furnished to the Arctic Construction and Frost Effects Laboratory mono-mineral soils and additives for the frost tests. The frost tests were run and the test data summarized at the Arctic Construction and Frost Effects Laboratory by personnel of the Laboratory. The interpretation of the data and recommendations of this report are those of the contractor.

The contractor discussed various phases of the research with his colleagues on the staff of the Soil Stabilization Laboratory at the Massachusetts Institute of Technology, especially Professor Alan S. Michaels, an industrial chemist, and Dr. R. Torrence Martin, a clay mineralogist. Dr. Martin aided in the preparation of specimens, the conduct of chemical and mineralogical tests, and in the preparation of this report. The laboratory preparation of the various specimens furnished ACFEL was done by Mr. James K. Mitchell and Mr. Clyde N. Baker, Jr. of the M.I.T. Soil Stabilization Laboratory. The contractor discussed possible chemical additives to reduce frost heave with various chemical company representatives and obtained a number of experimental products from them.

PART II - EFFECT OF COMPOSITION ON FROST BEHAVIOR OF SOIL

2-01. Soils and Test Procedures. Gradation curves for the four soils used in this investigation are shown on Plate 1. More complete information on these and on sodium montmorillonite will be found in Appendix C, Volume 2 of the report for Fiscal Years 1952 and 1953[10]. These soils, on which additives were tried, are McNamara sand, Fort Belvoir sandy clay, New Hampshire clayey silt and Boston blue clay.

The methods of specimen preparation,freezing tests and examination of frozen specimens are described in detail in Appendix D of the above referenced report.

Miniature specimens were used for most of the tests, but the larger standard specimens were also used (see table below). Unless otherwise stated, all soil specimens were blended, adjusted approximately to optimum water content (based on the property of the untreated soil), equilibrated for at least 24 hours, molded, saturated with water and frozen in an open system type of test at a rate of 32°F. penetration of approximately 1/4-inch per day.

Plots showing the heave, degree-hours, and penetration of the 32°F. temperature versus time are shown in Appendix A, Plates A1 through A10.

The specimen sizes and freezing rate for both miniature and standard specimens are as follows:

	Miniature Specimens	Standard Specimens
Diameter (in.)	1.25	5.91
Height (in.)	3.108	6
Volume (cu. ft.)	1/454	0.095
Rate of freezing	0.25 in/day	0.25 in/day
Seeding used	At 28°F.	If necessary at 28°F.
Specimens frozen in each run	36	4

2-02. Effect of Sodium Montmorillonite. The Arctic Construction and Frost Effects Laboratory first tried to correlate composition and frost behavior of soil by making mineral analyses on a number of soils with known frost behavior. The soils analyzed were, however, too heterogeneous for any conclusions to be drawn. It was then decided that more progress could be made by subjecting to freezing tests soils to which fines of known composition had been added and soils having essentially mono-mineral fines. During the period covered by this report, it was planned to make a number of tests in which selected mono-mineral fines were added to a non-frost-susceptible sand. The pressure of other work at ACFEL necessitated the postponement, until the Fiscal Year 1955, of most of the tests on non-frost-susceptible soils plus selected fines. Since the very few results obtained do not permit the drawing of conclusions over those reported in last year's report[10], they will not be included in this report but will be given in the report covering the work of the Fiscal Year 1955.

Selected fines were also added to three frost-susceptible soils. A series of freezing tests was performed on miniature specimens to which either sodium montmorillonite or peat fines had been added. The test procedure is given briefly in Paragraph 2-01 above and is described in detail in a previous report[10] and the data obtained are presented in Appendix A, Table A1 of this report. Sodium montmorillonite, a clay mineral, (Wyoming Bentonite)was added to Fort Belvoir sandy clay, New Hampshire silt, and Boston blue clay* in concentrations varying from 0.01 to 12 percent of the soil dry weight. The specimens were then brought to a water content approximating optimum, equilibrated for at least 24 hours, compacted and then frozen. The results of these tests are presented in Plate 2 in which the rate of heave of each specimen, divided by the rate of heave of the specimen with no additive, is plotted as a function of additive concentration; the water content of the frozen specimen, divided by the water content of the blank is also plotted against additive concentration. Rate of heave ratios less than 1.0 show improvement, whereas ratios greater than 1.0 show that the mixture is not as satisfactory as the blank.

The data show few similar trends in all three soils. The sodium montmorillonite generally caused an increase in rate of heave when present in concentrations less than one percent but caused a decrease at greater concentrations. When the amount of sodium montmorillonite reached 12 percent, the rate of frost heave of all three of the treated soils was less than 25 percent of that of the natural soils. The presence of the sodium montmorillonite in the Fort Belvoir sandy clay and New Hampshire silt effected a reduction in the water content of the frozen treated soil compared to that of the frozen untreated soil. The reverse, however, was true with the Boston blue clay.

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* The results of classification tests on these three soils and a discussion of sodium montmorillonite are given in a previous report[10].

The results (Plate 2) are in substantial agreement with those reported in last year's report and with those expected from theoretical considerations. The results indicate that for concentrations of sodium montmorillonite greater than about 2 percent of the dry soil weight, the permeability of the soil is too low for the soil to transmit sufficient water for excessive heaving at the freezing rate employed in the tests.

Since, generally, soil strength is inversely related to soil moisture content, the water content of the frozen specimen is some measure of specimen strength upon thawing. In accordance with this assumption, the strength of the Fort Belvoir sandy clay and the New Hampshire silt with the sodium montmorillonite should be stronger immediately after thawing than the natural soils after thawing.

While the presence of sodium montmorillonite in quantities greater than about two percent of the soil dry weight apparently can reduce the frost susceptibility of the soil, one should not infer that sodium montmorillonite is recommended as a frost modifier. There are possible undesirable effects (e. g. volume changes related to weather variations, reduction in rate of drainage, gradual increase of moisture content, increased compressibility) of sodium montmorillonite in soil which can more than offset any beneficial influence on frost behavior.

2-03. <u>Effect of Peat Fines.</u> Frost tests were run on miniature specimens of Fort Belvoir sandy clay, New Hampshire silt and Boston blue clay to which various concentrations of organic matter in the form of fibrous peat finer than 2 mm were added. The peat*, which had not been dried after sampling, was added to each soil, the mixture brought approximately to optimum moisture content, equilibrated for at least 24 hours, compacted and then subjected to frost tests. The results of these tests, presented in Plate 2, show that the peat fines caused a reduction in rate of frost heave at all concentrations in the Fort Belvoir sandy clay and New Hampshire silt. At concentrations less than one percent and greater than 10 percent the peat fines caused an increase in the rate of frost heave of the Boston blue clay.

As was true with sodium montmorillonite, the peat fines should act to reduce frost heave by reducing the permeability of the soil. Since both sodium montmorillonite and peat fines increase the water holding capacity of the soil, they may serve to increase the frost susceptibility of the soil when subjected to very low rates of freezing.

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* The peat fines (minus 2 mm size) had a specific gravity of 1.61, liquid limit of 375 and a plastic limit of 260.

2-04. Halloysite ($4H_2O$) vs. Halloysite ($2H_2O$). The clay mineral, halloysite, a member of the kaolin group, was once thought to be a very rare mineral. Mineralogists now suspect it may not be as rare as once thought but that its presence is often missed because of the difficulties of properly identifying the mineral. While halloysite is chemically almost identical with, and structurally very similar to kaolinite[3], there is one major difference between the two minerals. Halloysite can contain water chemically combined in the mineral lattice up to 14 percent of its dry weight. There are, therefore, two limiting forms, halloysite ($4H_2O$) and halloysite ($2H_2O$) as well as all gradations between these two extremes. Since halloysite ($4H_2O$) can convert irreversibly to halloysite ($2H_2O$) very easily under normal environmental conditions, differences in properties between the two forms are important.

A specimen of the hydrated halloysite was obtained from a soil consisting mainly of this material in Nairobi, Kenya, East Africa, and subjected to detailed laboratory tests in the M.I.T. Soil Stabilization Laboratory[2]. Plate 3 summarizes some of the laboratory tests on the two extremes, halloysite ($4H_2O$) and halloysite ($2H_2O$). Particle size data are given in reference[2]. The $4H_2O$ form showed 56 percent and the $2H_2O$ form 50 percent finer than #200 sieve (0.074 mm).

Frost tests were run on the large standard specimens (Par. 2-01 above) of the two extreme forms, halloysite ($4H_2O$) and halloysite ($2H_2O$). These materials were not blended with sand, other soil or any other material except water. The results of these frost tests are presented in Table 1. These data show that the amount of frost heave and the water content of the frozen soil of the $4H_2O$ form were about twice the corresponding values of the $2H_2O$ form. Since the lattice water in the hydrated halloysite would be expected to freeze, the water content after freezing and the amount of heave would be expected to be only slightly larger in the hydrated form than in the dehydrated form. The permeability of the $2H_2O$ form is slightly less than that of the $4H_2O$ form which would also be expected to make the $2H_2O$ form somewhat less susceptible. The great difference between the two is, however, surprising. Based on the very limited test data available, from the viewpoint of frost susceptibility, halloysite ($4H_2O$) should be converted (if feasible) to halloysite ($2H_2O$) when encountered on a practical job.

PART III - EFFECT OF ADDITIVES

3-01. General. Studies have been made by the Corps of Engineers[7,8] and others to determine the effectiveness of salts and of bitumen in preventing ice segregation in soils. Salt can reduce frost heave primarily, by lowering the freezing point of the pore water and secondarily, by altering the structure of soil. Since the salt-pore water is usually replaced by salt-free ground water, the beneficial effects of salt as a frost modifier are generally temporary. Ice segregation can be prevented by the addition of bitumen; however, the amount required to reduce segregation to a negligible value approaches the bitumen content commonly employed for the construction of bituminous pavements.

For an additive to be an economical frost modifier, it must be either a very cheap material or it must function at a very low treatment level. Since additives considerably cheaper than bitumen are not likely to be found, the research described in this report was directed primarily toward the discovery of frost modifiers effective at very low concentrations. Logic suggests that a soil additive effective in trace quantities must function through a reaction with the soil, since the volume of voids in soil is of such a magnitude that high levels of inert fillers are required to plug the voids.

The trace additives investigated are discussed under three groups; dispersants, aggregants, and other additives, and are listed in Table 2. Miniature specimens of three soils, Fort Belvoir sandy clay, New Hampshire silt, and Boston blue clay were treated with various concentrations of various additives and subjected to freezing tests. The soils and detailed test procedures employed are described above, Paragraph 2-01, and in a previous report[10]. Concentrations of additive ranged from 0.01 to 1 percent of dry soil weight.

Experience showed that the scatter of experimental data within one tray of specimens was generally small; however, minor differences in freezing conditions among the various trays caused variations in rate of frost heave among the different trays. To permit comparison of the results from different trays, specimens or blanks were included in each tray and results have been plotted and analyzed as ratios in the same manner used on the tests with sodium montmorillonite (2-02 above). A similar procedure was employed to plot and study the water content of specimens after freezing.

3-02. Dispersants.

a. Theory. Soil engineers have known for many years that the properties of a fine-grained soil depend, to a considerable extent, on the arrangement of particles, or "structure". The strength, compressibility, and permeability of soils can be altered by rearranging particles by mechanical work; i.e., remolding. The ACFEL[10] found that remolding reduced the heave of a non-stratified soil when frozen with access to water. The causes of these property changes effected by remolding have been discussed elsewhere[5].

The structure of a soil can also be altered by chemical, or most effectively by chemical plus mechanical means. Certain chemicals, called dispersants, can increase the electrical repulsion between particles thereby facilitating movement of particles to positions of greater stability to gravitational, seepage and electrical forces. The most stable arrangement of the flat clay crystals is one of parallelism; i.e., a high degree of crystal orientation. The ability of dispersants to modify the engineering behavior of soil has been shown[6].

The exact mechanism by which dispersants function is not known. The polyanion part of the dispersant removes exchangeable polyvalent cations from the soil and permits the cations of the dispersant to become soil ions. This exchange of monovalent cations, usually sodium, for polyvalent cations such as calcium results in an increase of negative electrical potential which constitutes the repulsion between particles. There is evidence that some of the anions from the dispersant also become attached to the soil particles and thereby further increase the negative potential of the soil. Tests have shown that small treatments of dispersant can cause significant increases in the exchange capacity of soil.

b. Effect of Various Dispersants. The results of freezing tests on Fort Belvoir sandy clay, New Hampshire silt and Boston blue clay treated with various dispersants are summarized in Appendix A, Tables A1 and A2, and plotted on Plates 4, 5, and 6. Plate 4 shows the following trend:

(1) The higher the dispersant concentration (within the limits tested), the lower was the rate of heave.

(2) There is no dispersant clearly superior to the others.

While the data are too limited to draw broad conclusions, they do permit some theoretical examination. Since the dispersant-soil reaction is one between the chemical and the soil particle surface, the amount of dispersant required is directly related to the surface area of the particles, or specific surface. Since the blue clay (92 percent finer by weight than 0.02 mm) has a much higher specific surface than that of the sandy clay (47 percent finer than 0.02 mm) and silt (60 percent finer than 0.02 mm), its higher dispersant requirements are expected (see Figures 1 and 3, Plate 4).

In addition to surface area, the state of aggregation of the natural soil influences the effect of the dispersant. There is, as yet, no good method of measuring this most important soil characteristic. While the Boston blue clay exists in situ in a moderately high state of aggregation, some of this structure has been destroyed by remolding. A more indicative test procedure would compare specimens: (1) undisturbed, (2) mechanically dispersed (remolded) by a known amount of work per mass of soil, and (3) dispersed mechanically (known amount of work) and chemically (known amount of chemical).

Research[1,6,10] has shown the importance of dispersion and mixing uniformity on soil behavior. The contractor believes that the amount of mechanical dispersion work employed in preparing specimens for frost tests or strength tests should be measured and recorded. For example, available data[10] suggest that, if a runway had to be constructed at a site with Boston blue clay in the freezing depth, the clay should be remolded and re-compacted to reduce heaving. Figure 3, Plate 4 indicates that one percent of dispersant would reduce the heave still further. The amount of work to remold the clay, or more important, the possible reduction of this work by a dispersant, is not shown by the data. In other words, the benefits of the chemical in reducing the remolding work are not measured or recorded.

Figure 3, Plate 4 indicates that dispersants at low concentrations apparently had an adverse effect on the Boston blue clay. A comparison of Table A1 in Appendix A with Figure 3 Plate 5 shows that, whereas the maximum dry density of Boston blue clay with dispersant is greater than that of the untreated clay (e.g., 106.0 pcf with 0.5 percent dispersant; 103.4 pcf with 0.1 percent dispersant; and 102.4 pcf untreated), the dispersant-treated specimens, from which the data in Figure 3 Plate 4 were obtained, have compacted densities considerably lower than the blanks. Plate 6 shows that 0.5 percent sodium tetraphosphate reduced the average rate of heave of the Boston blue clay to about half of the untreated value. (Note that on Plate 6 the ordinates are the actual rates of heave, not a ratio as plotted on Plate 4). These facts suggest that the use of too much or too little molding water resulting in low dry density explains the unusually high rate of heaves shown on Plate 4. On theoretical grounds at least, a dispersant should have no detrimental effects on the frost characteristics of a reasonably homogeneous soil.

c. Effect of Molding Water Content. To see the effect of molding water content on the frost susceptibility of treated soils, specimens of soil were compacted at various moisture contents and subjected to freezing (see Table A2 in Appendix A). The results of these tests are presented in Plate 5; the rate of heave data in Plate 5 are replotted in Plate 6. Since the more the moisture (within limits), the easier the soil particles slide to positions of stability, specimens compacted slightly on the wet side of optimum would be expected to heave less. This expectation is exhibited by Boston blue clay (Figure 3, Plate 5) but not by the sandy clay or silt (Figures 1 and 2, Plate 5). There is apparently sufficient water in the neighborhood of optimum for maximum structure in the sandy clay and silt.

The rates of heave for the New Hampshire silt soil treated with 0.1 percent dispersant vary over a very wide range; the cause for this variability is not known.

d. Conclusions. The data show that dispersants can cause a significant reduction in the frost susceptibility of soil. In some cases a treatment of 0.1 to 0.5 percent of the dry soil weight reduced the rate of heave of New Hampshire silt and Fort Belvoir sandy clay to as little as 1/2 to 1/7 that of the untreated soil. For the most part treatment of 0.5 percent reduced the heave ratio of Boston blue clay to 0.5 or less. In general, the higher the dispersant treatment, up to the maximum value tested of one percent of dry weight, the greater is the reduction in heave.

The cheapest dispersants (7 to 10 cents a pound) were as effective as any. The cost of the additive for treatment with 0.5 percent of a 10 cent a pound chemical would be about 6 cents per cubic foot.

Field mixing, or mechanical dispersion alone, might reduce the frost susceptibility of a soil. Altered testing techniques should permit an approximate evaluation of the contribution of mechanical and chemical dispersion both separately and when combined.

3-03. Aggregants.

a. Theory. There are additives which decrease the electrical repulsion between soil particles, thereby effectively increasing the interparticle attractive forces. There are also additives consisting of long chain molecules, the ends of which can link to particles. If such additives, termed "aggregants", are added to soils in suspension or in a very loose state, they will cause the soil particles to form loose aggregates.

The addition of aggregants to soils in a loose state, in effect, makes larger particles out of the smallest ones. Theoretical considerations suggest that aggregants might cause coarse soils with some fines to behave more like coarse soils by "removing" the fines. The frost susceptibility of silts, silty sands, and silty gravels should be reduced by aggregants.

A series of frost tests was run on Fort Belvoir sandy clay, New Hampshire silt and Boston blue clay treated with various aggregants to evaluate the effectiveness of aggregants as frost modifiers. The results of these tests are summarized in Table A1, Appendix A and Plate 7.

b. Effect of Various Aggregants. Figure 1, Plate 7 shows that all of the aggregants reduced the rate of frost heave of Fort Belvoir sandy clay but had little influence on the water content of the soil after freezing. The various aggregants were approximately equally effective but less effective than the dispersants (compare Plate 4).

Figure 2, Plate 7 shows that some of the aggregants are more potent frost modifiers on New Hampshire silt than some of the dispersants while others are, in fact, deleterious (compare Figure 2, Plate 4). The reason for the great influence of aggregant concentration on frost behavior is not known. While other tests have shown that aggregant potency is an important function of concentration, the very wide difference between the action of 0.1 percent Guartec (rate of heave = 5.5 mm/day) and 0.5 percent (rate of heave = 0.8 mm/day) is unexpected.

Figure 3, Plate 7 shows that the aggregants tried have essentially no beneficial influence on the frost behavior of Boston blue clay in the concentrations which were used.

c. Discussion of Results. Since aggregants act on particles of high specific surface, a soil must have at least a moderate specific surface to be affected by them; similarly, the lower the specific surface of a soil affected by an aggregant, the lower the quantity of aggregant required. A comparison of Figures 1 through 3, Plate 7 shows that aggregant requirements of the silt are smaller than those of the sandy clay. Probably the aggregant requirements of the blue clay are greater than the maximum amount (one percent) tested.

The aggregants are generally fairly expensive materials, costing in the neighborhood of 80 cents a pound. One exception is Flocgel, a modified starch, costing approximately 12 cents a pound. In view of the unfavorable economic picture, unpredictable behavior, and performance inferior to dispersants, the aggregants will be given only secondary consideration in future tests. An exception is pointed out in the next section.

3-04. Other Additives.

a. Theory. Under the heading of "Other Additives" are included all materials studied which were not discussed under "Dispersants" or "Aggregants". These other additives were evaluated as frost modifiers since all were known to undergo some reaction with soil mineral surfaces.

Several of the chemicals (e.g. SC-50, and XS-1) consist of molecules, one end of which reacts irreversibly with the soil surface and the other end of which is hydrophobic, thus making the soil non-wettable with water. Other chemicals [e.g. mercury bichloride ($HgCl_2$) and lead acetate ($PbAc_2$)] furnish cations for ion exchange reactions which cannot be hydrated. These materials are usually termed "waterproofers".

Some materials included in this section aggregate soil particles; they are included here rather than under "Aggregants" because it is suspected that they may also exhibit some waterproofing action. Also a dispersant (Lignosol) is included in this section as it may also perform other functions.

b. Specimen Preparation. Fort Belvoir sandy clay and New Hampshire silt were treated with the material being evaluated, compacted into miniature specimens and then subjected to freezing tests. The method of chemical treatment varied from chemical to chemical. Most of the waterproofers were applied to the soil which was then air-dried. Not much concern was given to the practicality of the method of preparation since the tests described herein are essentially screening tests.

c. Effect of Other Additives. The test results, summarized in Table A1, Appendix A, and plotted on Plate 8, show that the following materials were observed to reduce the rate of heave to one half or less at the minimum percentages indicated:

Fort Belvoir sandy clay

* 1. Siliconate (SC-50) .05%

* 2. Lignosol 0.1%

* 3. Iron Chloride ($FeCl_3$) $< 0.3\%$

* 4. Quilon 0.5%

* 5. Volan 0.5%

* 6. Carbowax 200 0.5%

7. Lead Acetate ($PbAc_2$) $< 0.8\%$

* 8. Di-n-butylamine 1.0%

9. Tall Oil 1.0%

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* Materials found promising in tests during Fiscal Year 1953 (see reference 10, Volume 2, Table C6, Appendix C).

New Hampshire silt

* 1. Iron Chloride ($FeCl_3$) < 0.1%
  2. Lead Acetate ($PbAc_2$) < 0.3%
  3. Siliconate (XS-1) 1.0%

The beneficial effects of the water-soluble siliconates are not as great as had been expected. In view of their high cost, they will be given secondary consideration in future tests.

Other effective materials, particularly the cheaper ones like iron chloride (ferric chloride, $FeCl_3$) and Lignosol, merit further study. Ferric ion is a most interesting soil ion because of its high replacing capacity (since it is trivalent) and its ability to become fixed, and therefore, non-exchangeable. When it becomes fixed, i.e. no longer exchangeable, it usually links adjacent soil particles together in a relatively strong bond. The concentrations of mercury bichloride ($HgCl_2$), lead acetate ($PbAc_2$) and ferric chloride ($FeCl_3$) plotted in Plate 8 are those needed to satisfy the exchange capacity of the soils (estimated values, silt = 2 milli-equivalents (m.e.)/100 g and clay = 5 m.e./100 g). There is a possibility that some of the added salt did not participate in exchange but stayed in solution, thereby lowering the freezing point of the pore water.

Another cation that will become fixed to soil minerals is potassium. In view of the encouraging results with iron, potassium salts will be studied as possible frost modifiers. Usually the soil must be air-dried to cause ion fixation; the necessity of this drying in reducing frost will be investigated.

---

* Materials found promising in tests during Fiscal Year 1953 (see reference 10, Volume 2, Table C6, Appendix C.)

PART IV - CONCLUSIONS

Based on the test results presented in this report, a number of conclusions are drawn below. Because of the limited amount of data and the necessarily simplified testing conditions, the conclusions drawn must be considered tentative pending more extensive laboratory and, ultimately, field evaluation.

4-01. Composition and Frost Behavior of Soil.

a. At concentrations greater than one percent of the dry soil weight, montmorillonite decreased the rate of heave of the sandy clay, silt, and clay tested.

b. Peat fines (minus 2 mm size) caused a reduction in rate of heave in the sandy clay and silt; however in Boston blue clay, at concentrations less than one percent and greater than 10 percent, peat fines caused an increase in the rate of heave.

c. A specimen of halloysite ($4H_2O$) and a specimen of halloysite ($2H_2O$) were both highly frost-susceptible, with the $4H_2O$ form heaving twice as must as the $2H_2O$ form.

4-02. Dispersants.

a. Dispersants are very promising frost modifiers.

b. Because they are relatively cheap (7 to 11 cents a pound and up) and effective at low concentrations, dispersants offer promise of relatively economical soil treatment.

c. The cheap dispersants appear as effective as the expensive ones.

d. The effectiveness of dispersants is apparently independent of minor variations in molding water content.

4-03. Aggregants.

a. The relatively high cost, the unpredictableness, the sensitivity to concentration and the modest effectiveness, make those aggregants which have been tried, relatively unpromising as frost modifiers.

4-04. Other Additives.

a. Several other additives reduced the rate of heave on the two soils tested, Fort Belvoir sandy clay and New Hampshire silt.

b. Because of significant reduction in the rate of heave which they exerted and their relatively low cost, Lignosol and iron chloride are particularly promising.

PART V - RECOMMENDATIONS

Detailed recommendations based on the results obtained to date are given in paragraphs 5-01 and 5-02 below.

5-01. Composition and Frost Behavior of Soil.

a. Perform those tests on McNamara sand plus selected fines not completed during 1954.

b. Carry out frost-susceptibility tests on natural soils with addition of fines which are essentially monomineral.

c. Study the effect of natural organic matter on the frost characteristics of soil, by treating various soils with it and subjecting them to freezing tests. Investigate the effect of freezing rate on these soils.

5-02. Soil Additives.

a. Determine the effectiveness of dispersants on different soil types, by treating a number of frost-susceptible soils with a single cheap dispersant, e.g., sodium tetraphosphate (Quadrafos), and freezing them.

b. Search for a cheaper dispersant that is an effective frost modifier.

c. Consider tests that measure the work employed in mechanical dispersion and the strength of specimen after thawing.

d. Treat with an aggregant several silty and clayey gravels with borderline susceptibility, and subject them to frost tests.

e. Evaluate ion exchange-fixation treatments [e.g., with ferric chloride ($FeCl_3$) and potassium chloride (KCl)] for reducing frost heave.

f. Carry out tests employing a swelling polymer and tests with Portland cement plus dispersant (Daxad 11).

g. Investigate the effectiveness of treatments which alter the water holding capacity of soil; i.e., alcohol, methanol, swelling polymers, etc.

h. Consider application techniques for applying promising additives, especially means of in situ treatment such as leaching.

REFERENCES

1 Baker, C. N., Jr., Strength of Soil-Cement as a Function of Mixing. Highway Research Board, Washington, D. C., 1954.

2 Egbert, J. S. and Jones, T. T., A Comparative Engineering Study of the Hydrated ($4H_2O$) Forms of Halloysite. Submitted in partial fulfillment of the requirements for the S. M. degree, M.I.T., Cambridge, Massachusetts, 1954.

3 Grim, Ralf E., Clay Mineralogy. McGraw-Hill Book Co., Inc., New York, N. Y., 1953.

4 Hardy, R. M., Prevention of Frost Heaving by Injection of Spent Sulphite Liquor. Proceedings of Third International Conference on Soil Mechanics and Foundation Engineering, Vol. II, pp. 103-106, Switzerland, 1953.

5 Lambe, T. W., The Structure of Inorganic Soil. Proceedings American Society for Civil Engineers, Vol. 79, Separate No. 315, 1953.

6 __________, The Improvement of Soil Properties with Dispersants. Journal of Boston Society of Civil Engineers, Vol. 41, No. 2, pp. 184-207, 1954.

7 U. S. Army Engineer Division, New England, Corps of Engineers, Arctic Construction and Frost Effects Laboratory, Technical Report No. 4, Frost Investigation (1945-1946), Report on Studies of Base Course Treatment to Prevent Frost Action. Waltham, Massachusetts, 1946.

8 __________, Technical Report No. 11, Frost Investigation (1946-1947), Report on Studies of Base Course Treatment to Prevent Frost Action. Waltham, Massachusetts, 1947.

9 __________, Technical Report No. 36, Frost Investigations, Fiscal Year 1951, Cold Room Studies, Second Interim Report of Investigations. In two volumes, Waltham, Massachusetts, 1951.

10 __________, Technical Report No. 43, Frost Investigations, Cold Room Studies, Third Interim Report of Investigations. In two volumes with appendix by T. W. Lambe, Waltham, Massachusetts, Revised October 1958.

TABLE 1

SUMMARY OF FREEZING TESTS ON HALLOYSITE

LABORATORY SPECIMEN NUMBER (1)	DRY UNIT WEIGHT pcf	SPECIFIC GRAVITY	VOID RATIO e	INITIAL DEGREE OF SATURATION %	AVERAGE WATER CONTENT		HEAVE (2) %	AVERAGE RATE OF HEAVE mm/day	FROST SUSCEPTIBILITY CLASSIFICATION
					BEFORE TEST %	AFTER TEST %			
H-1	73.9	2.95	1.492	98.2	49.7	117.3	111.0	6.4	High
H-2	67.8	3.03	1.790	99.8	58.9	212.7	221.3	10.7	Very High

NOTES:

(1) Specimen H-1 designates halloysite ($2H_2O$)

Specimen H-2 designates halloysite ($4H_2O$)

(Standard, not miniature, specimens were used for these frost tests)

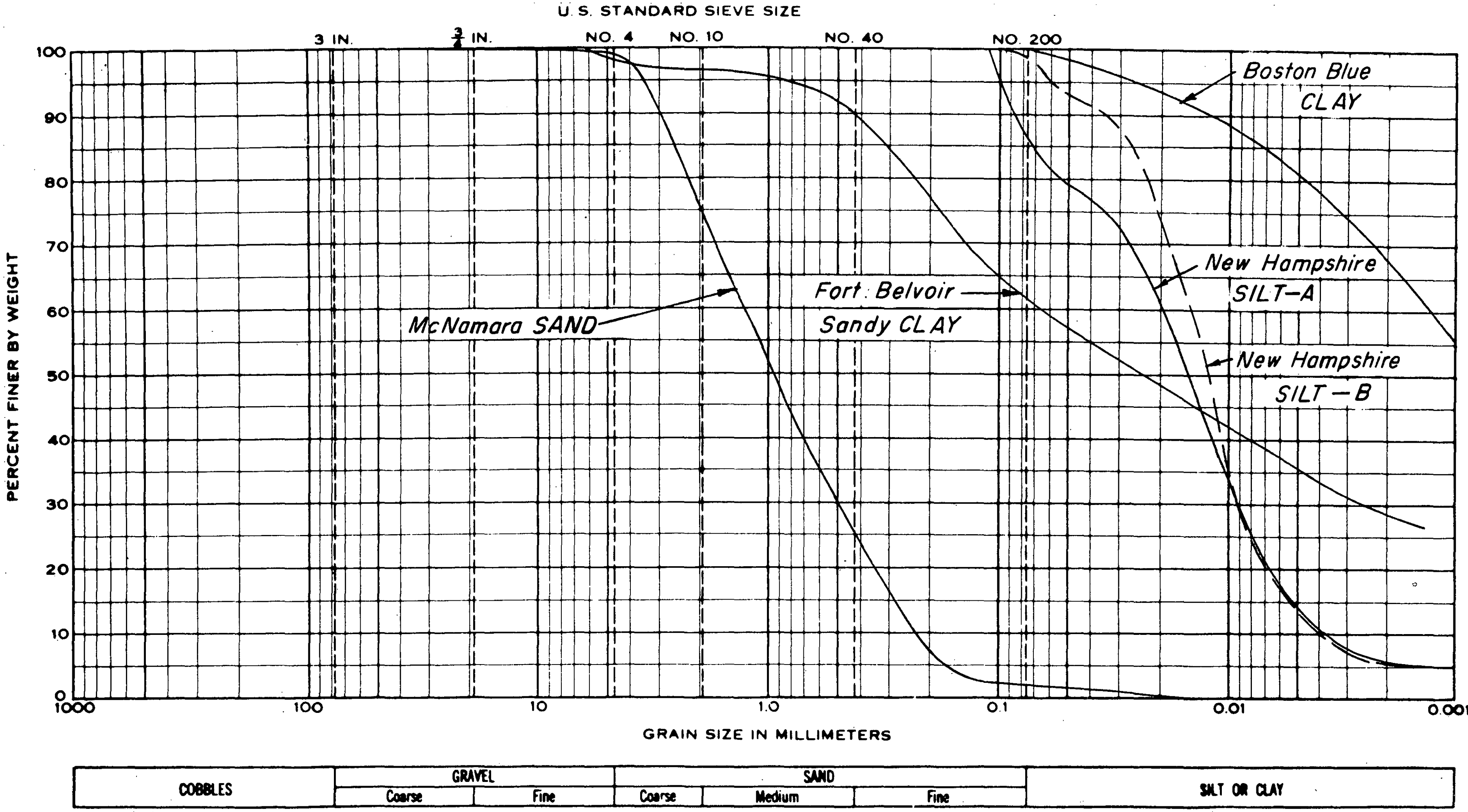
(2) Percent heave is based on original height of frozen specimen.

TABLE 2

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954
TABLE 2

ADDITIVES TRIED AS FROST MODIFIERS

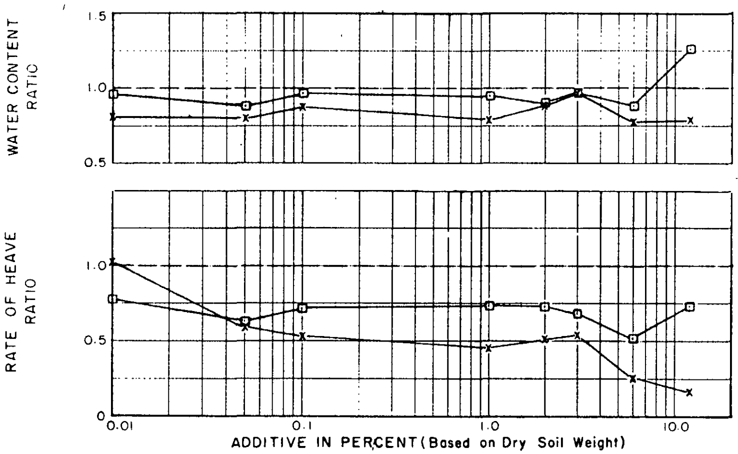
CLASS	TRADE	CLASS OF CHEMICAL	CHEMICAL NAME	APPROX. PRICE PER ACTIVE LB. (1954)	FORM SUPPLIED	SUPPLIER
I Dispersants	-	Polyphosphate	Sodium Tripolyphosphate, $Na_5P_3O_{10}$	$ 0.10	Powder, Crystalline	Westvaco Chemical Company
	-	Polyphosphate	Sodium Hexametaphosphate, $NaPO_3$	$ 0.105	Powder, Granular, Flakes	Westvaco Chemical Company and Rumford Chemical Works
	Quadrafos	Polyphosphate	Sodium Tetraphosphate, $Na_6P_4O_{13}$	$ 0.105	Powder, Granular	Rumford Chemical Works
	Marasperse C	Lignosulfonate	Calcium Lignosulfonate	$ 0.0675	Powder	Marathon Corporation
	Marasperse N	Lignosulfonate	Sodium Lignosulfonate	$ 0.105	Powder	Marathon Corporation
	Versenate	Di-Sodium Salt of Ethylene Diamine Tetra Acetic Acid (Dihydrate)	-	$ 0.55	-	Bersworth Chemical Company
	Daxad 11	Sodium Sulfonate	Polymerized Sodium Salts of Alkyl Napthalene Sulfonic Acid (Alkyl, - Short Chain)	$ 0.25	Powder	Dewey & Almy Chemical Company
	Tamol 731	-	-	$0.75 to $1.00	Granular	Rohm & Haas Company
II Aggregants	CRD-197	Sodium Salt of a Polymer	-	$0.50 to $1.00	Powder	Monsanto Chemical Company
	Flocgel	Starch	-	$ 0.12	Powder	W. A. Scholten's Chemische Fabrieken N. V., Foxhol, Netherlands
	Guartec	-	-	-	Powder	-
	PVA	-	Polyvinyl Alcohol	$ 0.75	Powder	DuPont, Electrochemicals Division
	Krilium #6	Maleic Polymer	-	$0.50 to $1.00	Powder	Monsanto Chemical Company
	Agrilon Na	Polyacrylate	Sodium Polyacrylate	$0.50 to $1.00	Solution, Flakes	American Polymer Corporation
III Other Additives	Vegetable Pitch 250	-	-	$ 0.02	Liquid	General Mills, Incorporated
	-	Tall Oil	-	$ 0.03	Liquid	General Mills, Incorporated
	-	Spent Vegetable Residue	-	-	Liquid	General Mills, Incorporated
	SC-50	Siliconate	Sodium Methyl Siliconate	> $ 2.00	Solution	General Electric
	Volan	Chrome Complex	Methacrylate Chromic Chloride	$ 1.50	30% By Weight in Isopropanol	DuPont, Grasselli Works
	Quilon	Chrome Complex	Stearated Chromic Chloride	$ 0.55	30% By Weight in Isopropanol	DuPont, Grasselli Works
	-	Di-n-Butylamine	-	-	Liquid	-
	Lignosol	Lignosulfonate	-	$ 0.05	Solution or Powder	Lignosol Chemicals, Limited
	-	Salt	Lead Acetate	$ 0.22	Crystalline	Mallinckrodt Chemical Works
	-	Salt	Ferric Chloride	$ 0.055	Crystalline	Mallinckrodt Chemical Works
	-	Salt	Mercuric Chloride	$ 0.0478	Crystalline	Mallinckrodt Chemical Works
	Carbowax 6000	-	Polyethylene Glycol 6000	$ 0.35	Granular	Carbide & Carbon Chemical Co.
	Carbowax 200	-	Polyethylene Glycol 200	$ 0.25	Liquid	Carbide & Carbon Chemical Co.
	-	-	Hexamethylene Diamine	$ 0.45	-	Carbide & Carbon Chemical Co.
	Primene 81R	Amine	Tertiary Alkyl Amine	$ 0.415	Solution	Rohm & Haas Company
	XS-1	Siliconate	Sodium Methyl Ethyl Propyl Siliconate	> $ 2.00	Solution	Dow Chemical Company



GRADATION CURVES OF SOILS SELECTED FOR TESTS

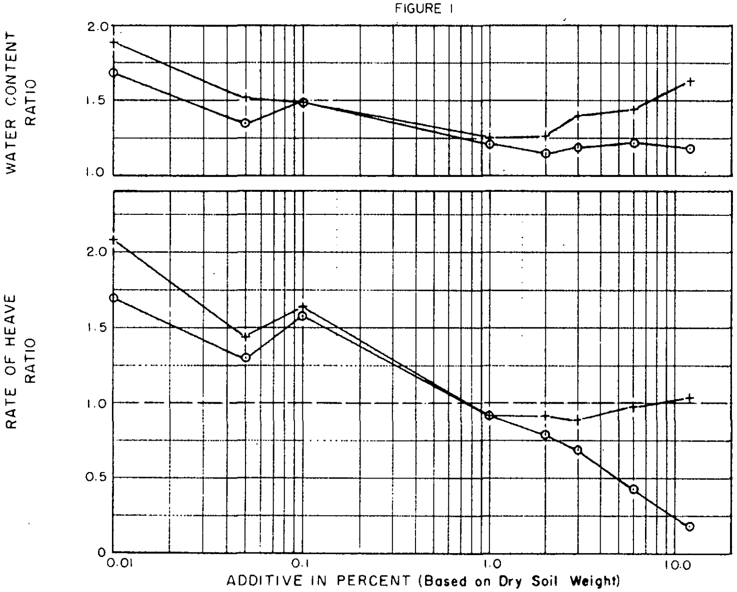
PLATE 1

PLATE 2



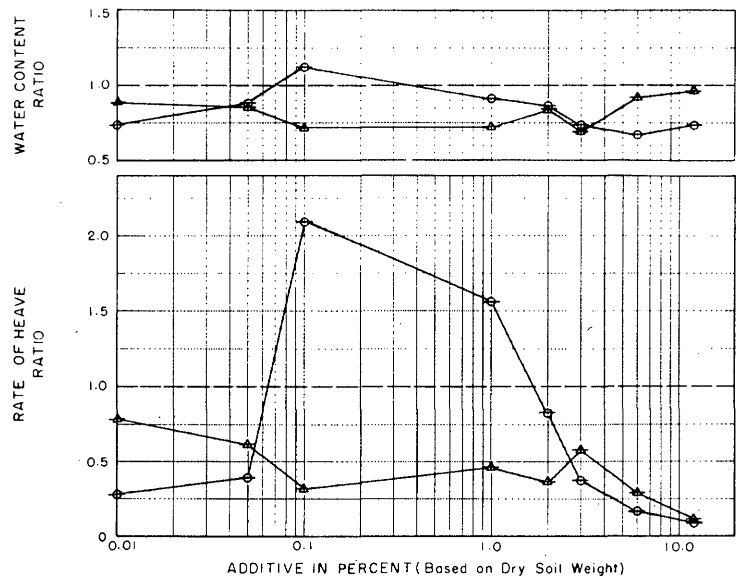
FORT BELVOIR SANDY CLAY

FIGURE 1



BOSTON BLUE CLAY

FIGURE 3



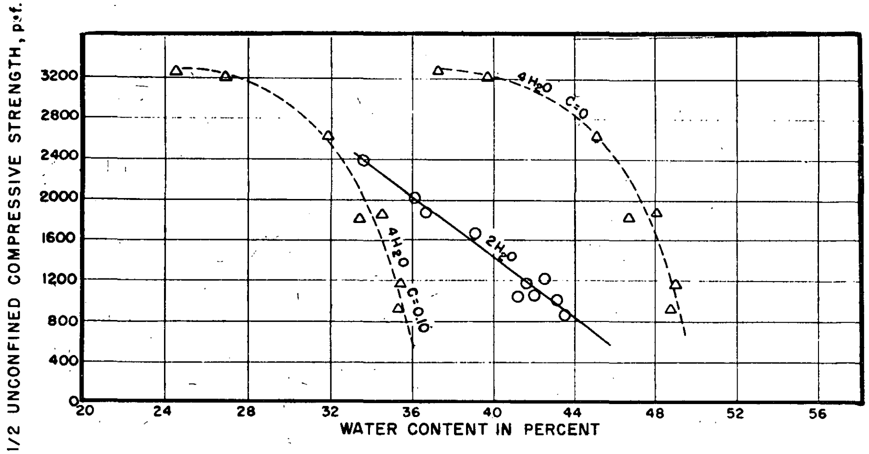
NEW HAMPSHIRE SILT

FIGURE 2

LEGEND:

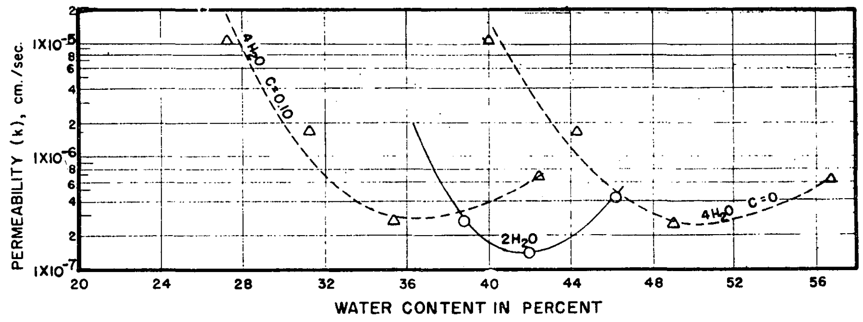
X – *Fort Belvoir Sandy Clay & Sodium Montmorillonite*
⊡ – *Fort Belvoir Sandy Clay & Peat Fines*
⊖ – *New Hampshire Silt & Sodium Montmorillonite*
Δ – *New Hampshire Silt & Peat Fines*
⊙ – *Boston Blue Clay & Sodium Montmorillonite*
+ – *Boston Blue Clay & Peat Fines*

EFFECT OF SODIUM MONTMORILLONITE AND PEAT FINES



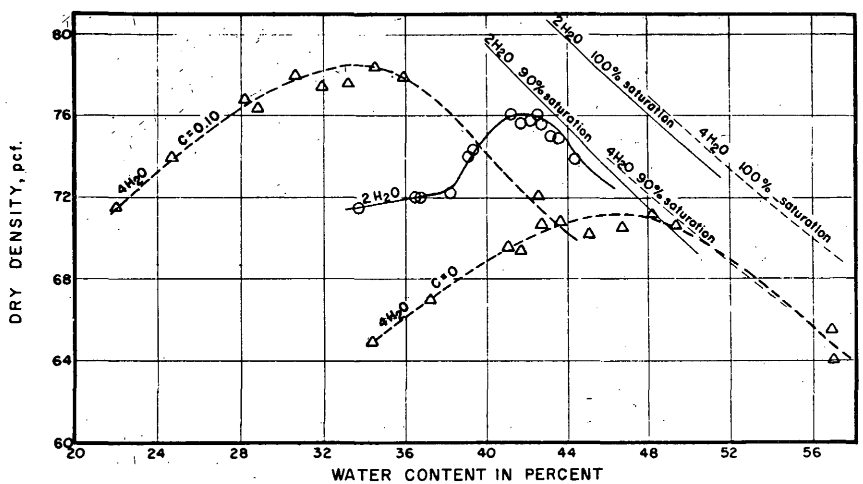
UNCONFINED COMPRESSION

FIGURE 1



PERMEABILITY

FIGURE 2



COMPACTION

FIGURE 3

NOTES:

1. *Data reproduced from thesis by Egbert, J. S. and Jones, T. T. entitled, "A Comparative Engineering Study of the Hydrated ($4H_2O$) and Dehydrated ($2H_2O$) Form of Halloysite," M.I.T., 1954.*
2. $C = \dfrac{\text{Interlayer Water Weight}}{\text{Dry Soil Weight}}$
3.

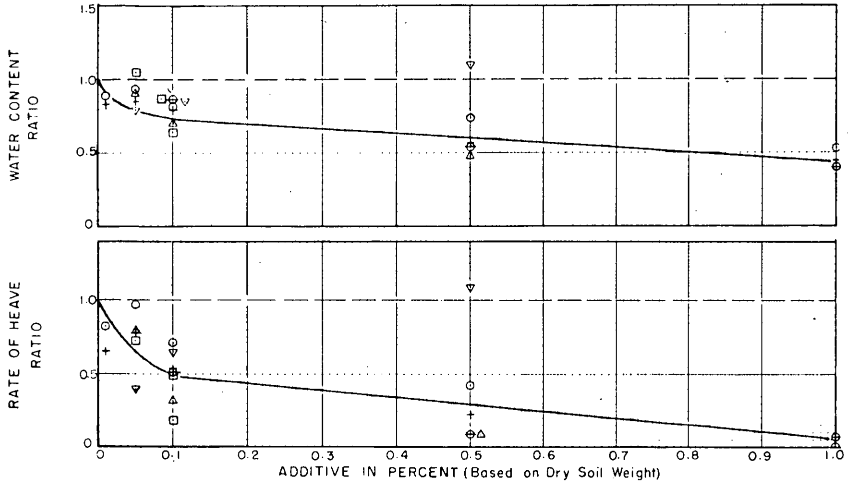
	$2H_2O$	$4H_2O$	
		C=0	C=0.10
Liquid Limit	57.7	70.4	54.6
Plastic Limit	47.3	55.7	41.6

4. *Compaction tests performed with Harvard miniature compaction apparatus.*
   Volume of mold — 1/454 Cu. Ft.
   No. of layers — 3
   Tamps per layer — 25
   40 lb. prestressed spring tamper
5. *The value of C = 0.10, equal to the interlayer water weight divided by the dry soil weight, was obtained by multiplying the 14 % maximum interlayer water by the percentage of hydrated halloysite in the sample. In halloysite ($2H_2O$) C = 0.*

EFFECT OF MOLDING WATER CONTENT ON PROPERTIES OF HYDRATED ($4H_2O$) AND DEHYDRATED ($2H_2O$) HALLOYSITE

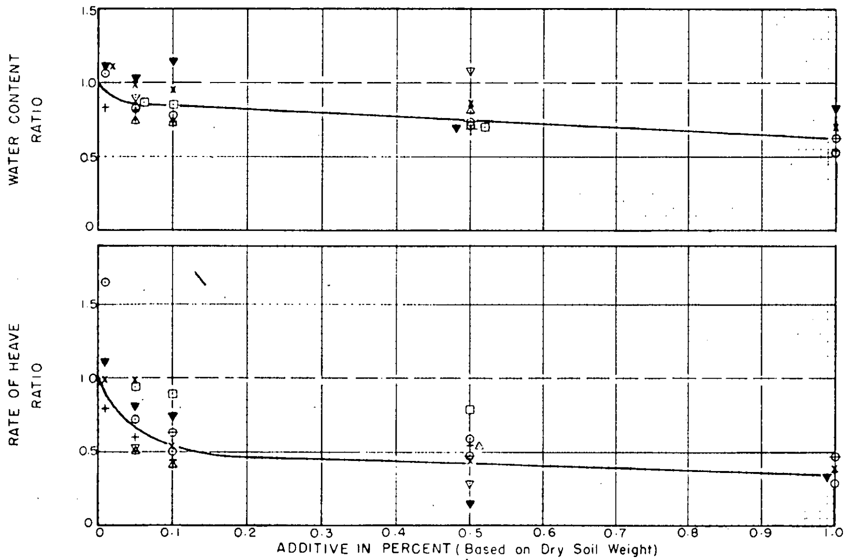
PLATE 3

PLATE 4



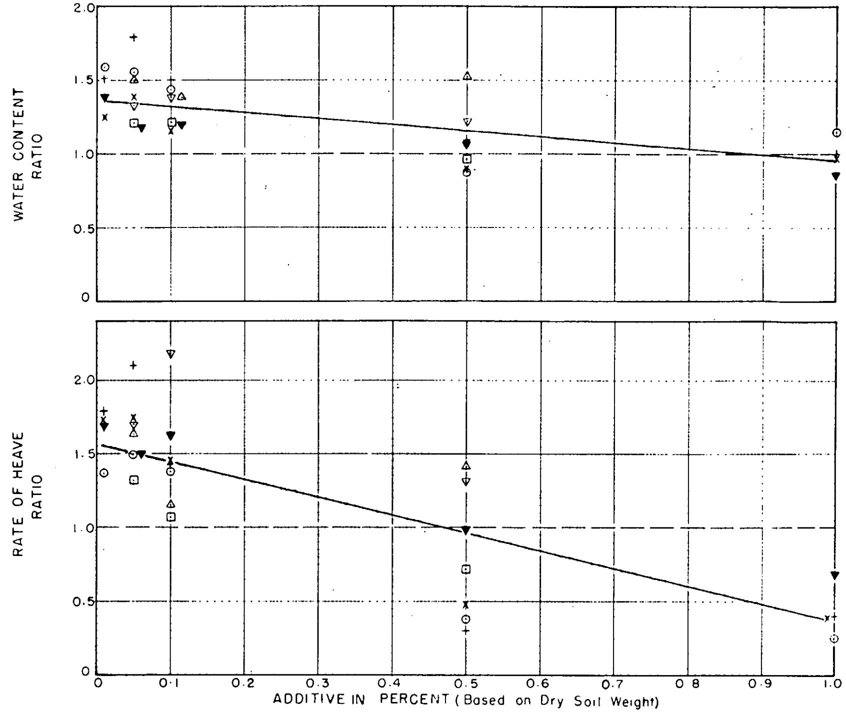
FORT BELVOIR SANDY CLAY

FIGURE 1



NEW HAMPSHIRE SILT

FIGURE 2



BOSTON BLUE CLAY

FIGURE 3

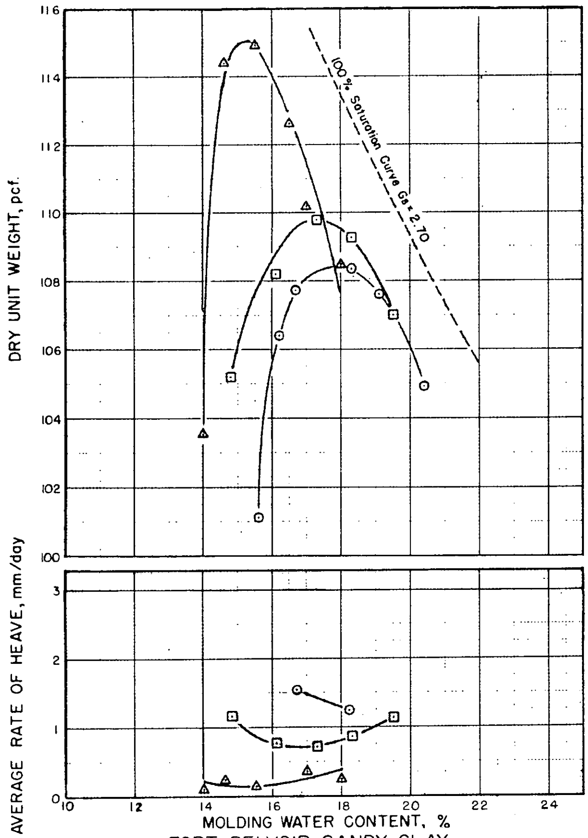
NOTE:

Additives were mixed in concentrations of 0.01, 0.05, 0.1, 0.5 and 1.0 percent, based on dry soil weight. Symbols adjacent to these percentages were so plotted for clarity only.

LEGEND:

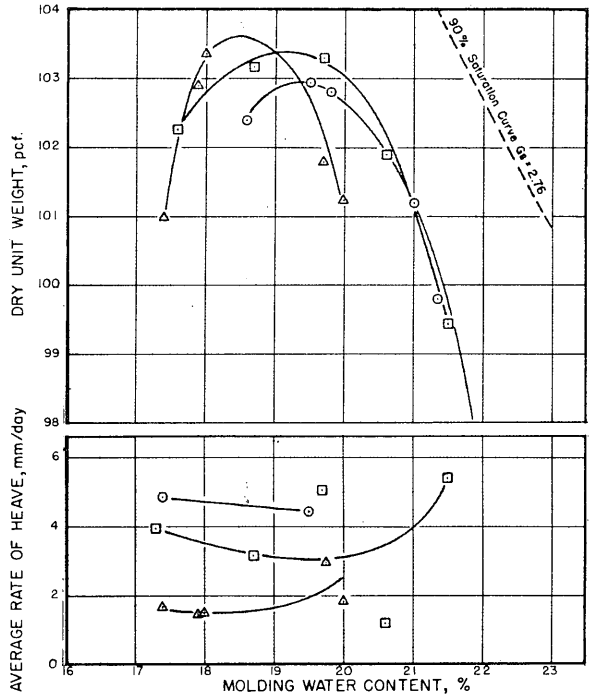
- ⊙ - - *Sodium Hexametaphosphate*
- + —— *Sodium Tetraphosphate*
- ⊖ —— *Sodium Tripolyphosphate*
- ▽ —— *Marasperse C*
- △ —— *Marasperse N*
- ⊡ - - *Versenate*
- ▼ —— *Daxad 11*
- x - - *Tamol 731*

EFFECT OF DISPERSANTS



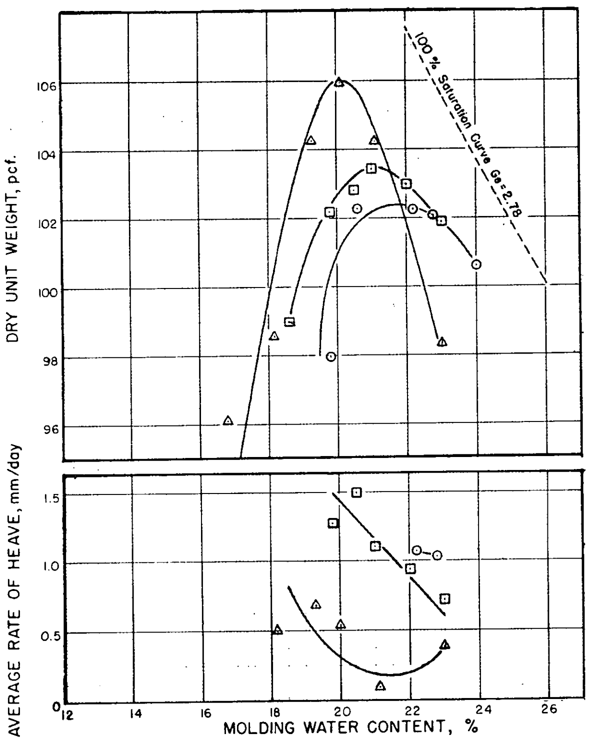
FORT BELVOIR SANDY CLAY

FIGURE 1.



NEW HAMPSHIRE SILT

FIGURE 2.



BOSTON BLUE CLAY

FIGURE 3.

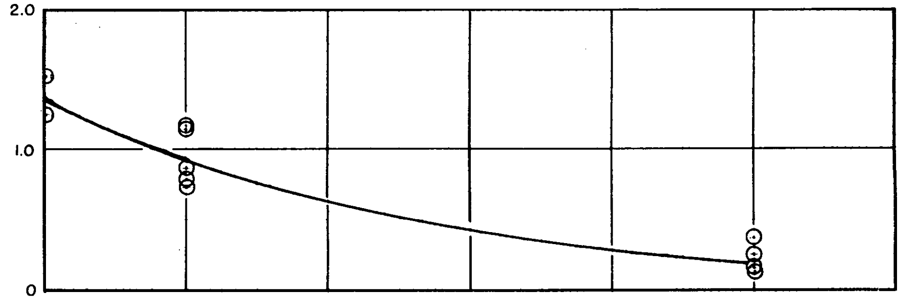
LEGEND:

- ○ — *Zero percent additive.*
- □ — *0.1 percent Quadrafos (Sodium Tetraphosphate).*
- △ — *0.5 percent Quadrafos (Sodium Tetraphosphate).*

NOTES:

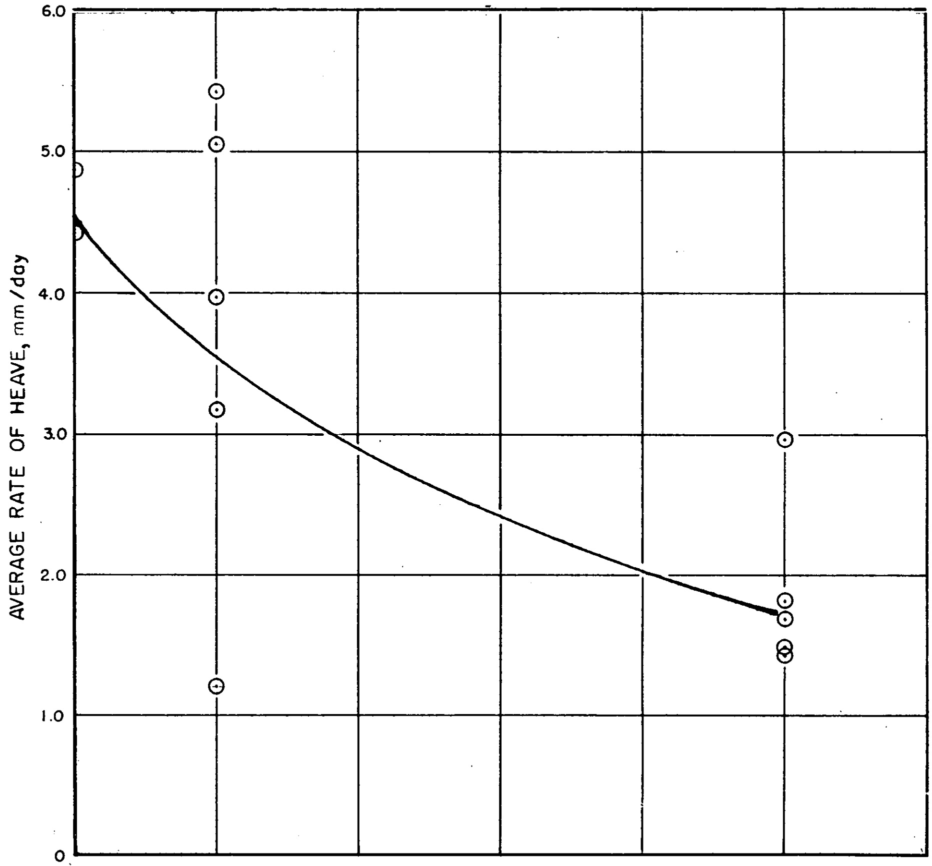
1. *All tests performed with Harvard Miniature Compaction Apparatus: Volume of mold - 1/454 cu. ft., No. of layers - 3, No. of tamps per layer - 25, 40 pound prestressed spring tamper.*
2. *Percent additive based on dry soil weight.*

EFFECT OF MOLDING WATER CONTENT ON DRY UNIT WEIGHT AND AVERAGE RATE OF HEAVE OF QUADRAFOS TREATED SOILS



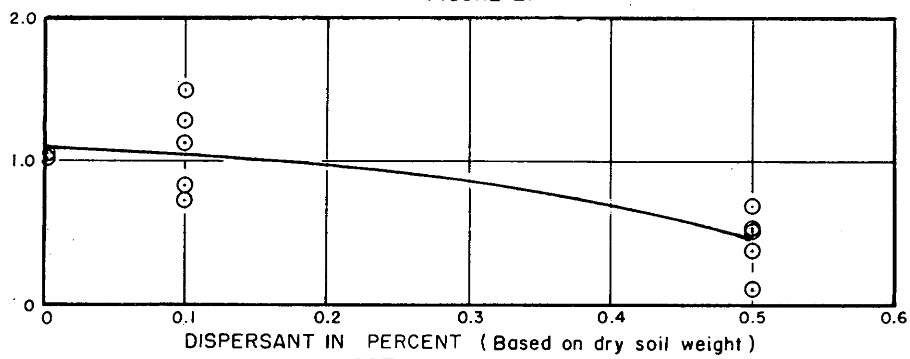
FORT BELVOIR SANDY CLAY

FIGURE 1.



NEW HAMPSHIRE SILT

FIGURE 2.

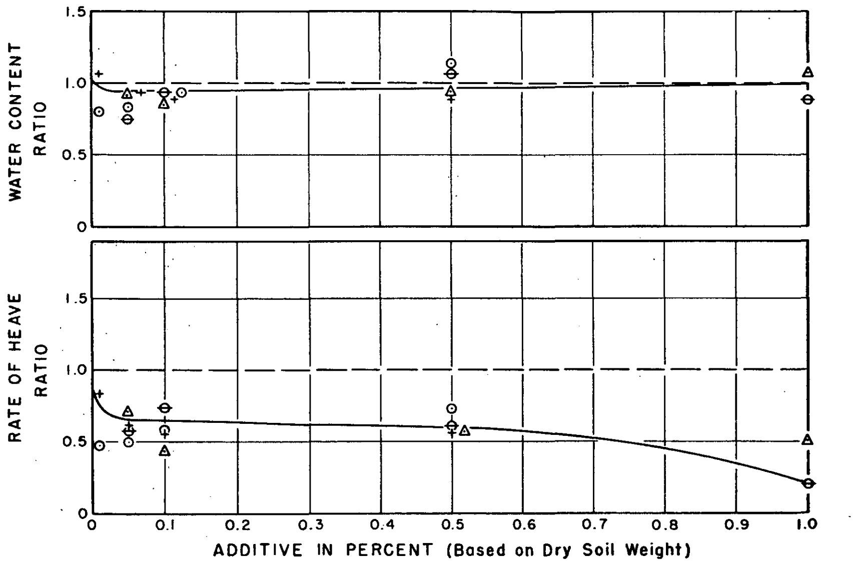


BOSTON BLUE CLAY

FIGURE 3.

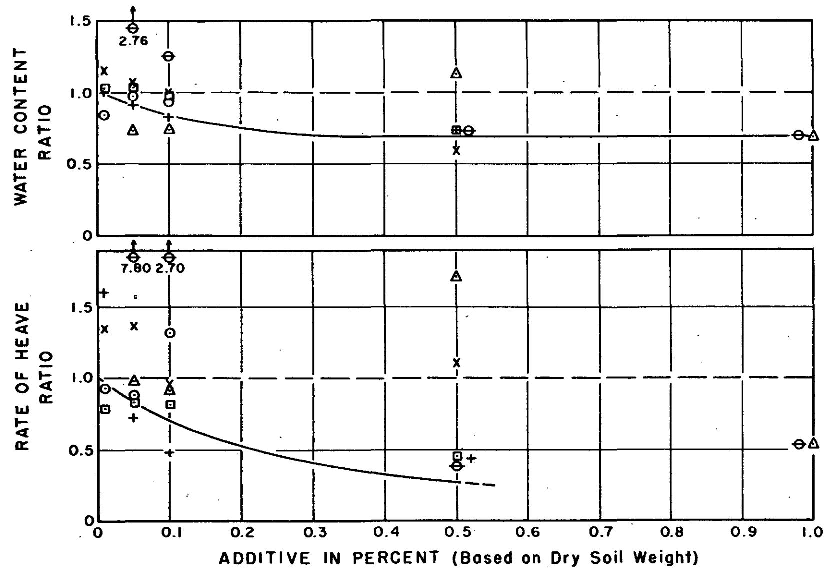
EFFECT OF QUADRAFOS ON AVERAGE RATE OF HEAVE

PLATE 6



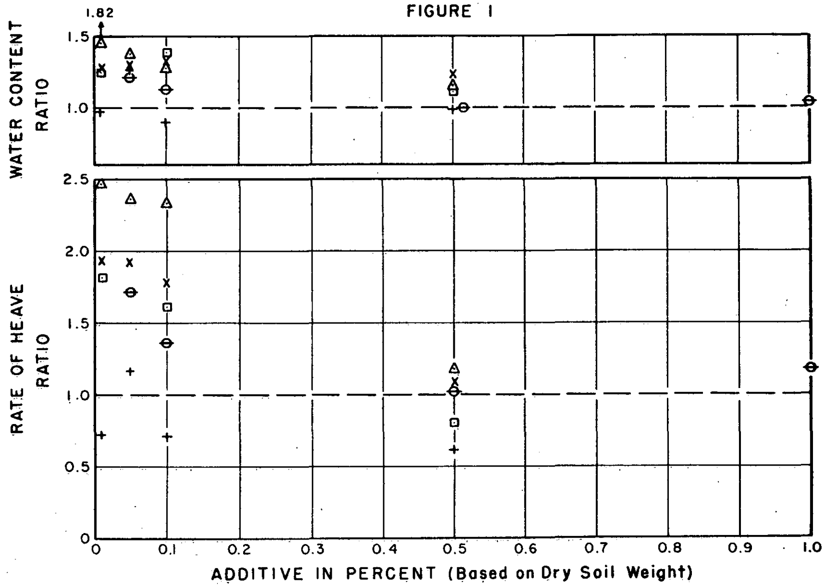
FORT BELVOIR SANDY CLAY

FIGURE 1



NEW HAMPSHIRE SILT

FIGURE 2



BOSTON BLUE CLAY

FIGURE 3

NOTE:

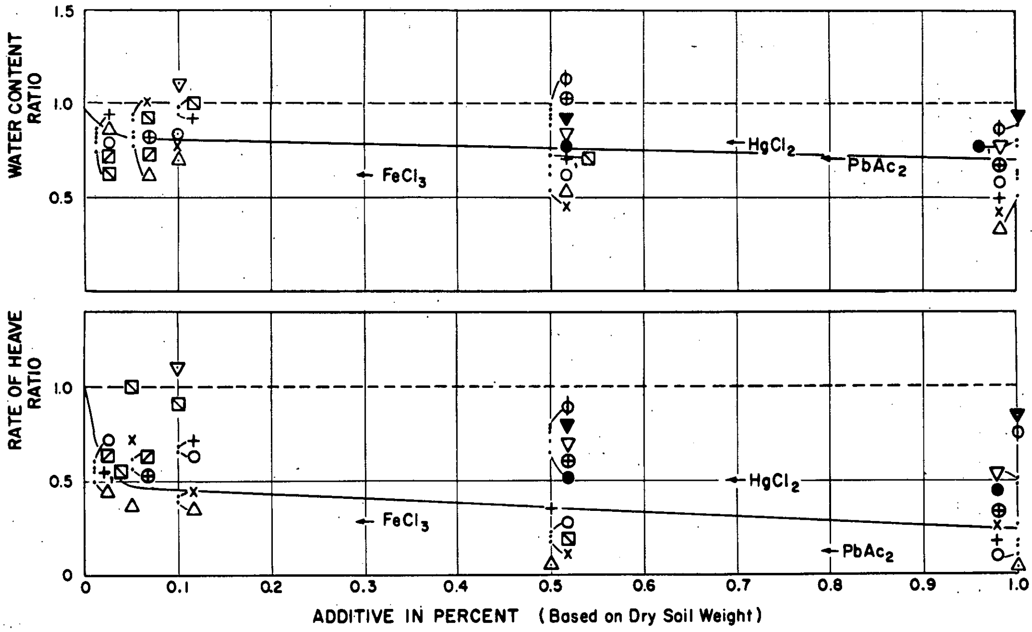
Additives were mixed in concentrations of 0.01, 0.05, 0.1, 0.5, and 1.0 percent, based on dry soil weight. Symbols adjacent to these percentages were so plotted for clarity only.

LEGEND:

- ⊙ — *CRD-197*
- \+ — *Flocgel*
- ⊖ — *Guartec*
- △ — *PVA*
- ⊡ — *Sodium Polyacrylate*
- X — *Maleic Polymer*

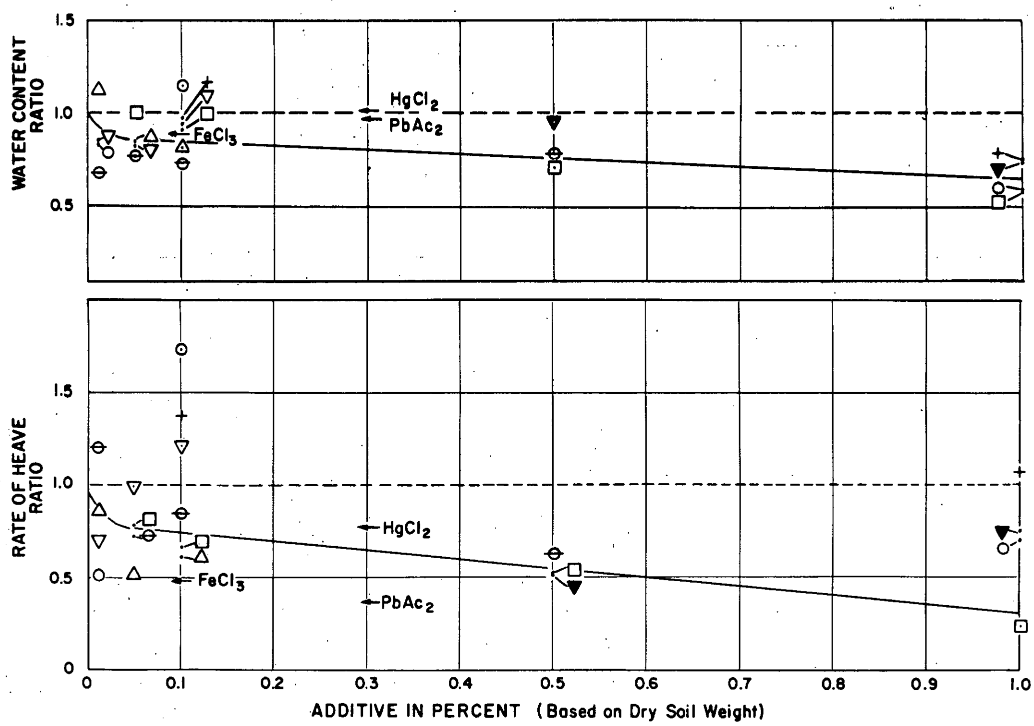
EFFECT OF AGGREGANTS

PLATE 7



FORT BELVOIR SANDY CLAY

FIGURE 1



NEW HAMPSHIRE SILT

FIGURE 2

LEGEND

- ⊙ — *Volan*
- + — *Quilon*
- ⊖ — *Primene 81R*
- ▽ — *Hexamethylene Diamine*
- △ — *Siliconate (SC-50)*
- ⊡ — *Siliconate (XS-1)*
- ▼ — *Vegetable Pitch 250*
- ● — *Tall Oil*
- X — *Lignosol*
- ⧅ — *Carbowax 200*
- ⧄ — *Carbowax 6000*
- Φ — *Spent Vegetable Residue*
- ⊕ — *Di-n-butylamine*
- *$PbAc_2$ — Lead Acetate*
- *$HgCl_2$ — Mercuric Bi-chloride*
- *$FeCl_3$ — Ferric Chloride*

NOTES

Additives were mixed in concentrations of 0.01, 0.05, 0.1, 0.5 and 1.0 percent, based on dry soil weight. Symbols adjacent to these percentages were so plotted for clarity only.

The concentrations of $PbAc_2$, $HgCl_2$ and $FeCl_3$ shown plotted as (←) are those needed to satisfy the exchange capacity of the soils (estimated values, Silt = 2 m.e./100g and Clay = 5 m.e./100g).

EFFECT OF OTHER ADDITIVES

PLATE 8

CORPS OF ENGINEERS, U. S. ARMY

FROST INVESTIGATIONS

COLD ROOM STUDIES

MINERAL AND CHEMICAL STUDIES

by

T. William Lambe

APPENDIX A: ACFEL INVESTIGATIONAL DATA

ARCTIC CONSTRUCTION

AND

FROST EFFECTS LABORATORY

PREFACE TO APPENDIX A

The following appendix presents detailed test data obtained and prepared by the Arctic Construction and Frost Effects Laboratory in connection with the mineral and chemical studies reported in this volume by Dr. T. William Lambe of the Massachusetts Institute of Technology.

FROST INVESTIGATIONS

APPENDIX A: ACFEL INVESTIGATIONAL DATA

TABLE OF CONTENTS

LIST OF TABLES

LIST OF PLATES

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954

TABLE A1

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM)

SPECIMEN NUMBER	MATERIAL	ADDITIVE			DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT PERCENT		WATER CONTENT RATIO (1)	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO (2)
		CLASS	TYPE	PERCENT				BEFORE FREEZING	AFTER FREEZING				
CM-515	Fort Belvoir Sandy Clay	Clay Minerals	Sodium Montmorillonite	0.01	109.3	0.541	84.3	16.9	27.0	0.81	28.6	1.61	1.02
516				0.05	108.7	0.560	96.2	19.6	26.5	0.80	16.7	0.91	0.58
517				0.10	105.7	0.593	93.0	20.4	28.8	0.87	19.6	0.84	0.53
518				1.00	106.2	0.586	88.8	19.3	26.3	0.79	15.4	0.71	0.45
519				2.00	105.0	0.623	85.0	19.0	29.2	0.88	14.8	0.81	0.51
520				3.00	101.9	0.653	93.1	22.5	31.9	0.96	15.1	0.86	0.54
521				6.00	104.5	0.612	93.6	21.2	25.6	0.77	8.4	0.39	0.25
522				12.00	101.5	0.659	91.9	22.4	26.1	0.79	4.3	0.25	0.16
530		Dispersants	Marasperse C	0.05	104.0	0.619	86.2	19.8	25.6	0.77	13.2	0.62	0.39
529				0.10	106.3	0.585	83.3	18.0	28.3	0.85	21.6	1.02	0.65
528				0.50	106.4	0.583	82.8	17.9	36.1	1.09	39.9	1.69	1.07
537			Marasperse N	0.05	108.2	0.556	89.3	18.4	30.6	0.92	27.0	1.24	0.79
536			Sodium Hexametaphosphate	0.01	106.3	0.584	94.3	20.4	29.2	0.88	26.7	1.30	0.82
534				0.05	105.6	0.594	78.7	17.3	31.1	0.93	31.2	1.52	0.96
535				0.10	106.8	0.577	81.2	17.4	26.8	0.81	21.6	1.11	0.71
533				0.50	110.3	0.527	90.6	17.7	24.5	0.74	15.1	0.66	0.42
532				1.00	114.1	0.476	91.1	16.1	17.7	0.53	6.1	0.10	0.06
523			Sodium Tetraphosphate	0.01	107.1	0.572	86.4	18.3	27.7	0.83	19.0	1.02	0.65
524				0.05	103.3	0.630	97.8	22.8	28.2	0.85	23.5	1.21	0.77
525				0.10	107.1	0.572	90.7	19.2	26.3	0.79	17.4	0.84	0.53
526				0.50	110.3	0.526	83.6	16.3	18.8	0.56	5.8	0.35	0.22
527				1.00	112.6	0.495	75.9	13.9	15.0	0.45	1.3	0.10	0.06
538		Other Additives	Spent Vegetable Residue	0.50	103.5	0.627	93.8	21.8	32.9	0.99	25.1	1.24	0.79
539				1.00	104.3	0.615	88.2	20.1	29.6	0.89	23.8	1.18	0.75
541				3.00	104.2	0.617	87.8	20.1	26.0	0.78	13.5	0.66	0.42
545			Tall Oil	0.50	104.1	0.618	93.2	21.4	29.4	0.88	21.9	1.02	0.65
546				1.00	105.2	0.601	93.2	20.8	26.6	0.80	15.1	0.76	0.48
547				3.00	106.8	0.577	81.6	17.4	21.4	0.64	12.2	0.59	0.37
542			Vegetable Pitch 250	0.50	103.2	0.633	92.6	21.7	30.6	0.92	21.9	1.21	0.77
543				1.00	105.5	0.596	93.6	20.7	31.7	0.95	31.5	1.35	0.85
544				3.00	105.1	0.603	78.5	17.5	20.1	0.60	13.8	0.53	0.34
540		Blanks	-	-	104.8	0.607	87.1	19.6	35.9	-	38.3	1.46	-
550				-	105.2	0.602	83.7	18.7	35.5	-	35.4	1.84	-
531				-	106.7	0.579	90.0	19.3	32.9	-	33.5	1.49	-
549				-	106.8	0.577	84.1	18.0	32.7	-	33.1	1.59	-
548				-	107.3	0.570	88.2	18.6	29.6	-	27.7	1.53	-

(1) Ratio of water content of treated specimen after freezing to average water content of blanks after freezing.

(2) Ratio of rate of heave of treated specimen to average rate of heave of blanks.

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954

TABLE A1
(Continued)

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM)

SPECIMEN NUMBER	MATERIAL	ADDITIVE			DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT PERCENT		WATER CONTENT RATIO	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO
		CLASS	TYPE	PERCENT				BEFORE FREEZING	AFTER FREEZING				
CM-552	Fort Belvoir Sandy Clay	Organic Matter	Peat Fines	0.01	108.1	0.558	90.3	18.7	32.6	0.96	34.4	2.03	0.76
553				0.05	105.0	0.604	87.6	19.6	29.9	0.88	23.8	1.68	0.63
554				0.10	104.1	0.618	91.7	21.0	32.7	0.96	30.6	1.91	0.72
561				1.00	105.7	0.594	84.8	18.6	32.2	0.95	29.0	1.98	0.74
562				2.00	105.6	0.595	88.7	19.5	30.5	0.90	27.4	1.93	0.73
565				3.00	102.3	0.647	89.1	21.4	32.6	0.96	21.6	1.83	0.69
555				6.00	98.9	0.703	100.0	26.0	29.7	0.88	17.1	1.37	0.52
567				12.00	91.7	0.837	85.9	26.6	42.9	1.26	31.2	1.97	0.74
571		Dispersants	Sodium Tripoly-phosphate	0.10	109.0	0.545	96.0	19.4	29.3	0.86	23.5	1.36	0.51
572				0.50	112.5	0.497	93.5	17.2	18.1	0.53	4.2	0.24	0.09
573				1.00	116.6	0.444	86.3	14.2	13.5	0.40	0.0	0.00	0.00
566			Versenate	0.05	108.4	0.553	93.2	19.1	35.6	1.05	32.8	1.91	0.72
570				0.10	103.5	0.627	80.3	18.6	29.4	0.87	24.5	1.31	0.49
568				0.10	108.8	0.548	92.6	18.8	21.6	0.64	7.4	0.49	0.18
549A		Aggregants	Flocgel	0.01	108.6	0.551	88.1	18.0	35.8	1.06	35.1	2.21	0.83
550A				0.05	106.5	0.581	93.5	20.1	31.6	0.93	28.0	1.61	0.61
551				0.10	104.6	0.609	93.3	21.0	29.9	0.88	20.3	1.47	0.55
556				0.50	103.7	0.624	94.0	23.1	30.3	0.89	24.1	1.47	0.55
557			Guartec	0.05	109.0	0.545	96.5	19.5	25.5	0.75	16.8	1.52	0.57
569				0.10	106.4	0.583	98.6	21.3	32.0	0.94	25.8	1.98	0.74
558				0.50	97.2	0.733	91.5	24.8	35.8	1.06	22.9	1.62	0.61
559				1.00	96.1	0.752	93.0	25.9	30.0	0.89	12.9	0.53	0.20
574			PVA	0.05	106.3	0.585	90.7	19.6	31.1	0.92	30.9	1.89	0.71
575				0.10	103.9	0.620	89.2	20.5	28.9	0.85	19.0	1.16	0.44
576				0.50	100.5	0.675	90.7	22.7	32.0	0.94	22.9	1.52	0.57
577				1.00	98.3	0.714	97.7	25.8	36.2	1.07	21.3	1.33	0.50
580		Other Additives	Carbowax 200	0.01	108.2	0.556	87.3	18.0	25.2	0.74	14.8	1.47	0.55
581				0.05	107.8	0.562	88.7	18.4	30.7	0.91	30.4	2.67	1.00
563				0.10	106.1	0.587	92.2	20.0	33.3	0.98	37.0	2.45	0.92
564				0.50	104.2	0.616	85.8	19.6	24.6	0.73	10.3	0.56	0.21
579			Carbowax 6000	0.01	107.4	0.568	83.3	17.5	27.1	0.80	20.6	1.52	0.57
578				0.05	106.3	0.584	80.5	17.4	27.9	0.82	26.4	1.64	0.62
560				0.10	102.6	0.642	82.5	19.6	38.6	1.14	41.0	2.36	0.89
582		Blanks	-	-	104.5	0.611	87.7	19.9	35.8	-	37.7	2.84	-
583				-	105.9	0.590	95.0	20.8	32.8	-	36.7	2.69	-
584				-	106.1	0.587	90.7	19.7	33.0	-	30.9	2.44	-

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954

TABLE A1
(Continued)

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM)

SPECIMEN NUMBER	MATERIAL	ADDITIVE			DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT PERCENT		WATER CONTENT RATIO	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO
		CLASS	TYPE	PERCENT				BEFORE FREEZING	AFTER FREEZING				
CM-618	Fort Belvoir Sandy Clay	Dispersants	Marasperse N	0.10	111.0	0.517	96.7	18.5	22.4	0.70	13.5	0.64	0.31
619				0.50	116.8	0.441	93.6	15.3	15.0	0.47	4.5	0.17	0.08
602		Aggregants	CRD-197	0.01	108.2	0.556	89.8	18.5	25.5	0.80	18.3	0.99	0.48
603				0.05	105.8	0.592	90.8	19.9	27.0	0.84	22.2	1.02	0.50
604				0.10	107.4	0.568	94.6	19.9	29.7	0.93	23.2	1.19	0.58
605				0.50	98.8	0.704	92.8	24.2	36.2	1.13	29.3	1.52	0.74
589		Other Additives	Di-n-butylamine	0.05	108.4	0.553	97.2	19.9	26.5	0.83	20.6	1.16	0.57
587				0.50	106.3	0.590	88.8	19.4	31.2	0.97	29.9	1.47	0.71
588				1.00	102.2	0.651	83.0	20.0	24.7	0.77	11.3	0.53	0.26
616			Ferric Chloride	-	112.2	0.501	90.9	16.9	19.8	0.62	7.4	0.60	0.29
594			Hexamethylene Diamine	0.10	105.0	0.603	90.1	20.1	35.2	1.10	39.9	2.29	1.12
595				0.50	106.6	0.580	92.0	19.8	29.3	0.91	27.7	1.56	0.76
596				1.00	105.9	0.590	89.5	19.5	25.8	0.80	18.3	1.04	0.51
615			Lead Acetate	-	112.9	0.492	97.7	17.8	22.6	0.71	9.6	0.25	0.12
611			Lignosol	0.05	108.1	0.558	87.9	18.2	30.2	0.94	25.4	1.50	0.73
612				0.10	111.9	0.505	95.9	17.9	24.6	0.77	16.7	0.86	0.42
613				0.50	114.6	0.469	94.4	16.4	17.3	0.54	7.7	0.36	0.18
614				1.00	110.2	0.529	92.9	18.2	19.3	0.60	6.1	0.36	0.18
617			Mercury Bi-chloride	-	108.2	0.557	87.9	18.1	25.5	0.79	19.0	1.02	0.50
597			Quilon	0.01	108.3	0.555	98.1	20.1	27.7	0.86	22.2	1.13	0.55
598				0.10	107.0	0.575	87.5	18.6	30.3	0.94	29.6	1.40	0.68
599				0.50	110.0	0.530	92.1	18.1	23.4	0.73	14.1	0.73	0.36
600				1.00	110.8	0.520	94.7	18.3	20.2	0.63	2.3	0.30	0.15
606			Siliconate (SC-50)	0.01	108.7	0.549	91.7	18.6	26.6	0.83	22.2	1.02	0.50
607				0.05	111.5	0.511	97.5	18.4	24.3	0.76	17.0	0.76	0.37
608				0.10	108.5	0.551	86.6	17.7	22.5	0.70	16.7	0.79	0.39
609				0.50	109.3	0.540	94.2	18.8	19.8	0.62	6.4	0.13	0.06
610				1.00	110.3	0.526	84.1	16.4	16.3	0.51	3.2	0.10	0.05
590			Volan	0.01	107.3	0.569	93.9	19.8	26.2	0.82	21.5	1.24	0.61
591				0.10	105.5	0.597	89.2	19.7	27.0	0.84	22.2	1.35	0.66
592				0.50	109.4	0.540	94.2	18.8	21.4	0.67	7.7	0.48	0.23
593				1.00	110.3	0.527	97.3	19.0	20.5	0.64	3.2	0.21	0.10
601		Blanks	-	-	105.4	0.598	88.9	19.7	32.0	-	33.1	2.03	-
620				-	107.1	0.573	84.1	17.8	33.6	-	32.5	2.24	-
621				-	108.9	0.546	94.1	19.0	31.2	-	30.6	1.83	-
622				-	109.3	0.540	91.7	18.3	31.4	-	30.9	2.08	-

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954

TABLE A1
(Continued)

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM)

SPECIMEN NUMBER	MATERIAL	ADDITIVE			DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT		WATER CONTENT RATIO	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO
		CLASS	TYPE	PERCENT				BEFORE FREEZING	AFTER FREEZING				
CM-367	New Hampshire Silt	Clay Minerals	Sodium Montmorillonite	0.01	91.2	0.889	92.2	29.7	35.5	0.75	19.0	0.56	0.27
368				0.05	89.7	0.920	88.5	29.5	41.1	0.87	29.9	0.80	0.39
370				0.10	89.4	0.927	87.4	29.3	53.1	1.12	50.8	4.28	2.09
371				1.00	89.5	0.925	91.5	30.6	43.1	0.91	32.4	3.20	1.56
372				2.00	84.7	1.035	100.0	37.5	40.6	0.86	16.7	1.68	0.82
373				3.00	89.2	0.930	100.0	33.8	34.7	0.73	12.9	0.76	0.37
374				6.00	84.1	1.058	96.4	36.7	31.7	0.67	2.6	0.33	0.16
375				12.00	79.8	1.175	95.1	40.2	34.8	0.73	1.0	0.18	0.09
394		Organic Matter	Peat Fines	0.01	91.4	0.884	91.0	29.1	42.1	0.89	32.8	1.61	0.79
395				0.05	94.7	0.818	96.7	28.6	40.3	0.85	31.5	1.27	0.62
396				0.10	93.2	0.848	88.2	27.1	33.7	0.71	20.3	0.65	0.32
397				1.00	91.5	0.882	94.2	30.1	34.9	0.74	19.7	0.95	0.46
398				2.00	89.4	0.927	95.2	32.0	40.1	0.85	23.1	0.73	0.36
399				3.00	84.9	1.028	96.1	35.8	32.6	0.69	16.7	1.19	0.58
401				6.00	81.1	1.125	93.5	38.1	43.2	0.91	16.7	0.58	0.28
402				12.00	74.1	1.325	94.3	45.3	45.7	0.96	13.8	0.22	0.11
391		Dispersants	Marasperse N	0.05	91.6	0.879	89.0	28.3	35.2	0.74	18.6	1.02	0.50
393				0.10	90.0	0.915	88.8	29.4	34.9	0.74	18.3	0.86	0.42
392				0.50	89.2	0.930	83.2	28.0	38.3	0.81	21.6	1.10	0.54
376			Sodium Hexametaphosphate	0.01	92.2	0.867	91.2	28.6	50.3	1.06	47.0	3.37	1.65
377				0.05	91.9	0.875	90.7	28.8	39.5	0.83	26.7	1.48	0.72
379				0.10	90.7	0.898	89.3	29.1	36.6	0.77	20.3	1.02	0.50
378				0.50	91.9	0.875	90.1	28.6	33.6	0.71	18.0	1.20	0.59
380				1.00	95.9	0.794	93.6	27.0	24.5	0.52	4.2	0.59	0.29
382			Sodium Tetraphosphate	0.01	89.7	0.920	89.5	28.7	39.3	0.83	26.1	1.61	0.79
383				0.05	89.5	0.925	88.7	29.7	38.7	0.82	25.1	1.22	0.60
385				0.10	93.1	0.851	87.5	27.0	35.0	0.74	20.6	0.91	0.44
384				0.50	92.3	0.866	91.8	28.8	33.1	0.70	15.4	1.10	0.54
386				1.00	94.2	0.828	90.0	27.0	25.6	0.54	2.9	0.73	0.36
387		Aggregants	Flocgel	0.01	92.8	0.855	97.4	30.2	47.4	1.00	45.7	3.30	1.61
388				0.05	90.9	0.894	91.6	29.7	43.4	0.92	36.0	1.47	0.72
390				0.10	90.7	0.898	89.4	29.1	40.1	0.85	23.8	0.98	0.48
389				0.50	94.1	0.830	91.7	27.7	35.2	0.74	19.9	0.91	0.44
400		Blanks	-	-	88.1	0.954	100.0	34.6	42.3	-	31.5	1.14	-
369				-	90.2	0.910	88.9	29.3	50.5	-	30.2	1.52	-
381				-	91.0	0.894	95.6	31.0	49.6	-	43.4	3.48	-

COLD ROOM STUDIES OF FROST ACTION IN SOILS
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TABLE A1
(Continued)

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM)

SPECIMEN NUMBER	MATERIAL	ADDITIVE			DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT PERCENT		WATER CONTENT RATIO	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO
		CLASS	TYPE	PERCENT				BEFORE FREEZING	AFTER FREEZING				
CM-623	New Hampshire Silt	Dispersants	Marasperse C	0.05	94.5	0.808	83.4	24.6	45.3	0.90	44.2	1.04	0.52
624				0.10	97.1	0.759	84.9	23.5	83.7	1.66	115.0	6.29	3.12
625				0.50	94.8	0.802	77.0	22.5	53.8	1.08	31.2	0.56	0.28
651			Sodium Tripoly-phosphate	0.10	100.9	0.693	90.6	22.9	44.8	0.89	27.0	1.27	0.63
652				0.50	-	-	-	-	36.5	0.73	33.0	0.96	0.48
653				1.00	96.3	0.774	83.6	23.6	31.3	0.62	18.4	0.93	0.46
629			Versenate	0.05	97.8	0.748	84.2	22.9	43.4	0.86	35.8	1.90	0.94
630				0.10	95.6	0.788	86.8	25.0	42.9	0.85	36.1	1.81	0.89
631				0.50	96.9	0.764	82.6	23.0	35.1	0.70	23.5	1.60	0.79
633		Aggregants	CRD-197	0.01	92.6	0.844	81.8	25.2	42.6	0.85	41.9	1.89	0.93
632				0.05	97.3	0.757	82.5	22.8	49.4	0.98	40.3	1.78	0.88
634				0.10	92.2	0.853	87.3	27.2	47.9	0.95	48.7	2.66	1.32
635			Guartec	0.05	93.2	0.834	83.3	25.4	139.0	2.76	200.0	15.69	7.80
626				0.10	94.1	0.816	87.0	25.9	63.3	1.26	73.7	5.53	2.70
627				0.50	89.5	0.910	89.9	29.9	36.7	0.73	17.4	0.78	0.39
628				1.00	96.8	0.766	99.4	27.8	35.0	0.70	21.9	1.07	0.53
636			PVA	0.05	95.1	0.797	87.4	25.4	37.0	0.74	35.4	1.98	0.98
637				0.10	94.7	0.805	83.1	24.4	37.6	0.75	33.9	1.88	0.93
638				0.50	96.7	0.767	80.9	22.6	57.3	1.14	59.0	3.56	1.76
655		Other Additives	Hexamethylene Diamine	0.01	91.4	0.870	79.2	25.2	43.4	0.86	29.0	1.41	0.70
656				0.05	91.2	0.873	85.1	27.1	42.0	0.84	34.5	1.99	0.99
645				0.10	93.0	0.838	82.5	25.2	48.5	0.96	44.5	2.44	1.21
657			Primene 81R	0.01	92.9	0.839	82.9	25.4	34.8	0.69	48.7	2.43	1.20
658				0.05	96.2	0.777	81.0	23.0	39.1	0.78	29.6	1.46	0.72
643				0.10	96.1	0.778	79.3	22.5	37.1	0.74	31.2	1.71	0.84
644				0.50	94.8	0.803	79.0	23.2	39.7	0.79	22.2	1.27	0.63
641			Quilon	0.10	93.8	0.822	86.2	25.8	49.1	0.98	52.5	2.76	1.37
642				1.00	98.6	0.734	81.8	21.9	38.0	0.76	34.5	2.18	1.07
654			Volan	0.01	93.9	0.819	81.0	24.2	42.2	0.84	26.1	1.02	0.51
639				0.10	92.6	0.845	94.8	29.2	58.7	1.16	60.6	3.48	1.73
640				1.00	93.3	0.832	76.5	23.2	29.9	0.60	39.6	0.34	0.7
648		Blanks	-	-	85.2	1.005	90.2	33.1	-	-	-	-	-
650				-	90.8	0.881	81.5	26.3	62.3	-	45.8	2.15	-
647				-	93.3	0.832	83.2	25.3	47.7	-	43.8	2.18	-
646				-	94.1	0.817	80.0	23.9	44.9	-	32.2	1.61	-
649				-	97.3	0.757	83.8	23.2	46.3	-	40.0	2.16	-

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954

TABLE A1
(Continued)

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM

SPECIMEN NUMBER	MATERIAL	ADDITIVE			DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT PERCENT		WATER CONTENT RATIO	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO
		CLASS	TYPE	PERCENT				BEFORE FREEZING	AFTER FREEZING				
CM-708	New Hampshire Silt	Dispersants	Daxad 11	0.01	95.3	0.795	83.8	24.3	46.5	1.11	50.0	5.15	1.11
709				0.05	93.7	0.823	85.8	25.8	43.4	1.03	47.1	3.85	0.83
710				0.10	93.0	0.839	79.2	24.2	48.3	1.15	34.8	3.43	0.74
711				0.50	90.3	0.895	92.7	30.2	29.1	0.70	9.4	0.67	0.15
712				1.00	99.0	0.700	81.3	21.6	34.2	0.82	38.7	1.52	0.33
699			Tamol 731	0.01	94.5	0.808	81.8	24.1	46.4	1.11	50.9	4.51	0.98
700				0.05	95.9	0.782	80.9	22.5	41.2	0.98	44.8	4.50	0.97
701				0.10	83.2	0.766	86.7	24.2	37.7	0.90	30.0	2.48	0.54
702				0.50	97.0	0.790	74.3	21.4	36.0	0.86	27.8	2.03	0.44
703				1.00	98.6	0.732	68.5	18.3	29.2	0.70	18.4	1.74	0.38
695		Aggregants	Maleic Polymer (Krilium#6)	0.01	95.8	0.784	90.5	25.9	49.5	1.18	45.2	6.25	1.35
696				0.05	94.9	0.801	89.3	25.5	45.2	1.08	44.1	6.28	1.36
697				0.10	95.4	0.788	95.7	27.1	42.8	1.02	33.8	4.42	0.96
698				0.50	95.8	0.784	90.9	26.0	24.9	0.60	1.4	0.51	1.10
722			Sodium Polyacry-late	0.01	91.3	0.875	85.3	27.2	43.4	1.04	32.9	3.66	0.79
723				0.05	94.0	0.818	87.3	26.0	43.4	1.04	30.0	3.85	0.83
724				0.10	88.3	0.929	80.0	27.2	41.2	0.98	22.1	3.81	0.82
725				0.50	91.7	0.865	85.3	26.8	31.0	0.74	12.9	2.09	0.45
716		Other Additives	Ferric Chloride	-	93.5	0.829	81.3	24.6	37.1	0.89	26.5	2.21	0.48
714			Lead Acetate	-	92.0	0.855	81.4	25.4	40.0	0.96	23.0	1.69	0.37
715			Mercuric Bi-chloride	-	92.7	0.845	84.7	26.1	42.3	1.01	39.0	3.56	0.77
704			Siliconate (SC-50)	0.01	95.3	0.710	86.1	22.3	47.4	1.13	45.8	3.94	0.85
705				0.05	98.6	0.734	85.1	22.8	36.2	0.86	27.1	2.36	0.51
706				0.10	98.4	0.737	87.0	23.4	35.0	0.83	31.9	2.75	0.60
717			Siliconate (XS-1)	0.05	94.2	0.814	83.3	24.7	43.1	1.03	35.5	3.60	0.78
718				0.10	94.4	0.813	82.4	24.5	38.5	0.92	45.8	3.05	0.66
719				0.50	98.4	0.739	85.4	23.0	30.2	0.72	21.3	2.44	0.53
720				1.00	97.8	0.750	82.6	22.6	24.6	0.59	7.1	1.06	0.23
727			Vegetable Pitch 250	0.50	95.1	0.798	83.3	24.2	40.6	0.97	24.9	2.40	0.52
728				1.00	95.2	0.796	78.3	22.8	31.4	0.75	19.4	3.31	0.72
729				3.00	100.0	0.708	73.4	18.9	35.2	0.84	30.3	4.37	0.94
721		Blanks	-	-	94.1	0.815	86.5	25.7	37.1	-	31.6	4.91	-
726				-	94.1	0.815	88.5	26.5	39.2	-	45.2	4.13	-
707				-	95.1	0.798	82.8	24.1	49.9	-	50.9	4.95	-
713				-	95.1	0.798	83.7	24.4	47.4	-	43.2	4.76	-
730				-	98.4	0.736	82.2	22.1	36.1	-	25.2	4.38	-

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954

TABLE A1
(Continued)

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM)

SPECIMEN NUMBER	MATERIAL	ADDITIVE CLASS	ADDITIVE TYPE	ADDITIVE PERCENT	DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT PERCENT BEFORE FREEZING	WATER CONTENT PERCENT AFTER FREEZING	WATER CONTENT RATIO	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO
CM-417	Boston Blue Clay	Clay Minerals	Sodium Montmorillonite	0.01	90.3	0.921	92.4	30.6	57.6	1.69	26.9	3.95	1.70
418				0.05	95.7	0.810	91.5	26.7	46.2	1.35	33.8	3.01	1.30
419				0.10	94.7	0.831	89.2	26.7	50.8	1.49	38.6	3.66	1.57
420				1.00	91.4	0.896	95.6	30.8	41.4	1.21	18.1	2.12	0.91
422				2.00	90.5	0.916	96.2	31.7	39.3	1.15	15.1	1.82	0.79
423				3.00	89.0	0.947	96.0	32.8	40.6	1.19	22.6	1.61	0.69
424				6.00	85.4	1.030	94.3	34.9	41.7	1.22	14.0	0.97	0.42
425				12.00	81.4	1.131	91.9	37.4	40.3	1.18	6.2	0.42	0.18
434		Organic Matter	Peat Fines	0.01	90.1	0.924	95.0	31.6	64.3	1.89	45.4	4.83	2.09
435				0.05	95.4	0.817	96.5	28.4	51.7	1.51	36.7	3.35	1.44
436				0.10	94.7	0.831	90.7	27.1	50.5	1.48	37.3	3.81	1.64
437				1.00	88.4	0.961	86.8	30.0	42.6	1.25	20.7	2.11	0.91
438				2.00	90.0	0.926	93.9	31.3	43.1	1.26	23.5	2.12	0.91
439				3.00	95.8	0.811	76.5	22.3	47.8	1.40	27.0	2.03	0.88
441				6.00	83.0	0.919	88.7	34.7	49.0	1.44	24.5	2.24	0.97
442				12.00	79.2	1.191	88.1	37.7	55.5	1.63	24.8	2.39	1.03
431		Dispersants	Marasperse N	0.05	94.3	0.840	90.7	27.4	51.0	1.50	37.0	3.77	1.63
432				0.10	91.7	0.890	90.3	28.9	47.5	1.39	27.5	2.67	1.15
433				0.50	88.5	0.958	94.5	32.6	52.0	1.52	30.1	3.26	1.41
426			Sodium Hexametaphosphate	0.01	89.9	0.932	92.1	30.8	53.9	1.58	33.8	3.15	1.36
427				0.05	89.2	0.944	87.8	29.8	53.5	1.56	34.4	3.47	1.49
428				0.10	91.7	0.891	90.4	29.0	49.1	1.44	33.2	3.18	1.37
429				0.50	97.6	0.777	91.2	25.5	29.8	0.87	13.6	0.85	0.37
430				1.00	86.0	1.017	91.9	33.6	39.3	1.15	12.6	0.59	0.25
412			Sodium Tetraphosphate	0.01	96.6	0.795	95.3	27.2	51.5	1.51	44.9	4.11	1.78
413				0.05	96.0	0.807	83.9	24.4	61.1	1.79	44.7	4.87	2.10
414				0.10	92.7	0.871	91.1	28.5	51.2	1.50	34.5	3.30	1.42
415				0.50	92.9	0.865	85.6	26.7	37.2	1.09	6.3	0.70	0.30
416				1.00	88.5	0.958	95.0	32.8	34.1	1.00	6.5	0.93	0.40
407		Aggregants	Flocgel	0.01	100.3	0.728	85.5	22.4	32.7	0.96	21.4	1.68	0.72
408				0.05	97.0	0.788	93.2	26.4	43.1	1.26	30.6	2.69	1.15
410				0.10	101.3	0.712	93.1	23.8	30.6	0.90	19.6	1.63	0.70
411				0.50	96.0	0.806	95.6	27.7	33.2	0.97	13.7	1.42	0.61
440		Blanks	-	-	100.7	0.722	89.3	23.2	35.8	-	25.1	2.39	-
421				-	102.0	0.702	91.5	23.1	33.4	-	20.2	2.12	-
409				-	104.6	0.658	93.6	22.2	33.0	-	23.4	2.44	-

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954
TABLE A1
(Continued)

SUMMARY OF ADDITIVE FREEZING TESTS
MINIATURE SPECIMENS

(OPEN SYSTEM)

SPECIMEN NUMBER	MATERIAL	ADDITIVE			DRY UNIT WEIGHT pcf	VOID RATIO e	PERCENT SATURATION AT START OF TEST	WATER CONTENT PERCENT		WATER CONTENT RATIO	PERCENT HEAVE	AVG. RATE OF HEAVE mm/day	RATE OF HEAVE RATIO
		CLASS	TYPE	PERCENT				BEFORE FREEZING	AFTER FREEZING				
CM-690	Boston Blue Clay	Dispersants	Daxad 11	0.01	91.9	0.886	93.6	29.9	47.4	1.38	36.7	1.89	1.69
691				0.05	96.5	0.797	88.7	25.4	40.4	1.18	31.3	1.69	1.50
692				0.10	97.6	0.776	93.2	26.0	41.2	1.20	34.2	1.83	1.63
693				0.50	98.6	0.759	100.0	27.3	36.2	1.06	23.2	1.09	0.98
694				1.00	101.3	0.712	94.0	24.1	29.4	0.86	15.5	0.76	0.68
662			Marasperse C	0.05	93.9	0.846	94.6	28.8	45.3	1.33	35.8	1.91	1.70
686				0.10	96.6	0.795	91.8	26.2	47.3	1.38	40.0	2.43	2.18
664				0.50	92.4	0.878	95.7	30.2	41.6	1.22	23.5	1.47	1.31
665			Tamol	0.01	98.8	0.754	91.5	24.8	42.8	1.25	40.3	1.94	1.73
666				0.05	94.1	0.843	95.5	29.0	47.2	1.38	38.4	1.96	1.75
667				0.10	97.5	0.779	91.2	25.6	39.4	1.15	31.3	1.62	1.45
668				0.50	97.0	0.787	92.3	26.1	30.3	0.89	11.0	0.54	0.48
669				1.00	95.2	0.822	92.8	27.4	32.7	0.96	13.6	0.44	0.39
659			Versenate	0.05	94.7	0.831	88.9	26.6	41.6	1.21	30.3	1.46	1.31
660				0.10	97.0	0.788	87.1	24.7	41.5	1.21	22.6	1.19	1.06
661				0.50	95.3	0.820	92.7	27.4	32.7	0.96	10.9	0.79	0.71
682		Aggregants	Quartec	0.05	98.9	0.752	88.4	23.9	41.9	1.22	35.5	1.91	1.71
689				0.10	100.2	0.731	92.1	24.2	38.3	1.12	30.6	1.52	1.35
684				0.50	102.4	0.694	94.6	23.6	34.1	1.00	25.5	1.14	1.02
685				1.00	92.1	0.883	92.8	29.5	34.9	1.02	12.6	1.30	1.16
678			Maleic Polymer (Krilium #6)	0.01	96.5	0.796	90.4	25.9	44.1	1.29	38.7	2.17	1.93
688				0.05	97.1	0.786	98.3	27.8	44.7	1.31	38.0	2.13	1.92
680				0.10	94.6	0.816	94.9	28.1	45.7	1.33	36.4	2.00	1.78
681				0.50	90.5	0.916	93.1	30.6	42.3	1.23	25.5	1.20	1.07
674			PVA	0.01	89.8	0.931	84.8	28.4	62.2	1.82	54.4	2.76	2.46
675				0.05	97.9	0.772	93.3	25.9	47.3	1.38	46.4	2.65	2.36
676				0.10	100.8	0.721	98.8	25.6	43.8	1.28	36.7	2.51	2.34
677				0.50	95.5	0.815	86.1	25.2	39.3	1.15	25.2	1.31	1.17
670			Sodium Polyacrylate	0.01	95.4	0.818	94.4	27.8	42.9	1.25	32.2	2.03	1.81
687				0.05	89.3	0.943	96.8	32.8	55.3	1.62	44.8	2.32	2.07
672				0.10	94.4	0.836	90.1	27.2	47.5	1.39	36.7	1.81	1.61
673				0.50	91.4	0.896	91.3	29.4	37.9	1.10	19.0	0.90	0.80
671		Blanks	-	-	98.9	0.753	78.4	21.4	34.3	-	23.2	1.02	-
683				-	100.9	0.718	83.9	21.7	32.8	-	22.3	1.05	-
679				-	103.5	0.677	91.0	22.1	31.8	-	22.3	1.11	-
663				-	103.5	0.677	95.7	23.3	37.7	-	32.9	1.29	-

COLD ROOM STUDIES OF FROST ACTION IN SOILS
FISCAL YEAR 1954

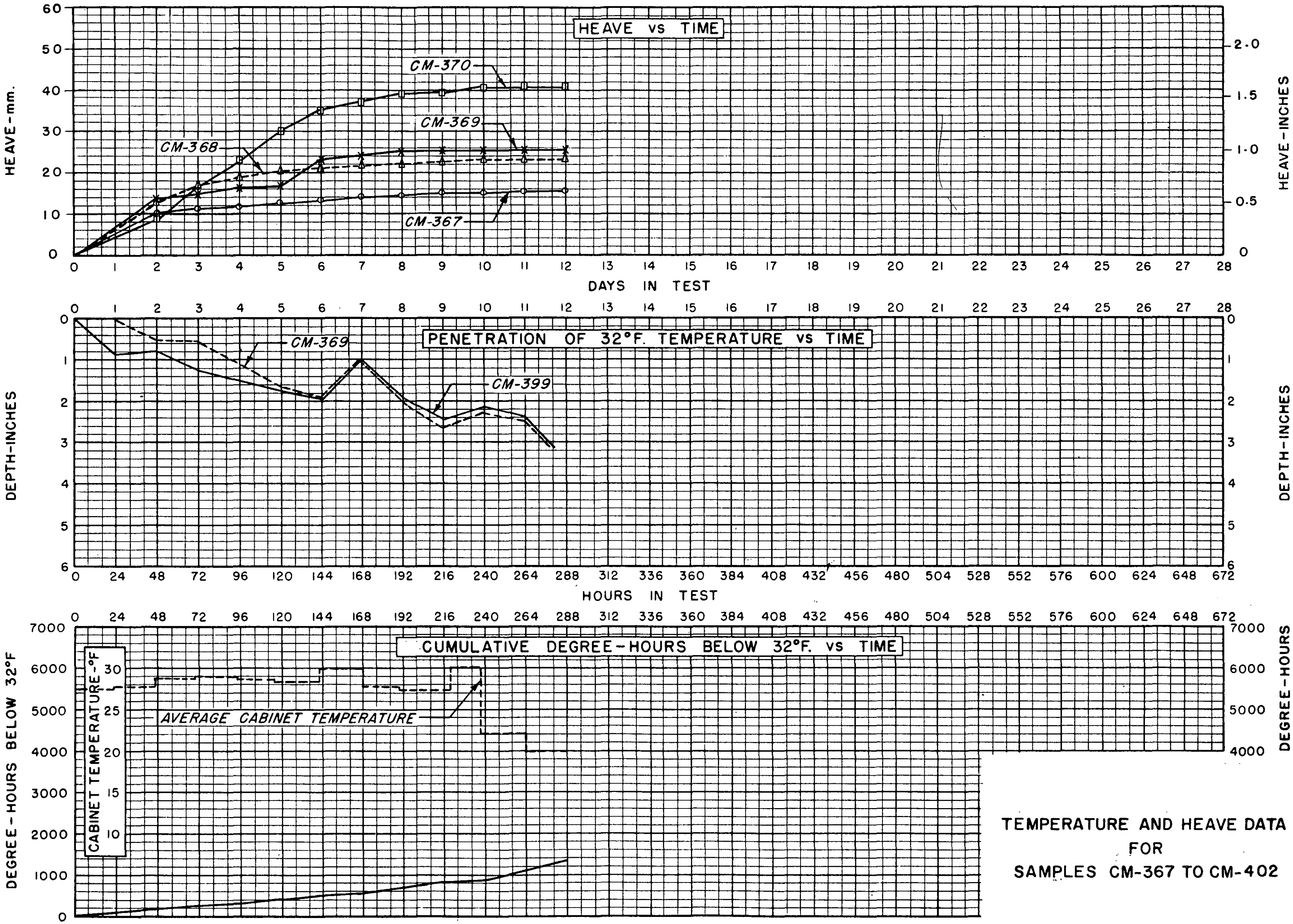
TABLE A2

SUMMARY OF FREEZING TESTS ON QUADRAFOS TREATED SOILS MINIATURE SPECIMENS

(OPEN SYSTEM)

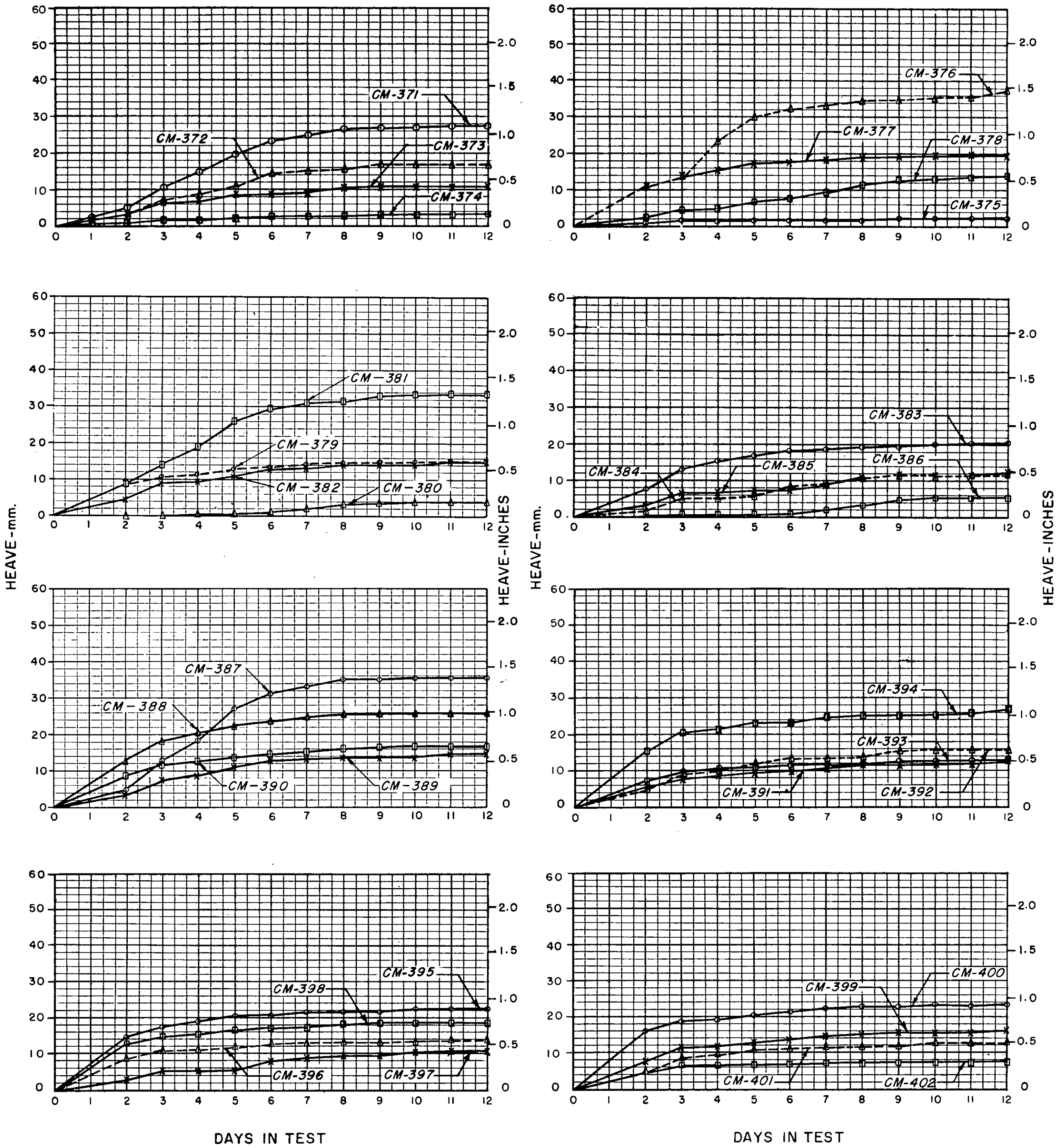
SPECIMEN NUMBER	MATERIAL	PERCENT QUADRAFOS	MOLDING CHARACTERISTICS				AFTER SOAKING CHARACTERISTICS				FREEZING TEST RESULTS		
			DRY UNIT WEIGHT pcf	VOID RATIO e	WATER CONTENT %	PERCENT SATURATION	DRY UNIT WEIGHT pcf	VOID RATIO e	WATER CONTENT %	PERCENT SATURATION	WATER CONTENT AFTER TEST	PERCENT HEAVE	AVERAGE RATE OF HEAVE mm/day
CM-473	New Hampshire Silt	0	103.4	0.664	17.4	80.6	101.1	0.703	21.0	82.4	56.1	70.8	4.87
474		0	102.9	0.672	19.5	80.0	102.0	0.689	21.5	86.2	47.2	56.6	4.42
468		0.1	99.5	0.731	21.5	81.2	98.8	0.743	23.2	86.5	63.5	82.4	5.42
456		0.1	101.9	0.689	20.6	82.5	104.7	0.644	21.6	92.8	39.5	32.5	1.20
470		0.1	102.3	0.683	17.6	71.1	100.7	0.710	22.4	87.1	53.2	62.4	3.97
469		0.1	103.2	0.668	18.7	77.3	100.8	0.708	21.6	84.2	46.4	50.0	3.17
453		0.1	103.3	0.667	19.7	81.6	104.4	0.649	20.2	86.0	66.5	80.5	5.05
477		0.5	101.0	0.705	17.4	68.2	98.2	0.752	22.0	80.8	38.4	30.9	1.69
460		0.5	101.2	0.700	20.0	78.8	102.1	0.687	19.7	79.1	38.8	37.0	1.81
461		0.5	101.8	0.691	19.7	78.7	102.7	0.678	21.5	87.5	50.2	55.9	2.96
463		0.5	102.9	0.673	17.9	73.4	101.0	0.705	21.4	83.0	31.8	22.2	1.43
459		0.5	103.4	0.665	18.0	74.7	99.2	0.735	21.5	80.7	38.8	33.5	1.49
443	Fort Belvoir Sandy Clay	0	107.7	0.563	16.7	80.0	107.7	0.563	17.4	83.5	30.0	26.7	1.52
444		0	108.3	0.555	18.2	89.1	108.3	0.555	18.9	90.6	34.7	27.3	1.24
465		0.1	105.2	0.601	14.8	66.5	105.2	0.601	22.3	83.7	32.6	-	1.16
467		0.1	107.0	0.574	19.5	91.7	106.4	0.583	20.3	94.3	28.0	22.5	1.14
464		0.1	108.2	0.557	16.1	78.1	108.2	0.557	17.5	84.8	25.7	19.6	0.79
466		0.1	109.2	0.542	18.3	91.2	109.2	0.542	18.6	92.8	27.7	20.3	0.86
448		0.1	109.8	0.534	17.3	87.5	109.8	0.534	17.9	90.7	26.5	16.1	0.73
458		0.5	103.5	0.627	14.0	60.3	103.5	0.627	18.1	77.9	21.2	2.6	0.11
472		0.5	108.5	0.553	18.0	87.9	108.5	0.553	20.1	98.2	22.4	8.0	0.25
471		0.5	110.2	0.529	17.0	86.8	110.2	0.529	19.0	97.2	20.9	12.2	0.36
450		0.5	114.4	0.472	14.6	83.5	114.4	0.472	15.6	89.4	18.3	7.7	0.25
449		0.5	114.9	0.465	15.5	90.0	114.9	0.465	15.8	91.5	17.4	3.5	0.15
445	Boston Blue Clay	0	102.0	0.699	22.8	90.6	101.8	0.703	23.3	92.2	34.0	25.7	1.02
446		0	102.3	0.695	22.2	88.7	102.3	0.695	22.2	88.7	34.8	28.6	1.05
447		0.1	101.9	0.701	23.0	91.2	101.9	0.701	23.9	94.6	40.0	23.2	0.72
451		0.1	102.2	0.697	19.8	79.0	101.7	0.705	23.1	91.0	34.3	26.0	1.27
457		0.1	102.8	0.686	20.5	83.1	105.0	0.651	22.4	95.7	30.6	28.6	1.49
475		0.1	103.0	0.684	22.0	89.4	103.0	0.684	23.0	93.3	31.9	22.8	0.83
452		0.1	103.5	0.676	21.0	86.4	103.5	0.676	21.9	90.1	35.3	24.5	1.11
478		0.5	98.4	0.763	23.0	83.8	104.3	0.664	20.0	84.0	30.9	9.6	0.38
476		0.5	98.6	0.759	18.2	66.6	98.6	0.759	23.6	86.1	31.1	12.2	0.51
455		0.5	104.2	0.664	21.1	88.3	-	-	-	-	32.7	1.4	0.10
454		0.5	104.3	0.663	19.3	80.9	104.3	0.663	20.5	85.8	29.5	15.8	0.69
462		0.5	105.9	0.637	20.1	87.8	105.9	0.637	20.1	87.8	25.2	15.1	0.53

TABLE A2



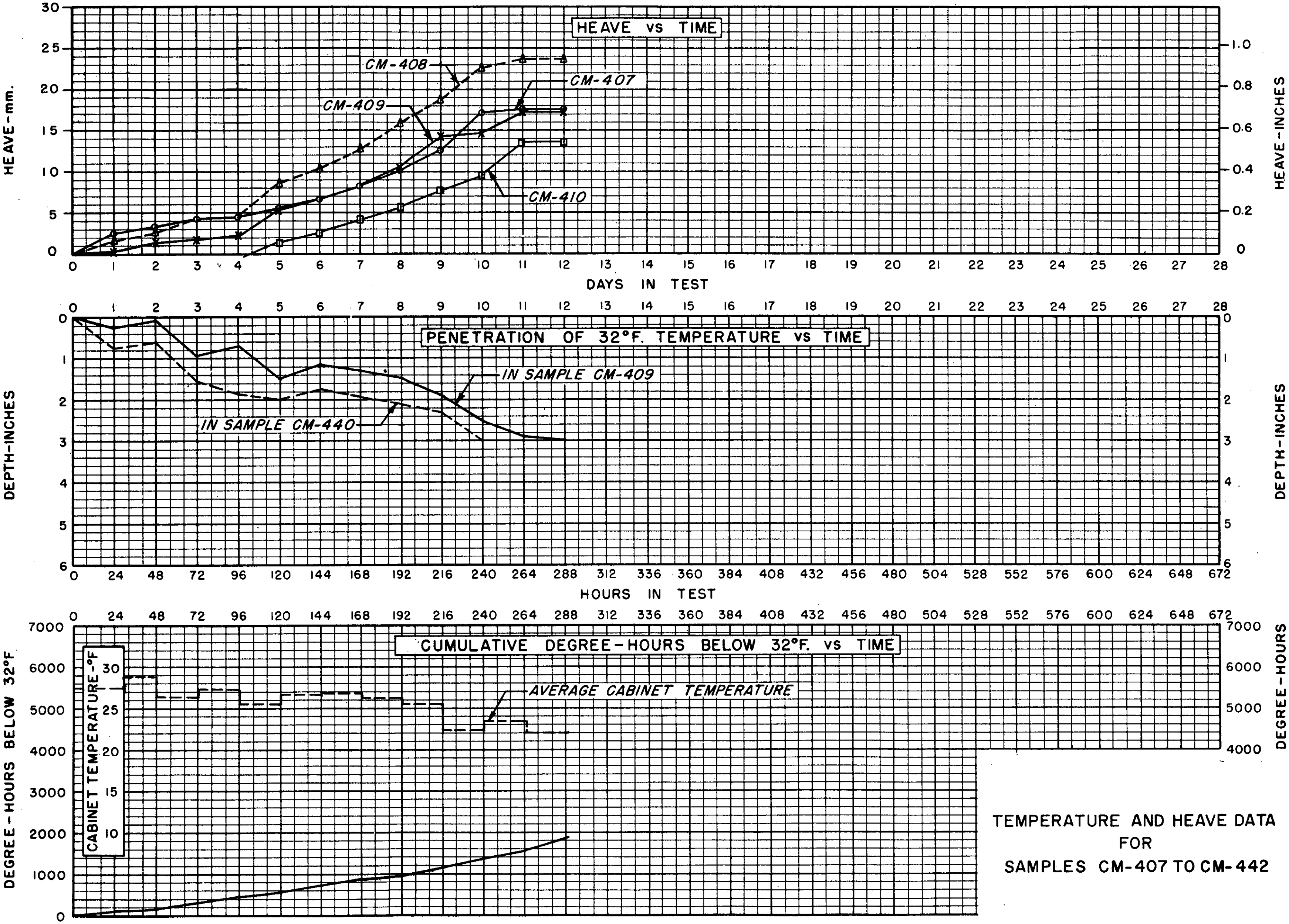
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-367 TO CM-402

Sheet 1 of 2 PLATE A1

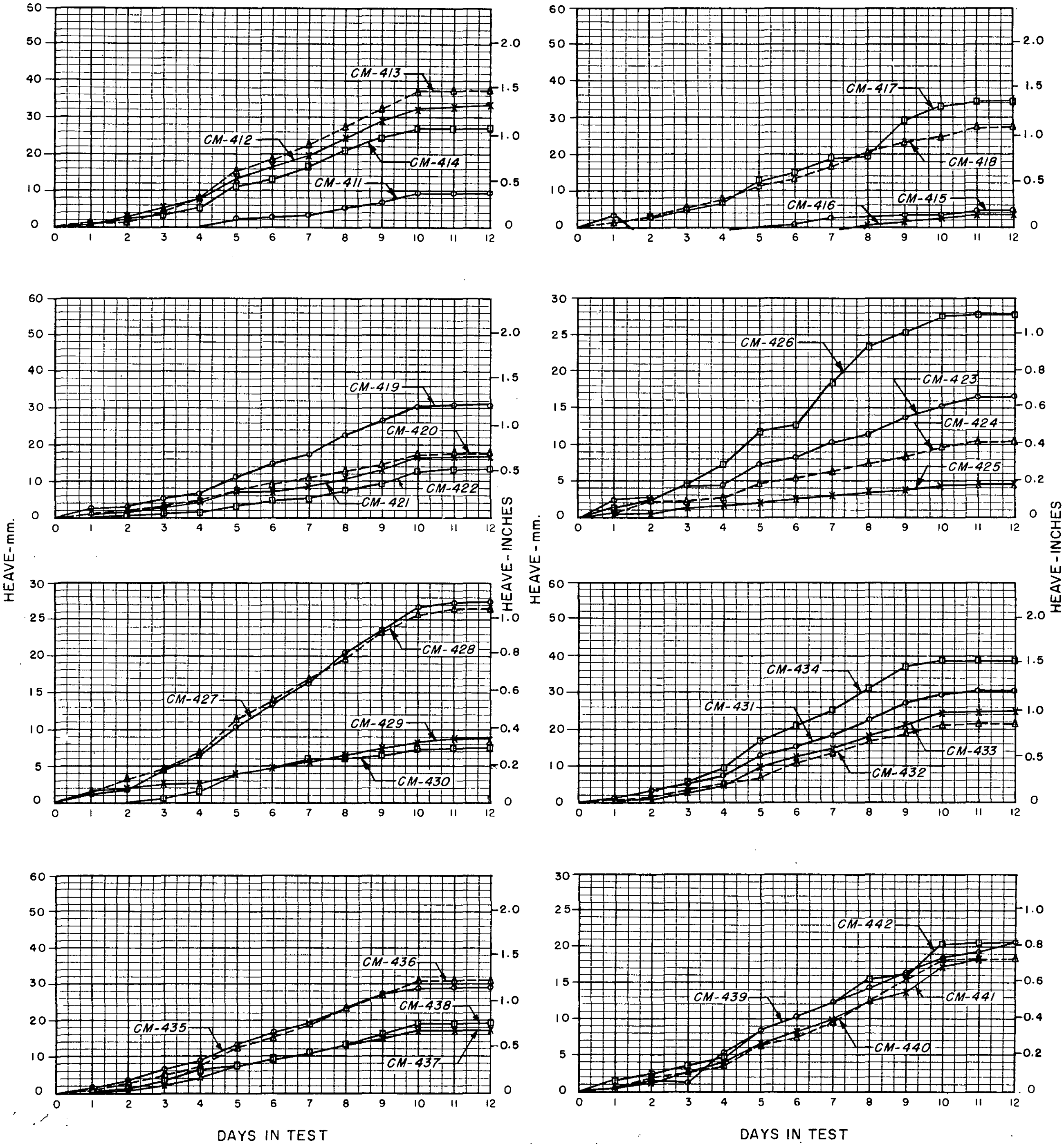


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-367 TO CM-402

PLATE A1 Sheet 2 of 2

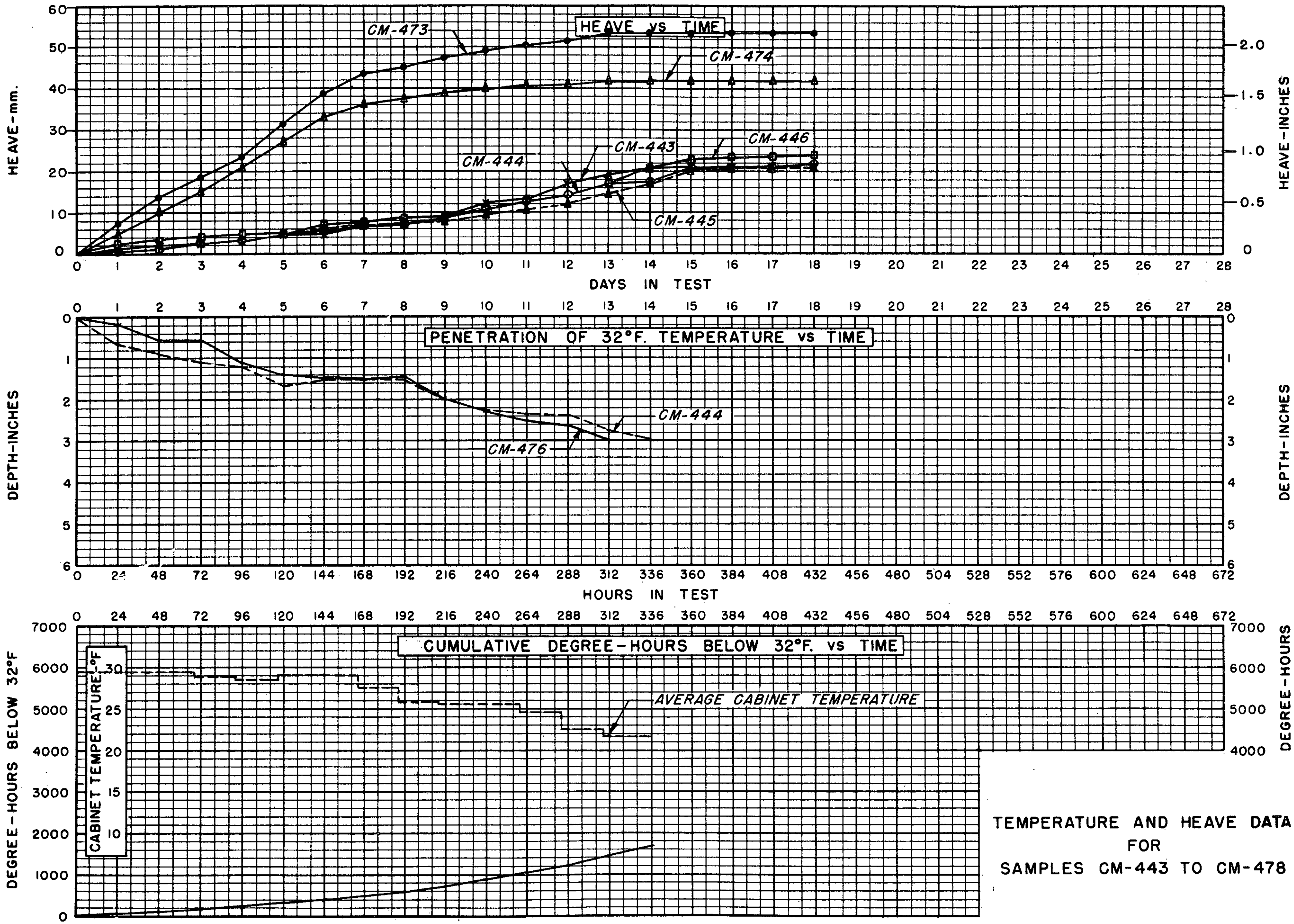


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-407 TO CM-442



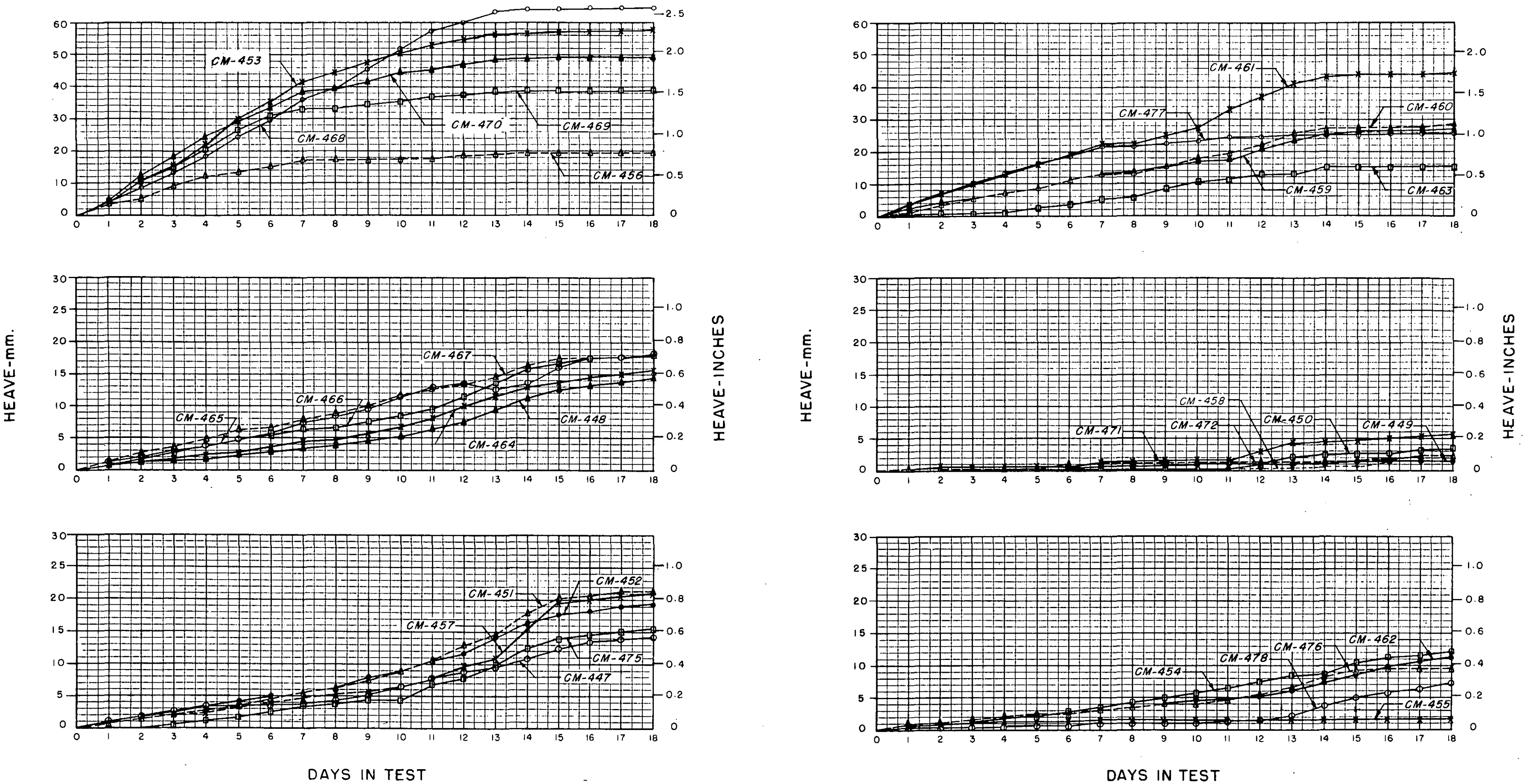
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-407 TO CM-442

PLATE A2 Sheet 2 of 2

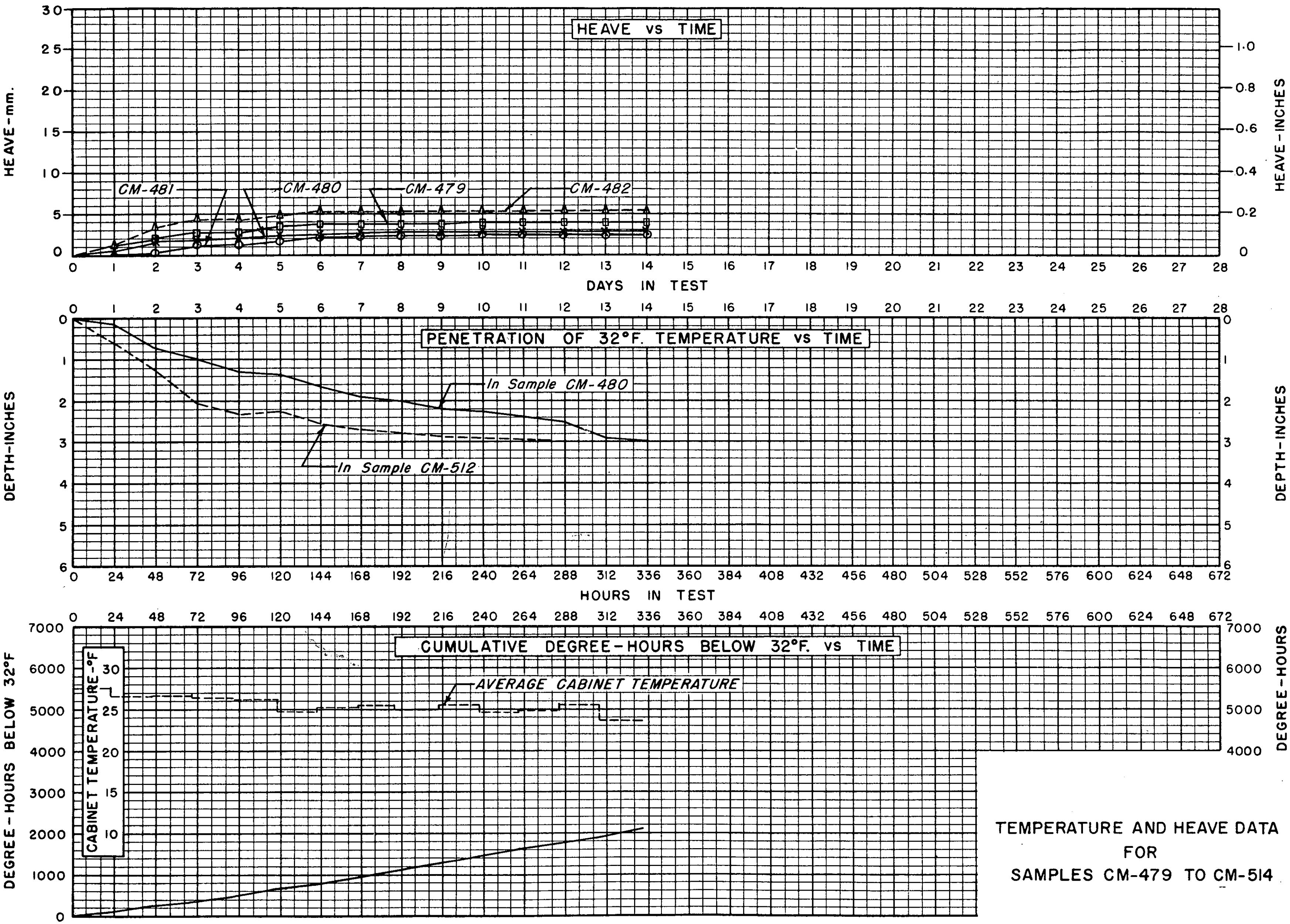


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-443 TO CM-478

PLATE A3 Sheet 2 of 2

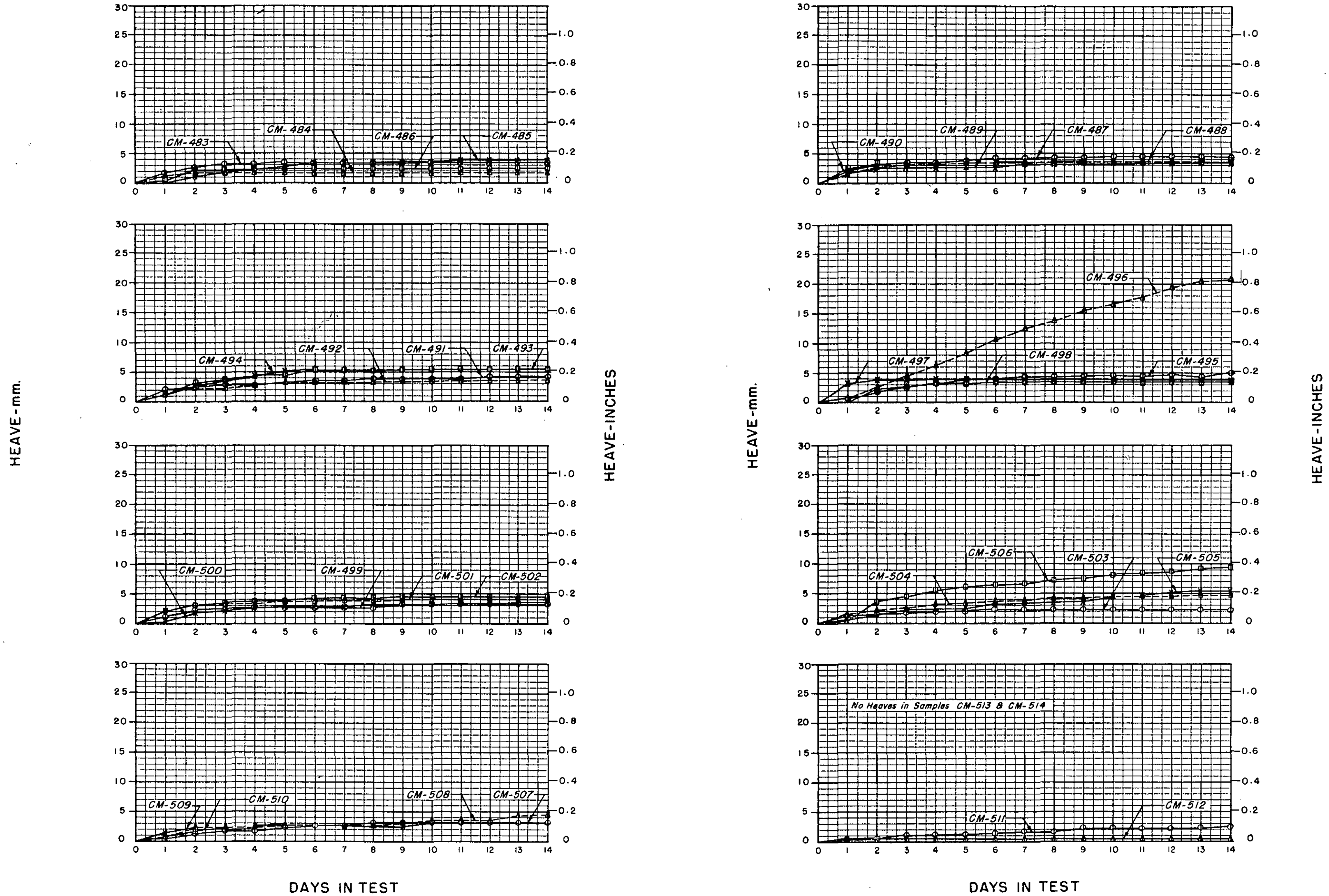


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-443 TO CM-478

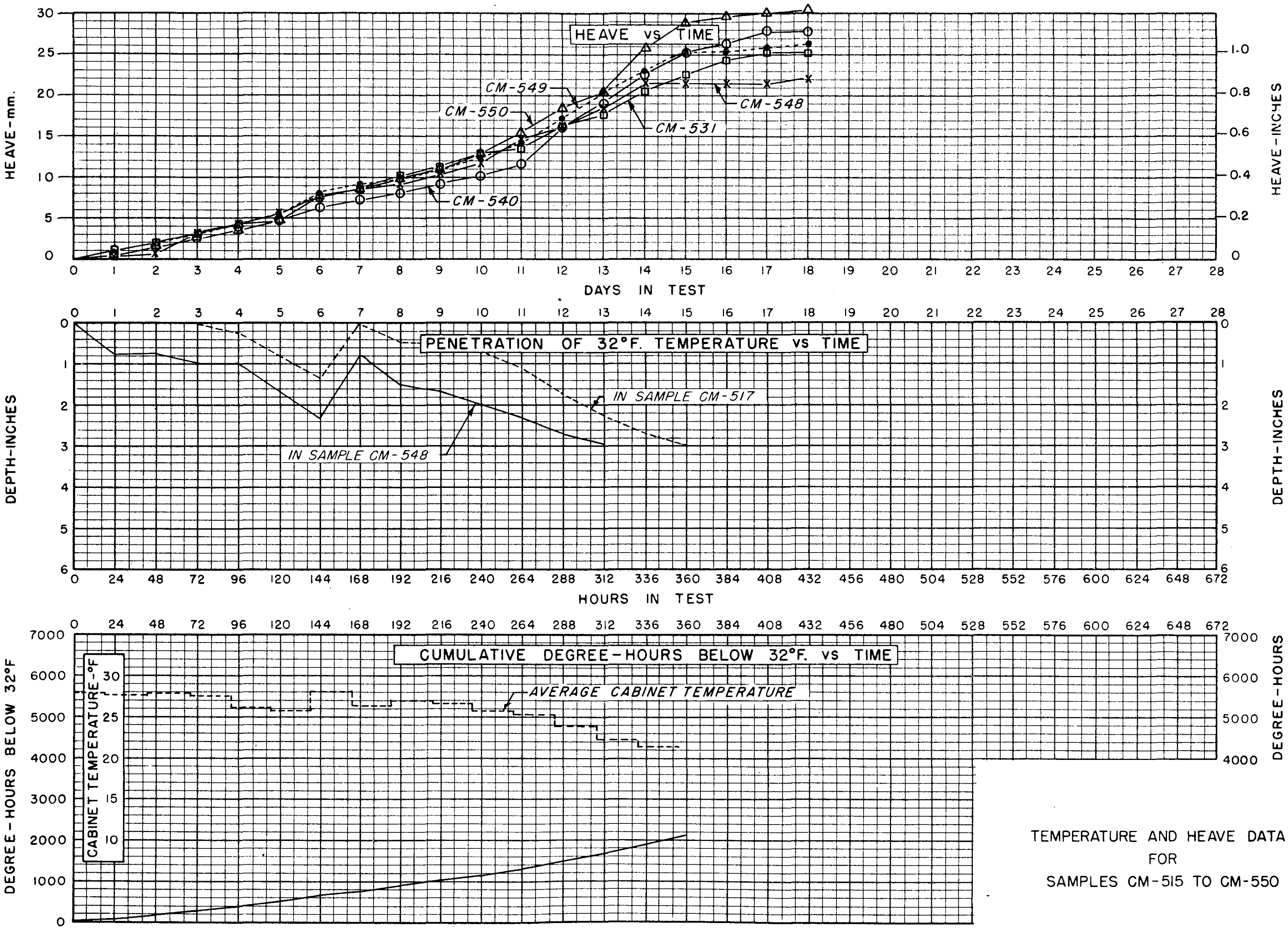


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-479 TO CM-514

Sheet 1 of 2 PLATE A4

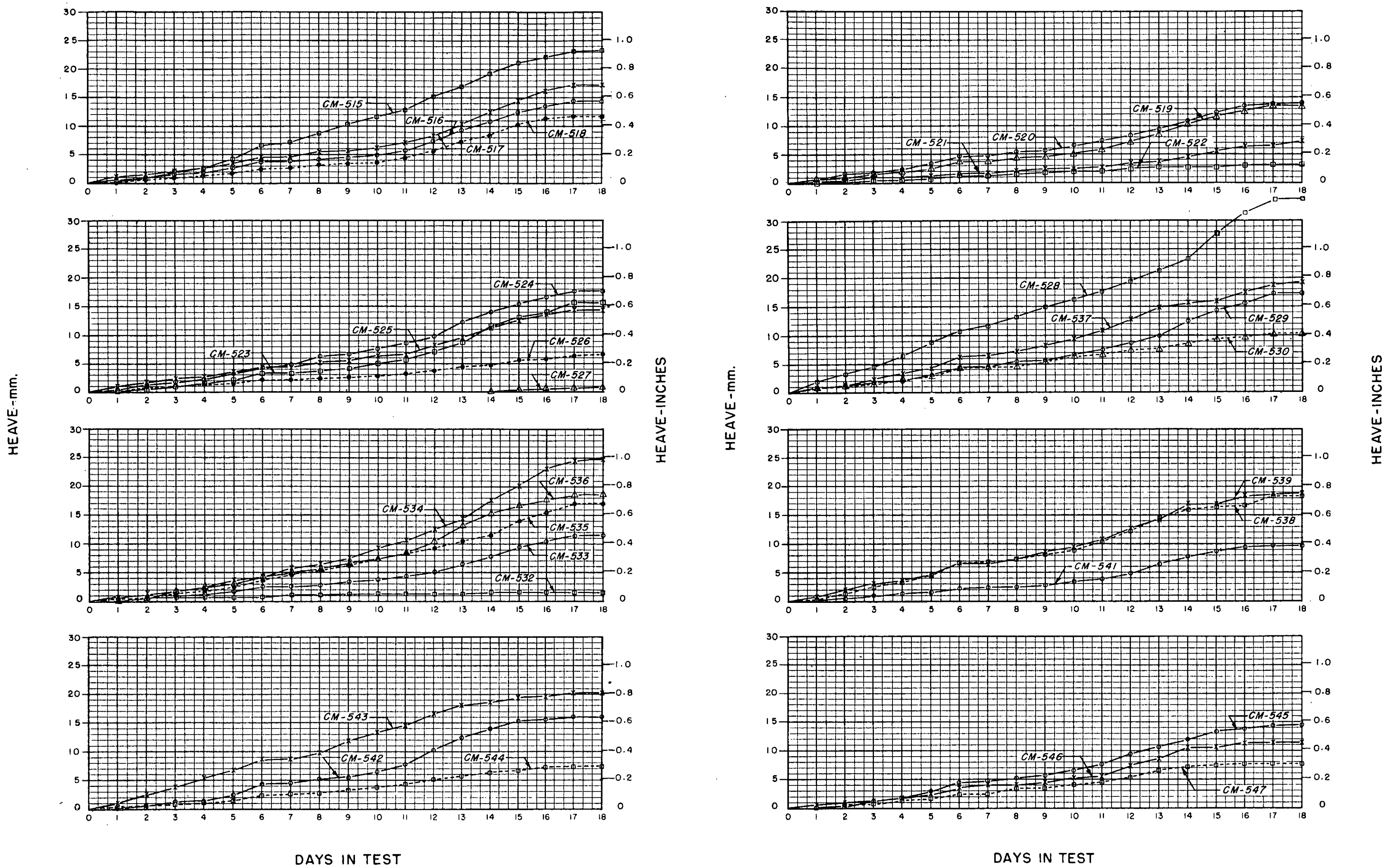


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-479 TO CM-514



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-515 TO CM-550

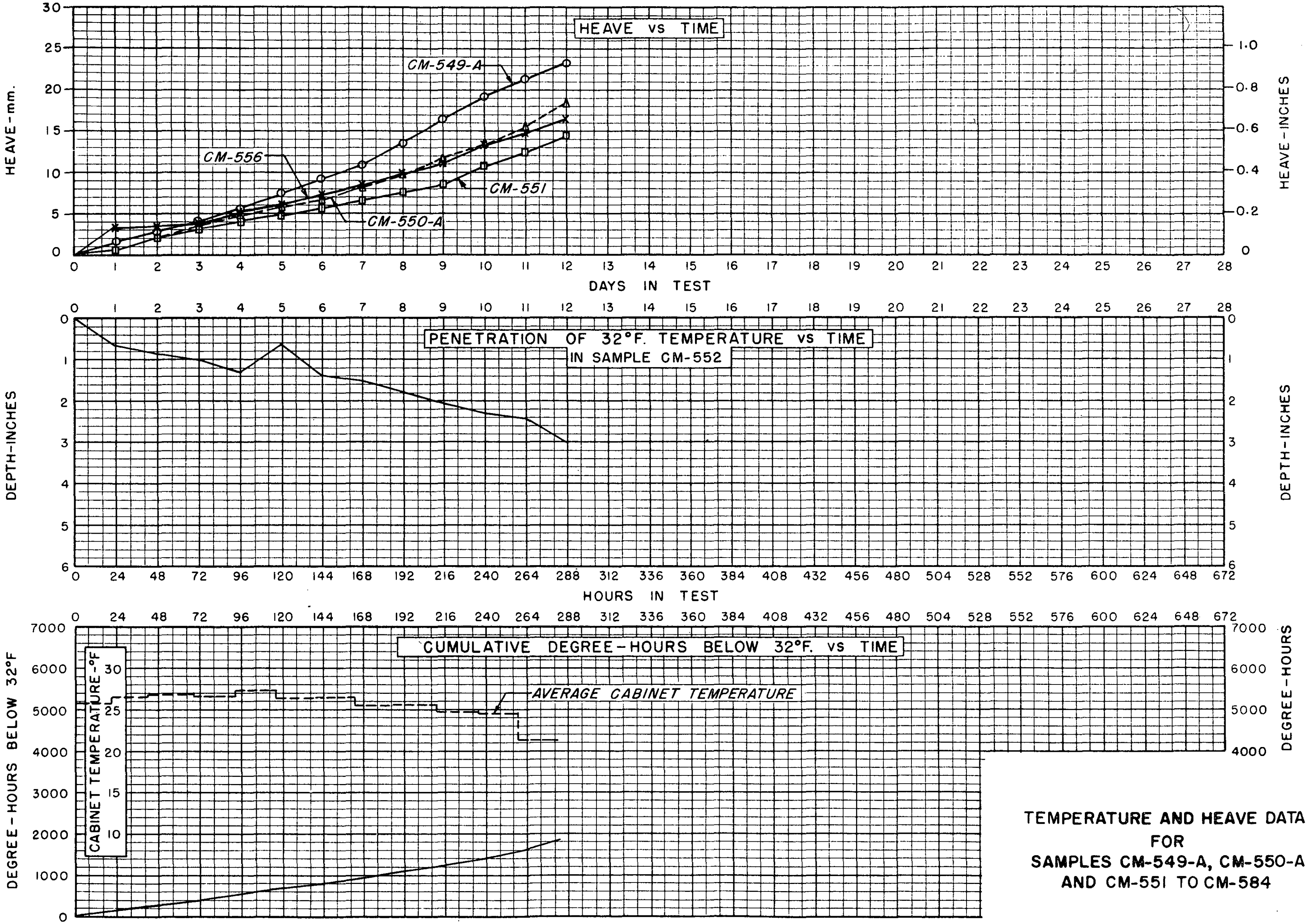
PLATE A5 Sheet 2 of 2



TEMPERATURE AND HEAVE DATA

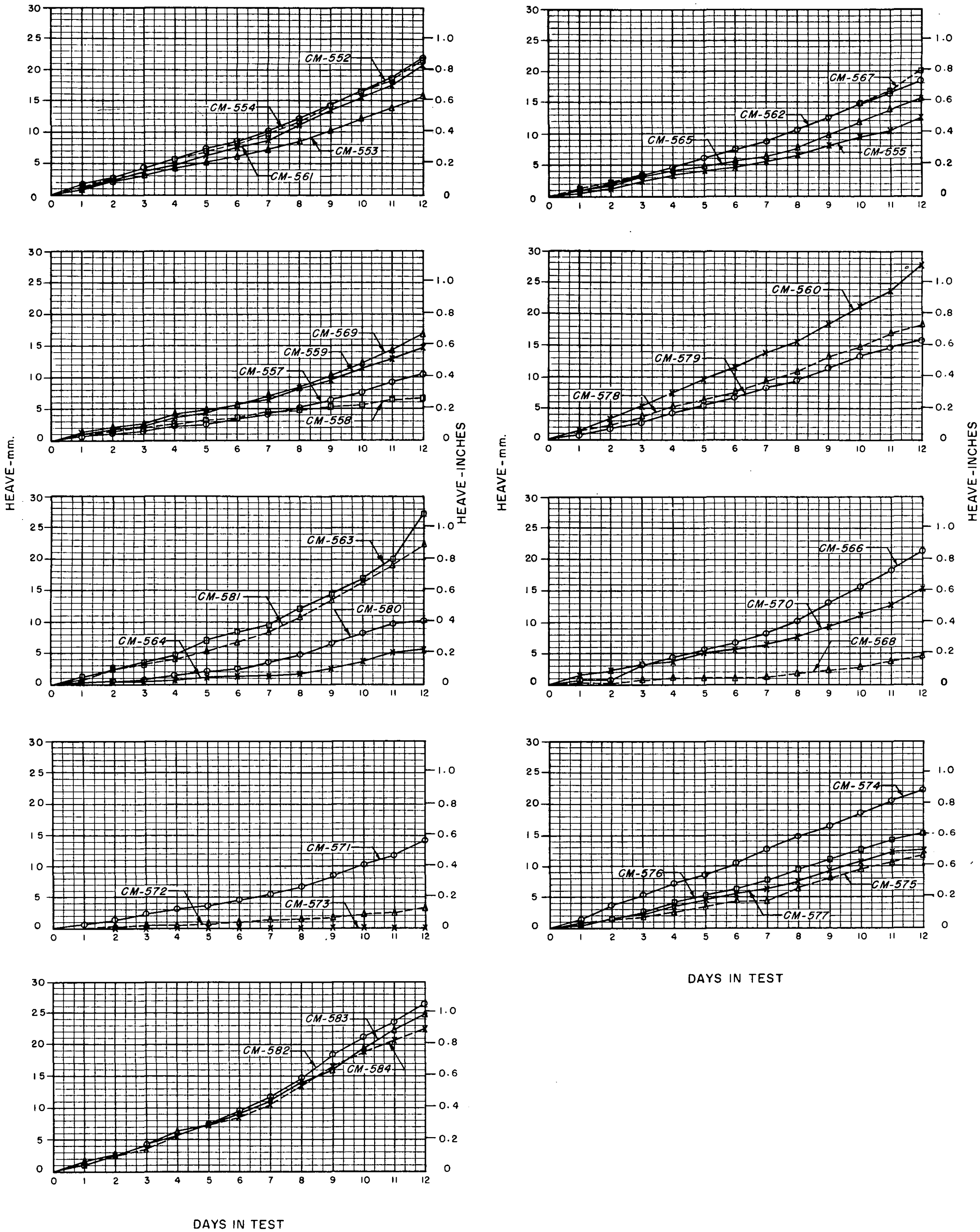
FOR

SAMPLES CM-515 TO CM-550



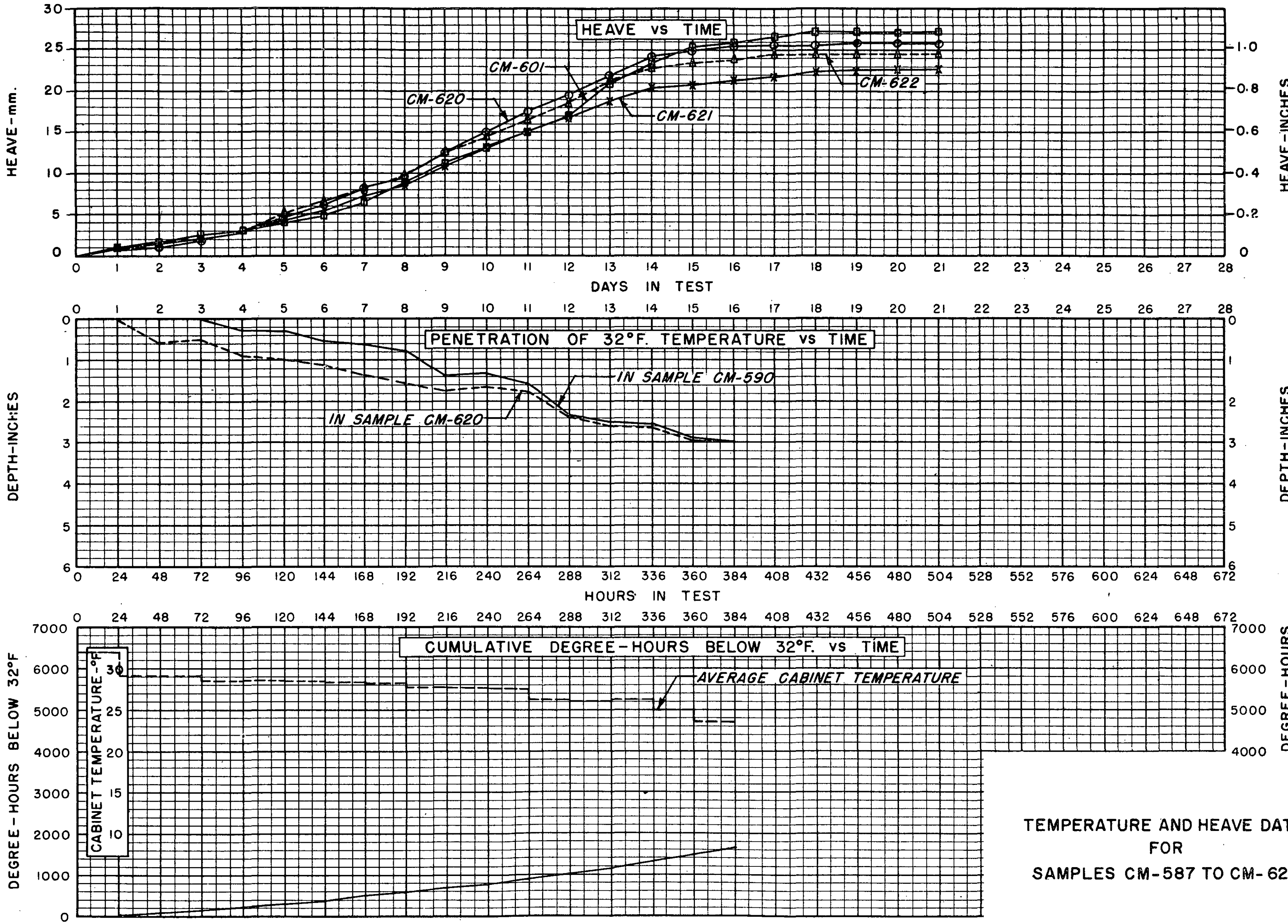
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-549-A, CM-550-A
AND CM-551 TO CM-584

Sheet 1 of 2 PLATE A6



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-549-A, CM-550-A
AND CM-551 TO CM-584

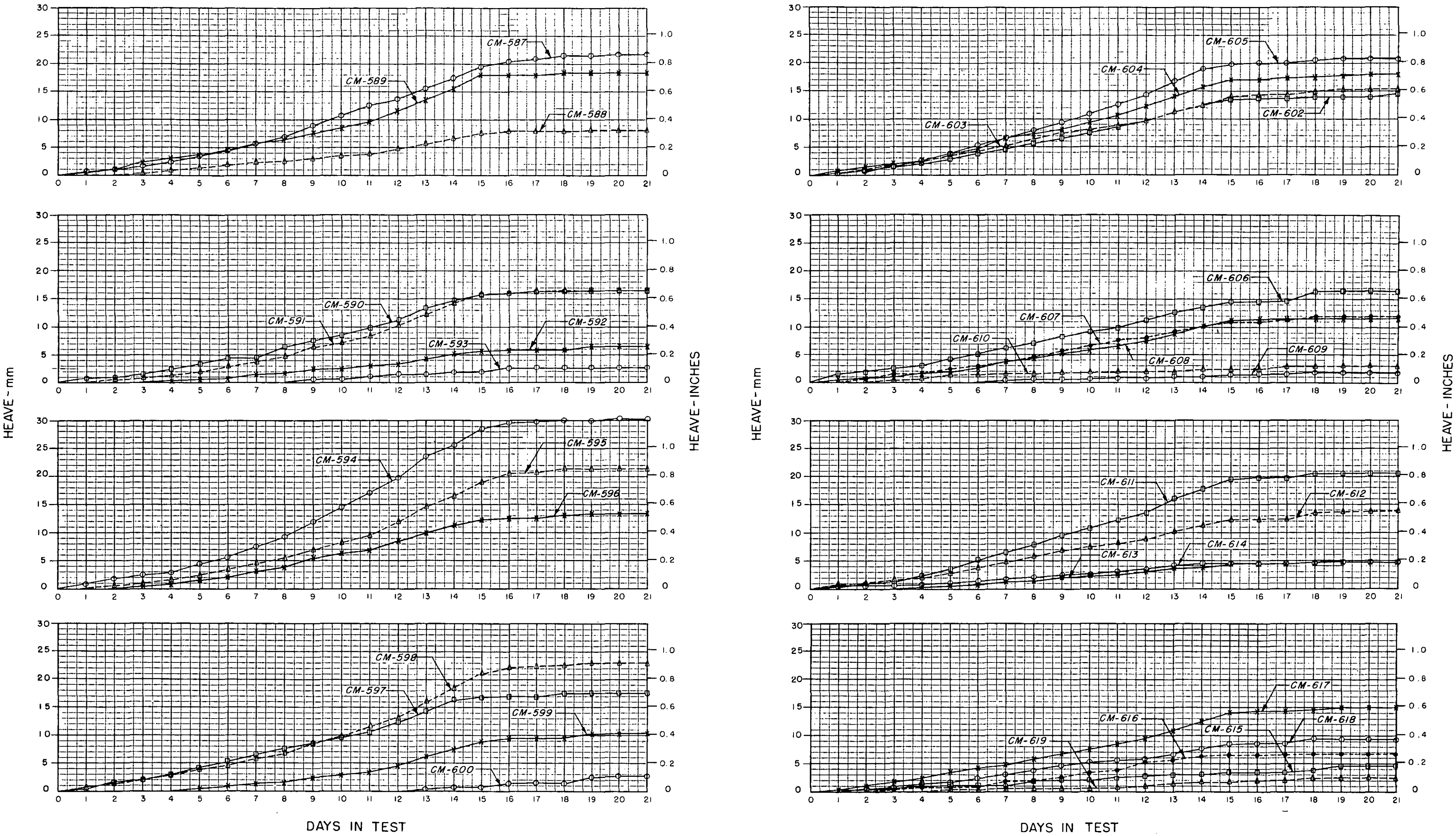
PLATE A6 Sheet 2 of 2



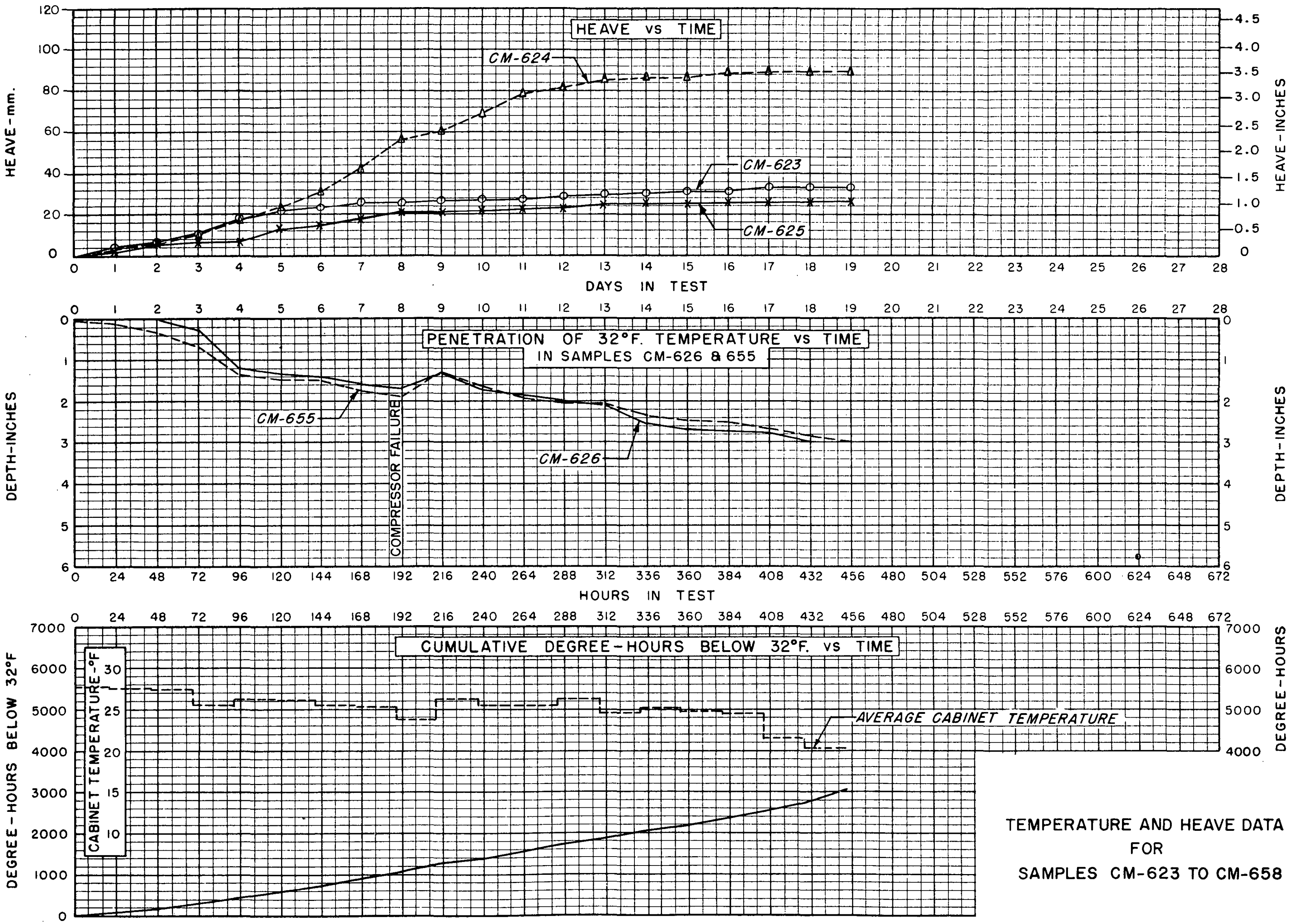
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-587 TO CM-622

Sheet 1 of 2 PLATE A7

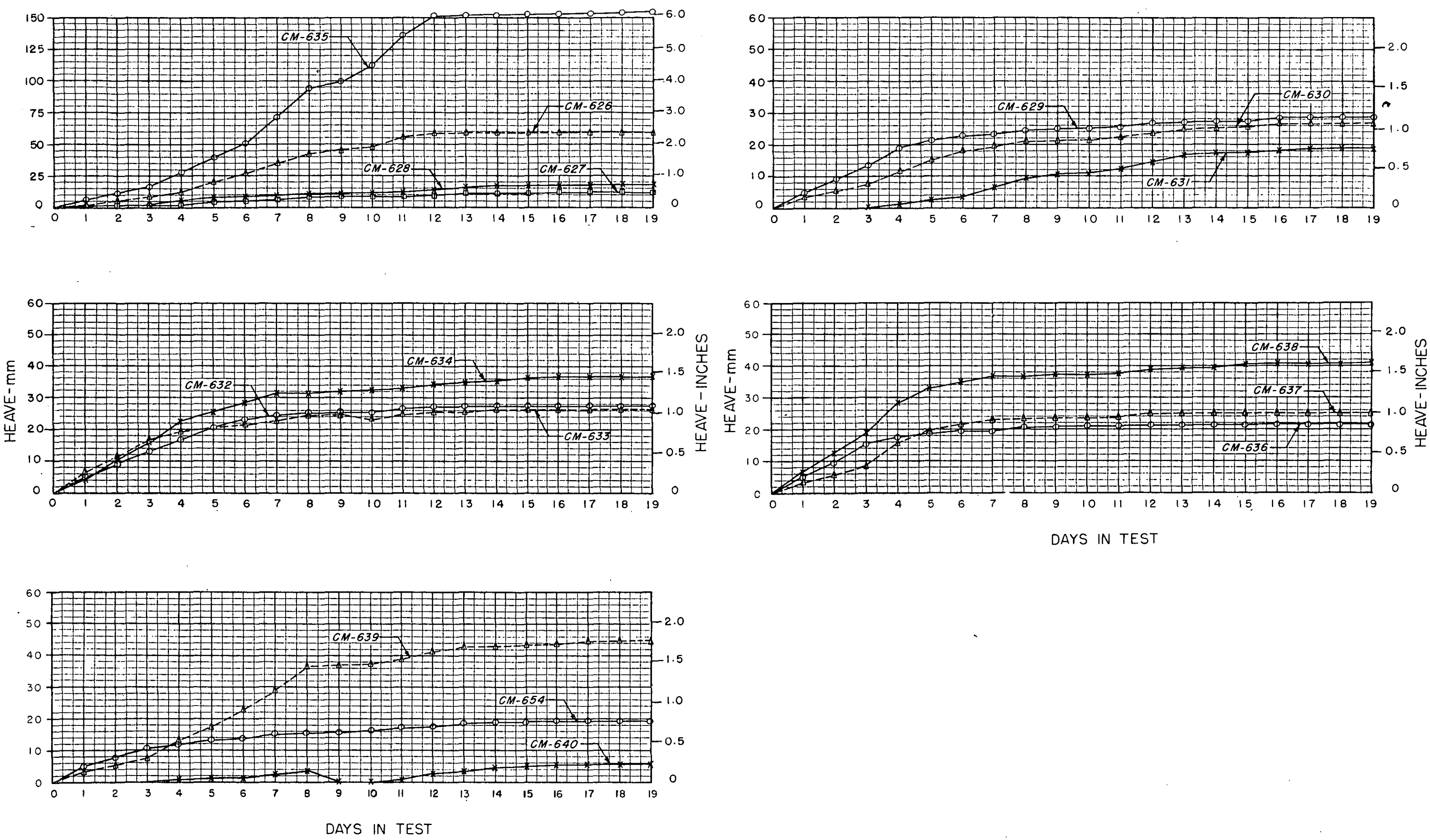
PLATE A7 Sheet 2 of 2



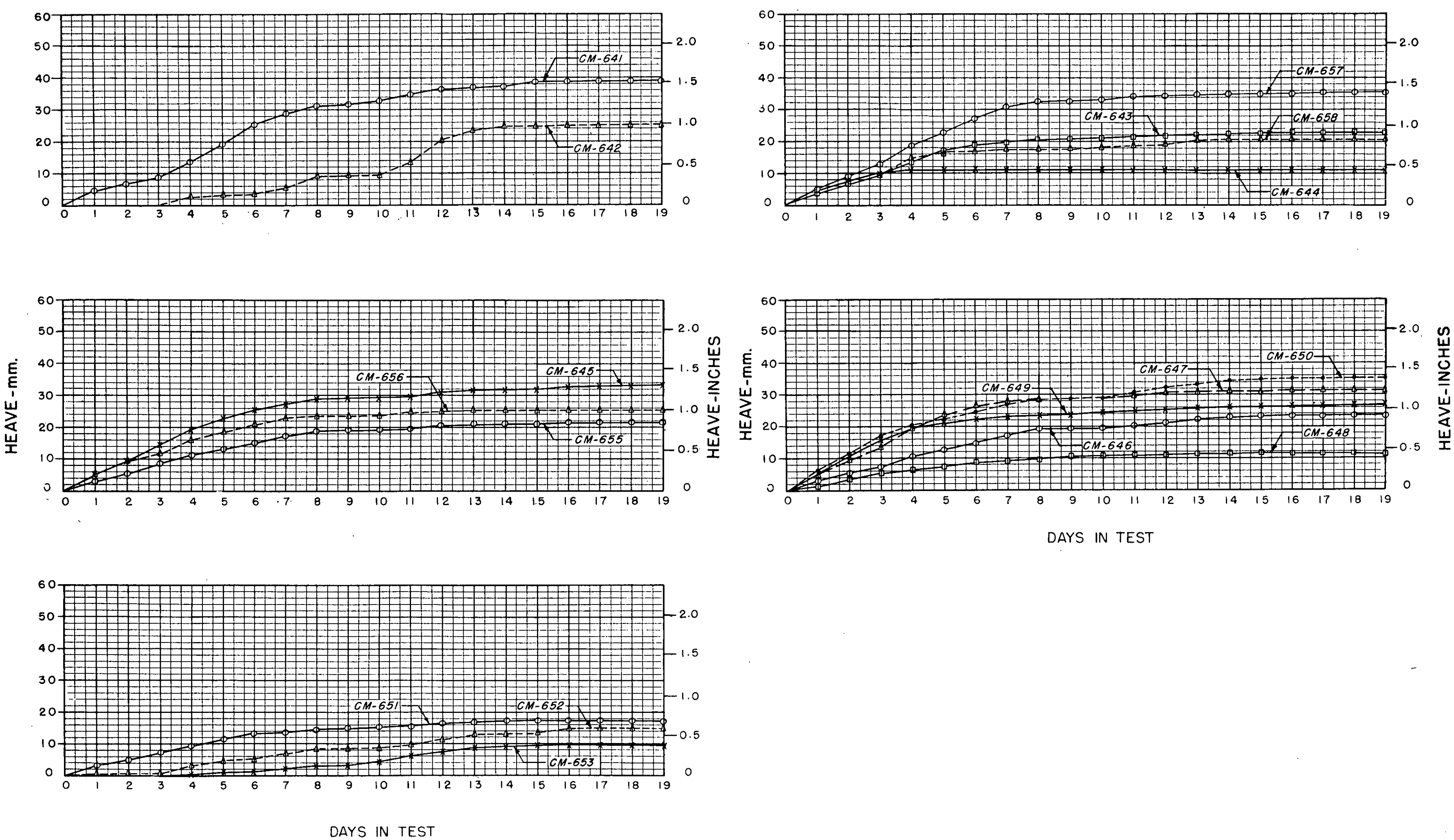
TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-587 TO CM-622



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-623 TO CM-658

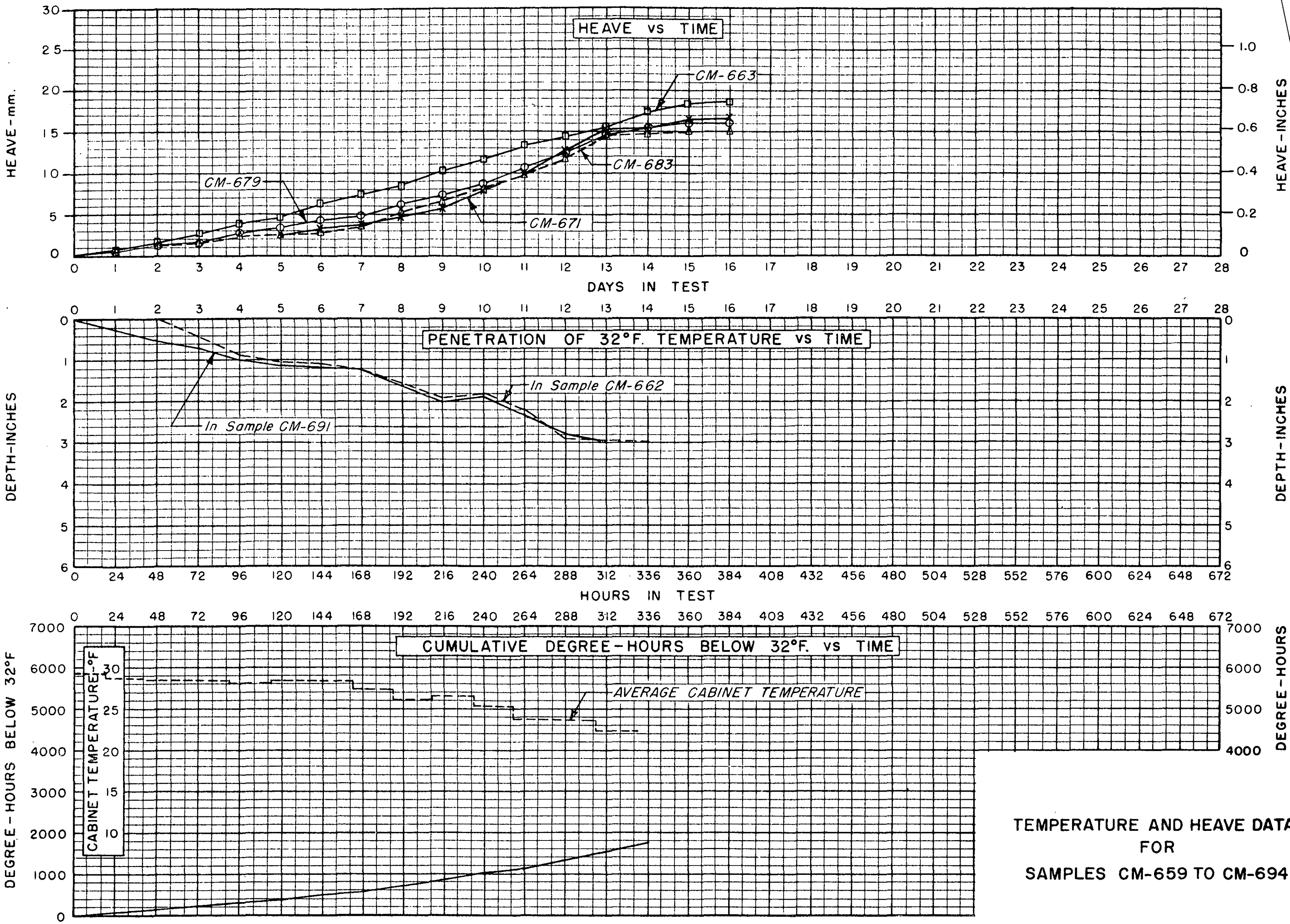


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-623 TO CM-658

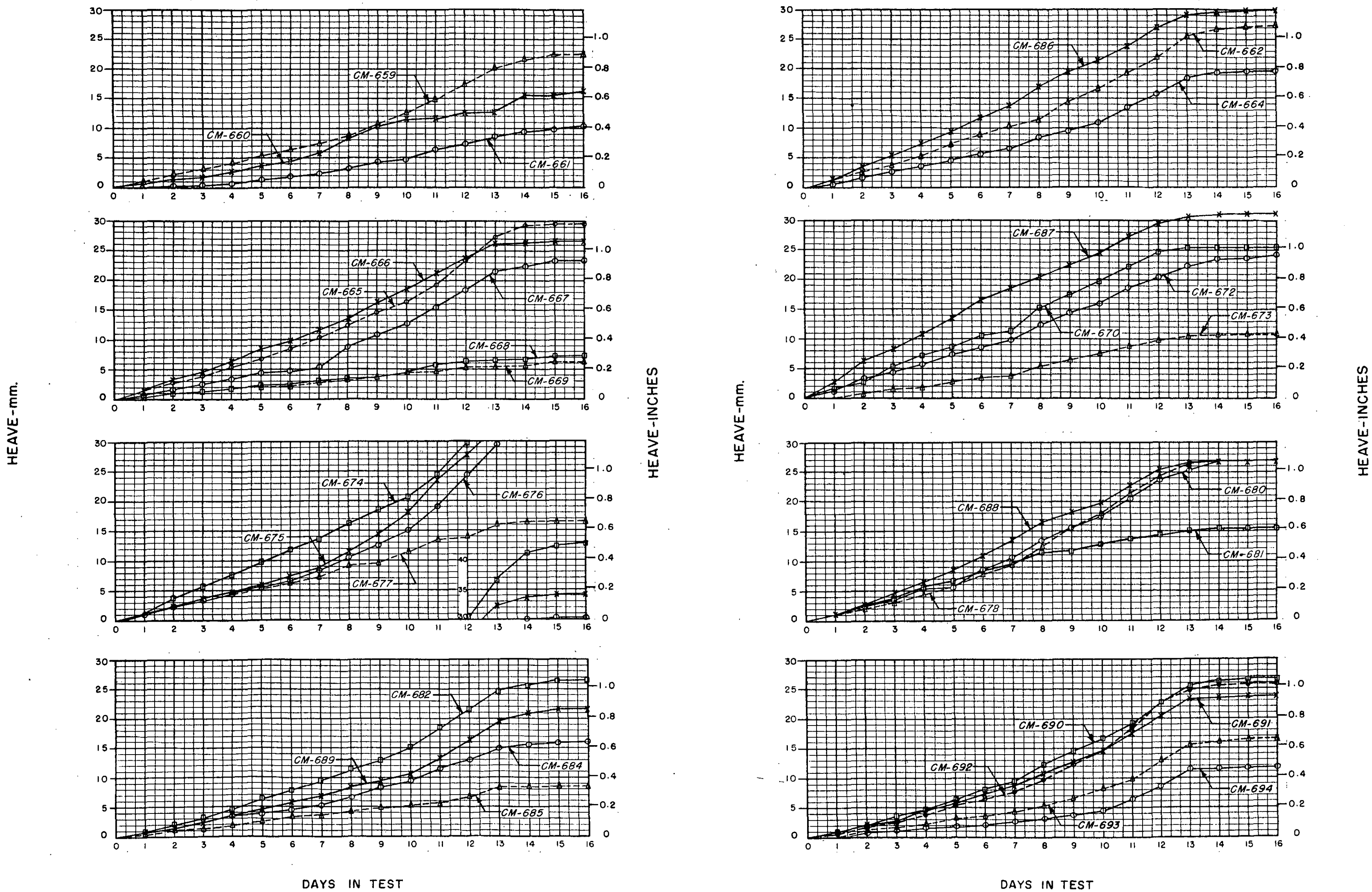


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-623 TO CM-658

Sheet 3 of 3 PLATE A8

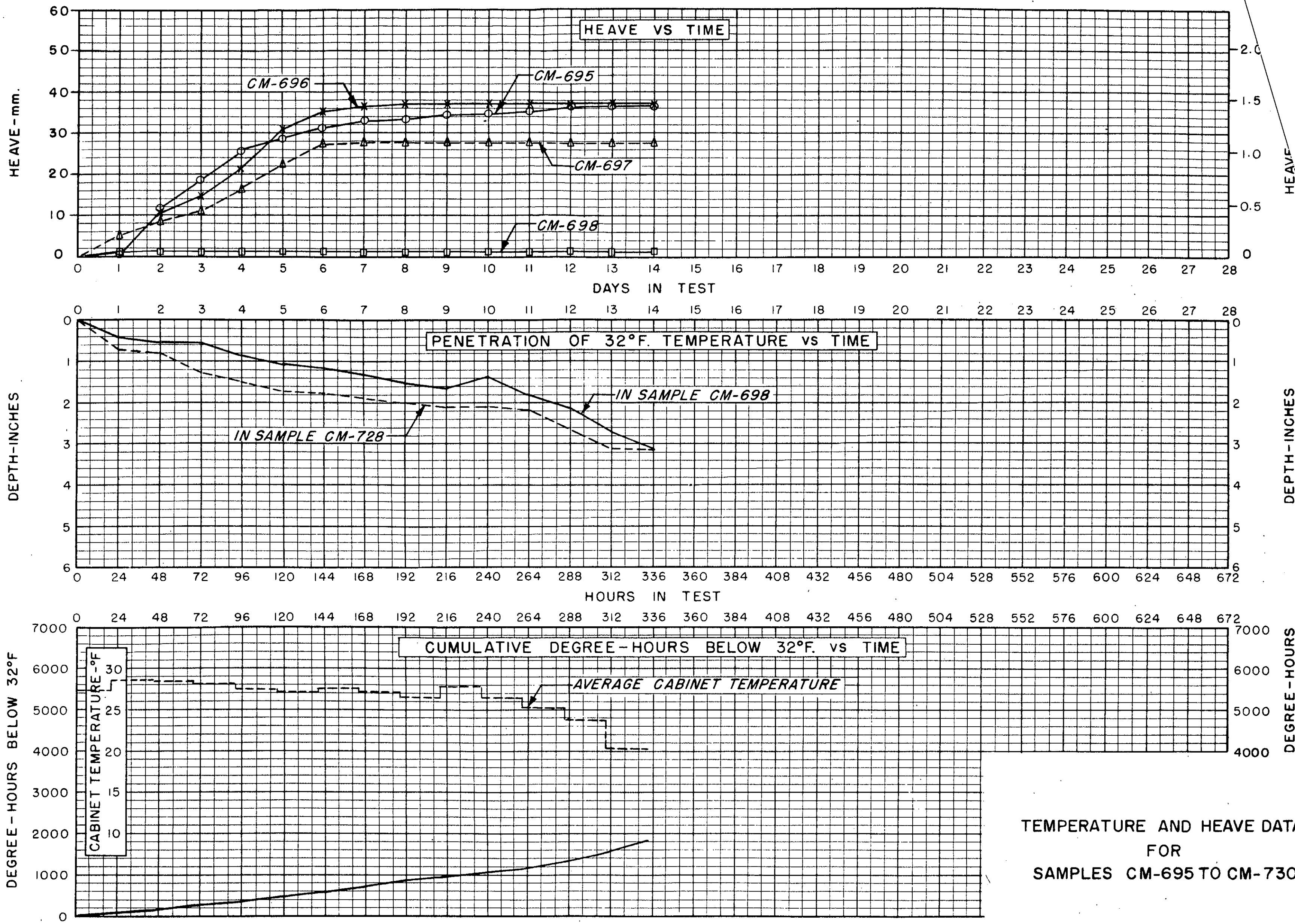


TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-659 TO CM-694

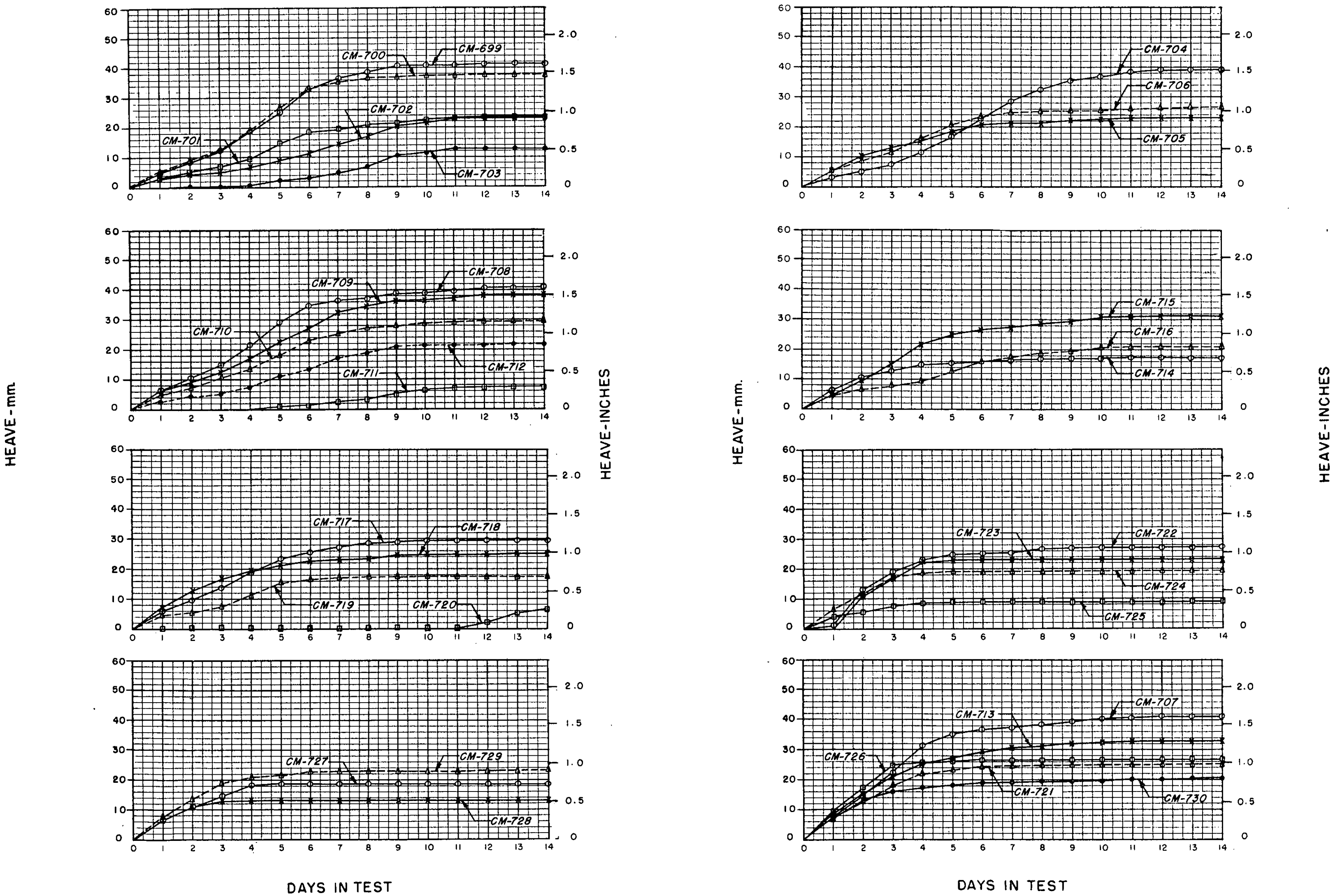


TEMPERATURE AND HEAVE DA
FOR
SAMPLES CM-659 TO CM-

Sheet 2 of 2 PLATE



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-695 TO CM-730



TEMPERATURE AND HEAVE DATA
FOR
SAMPLES CM-695 TO CM-730

Sheet 2 of 2 PLATE A10