THESIS

COMPACTION OF SOIL UNDER FREEZING CONDITIONS AND SUBSEQUENT THAWING

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ABSTRACT

This paper is a report of the investigation by laboratory and reference material of the practicability of compaction of frozen or freezing soils for such uses as airfields and roads. The work consisted of the determination of the major variable factors involved and an approximate verification in the laboratory of the effects of those factors. Three natural, sandy soils were tested, and the results indicate generally that use of frozen soils is probably limited to a very narrow range of moisture content near that of hygroscopic moisture and that their use rapidly becomes less practicable as moisture contents increase and as soil gradation goes from the granular into the silt and clay range.

INTRODUCTION

A. PURPOSE

To determine the practicable limitations, if any, in moisture content, compactive effort and temperature, or other factors, for the compaction of frozen or freezing soils to such a density that, after thawing, sufficient stability exists to support road and airfield type loads.

B. GENERAL

In present construction of compacted earth fills, specifications generally require that no frozen soil be used, nor shall fill be placed on frozen material. This is the usual current practice, and it obviously entails a more or less costly delay in operations, until natural thawing and drying or drainage has rendered the soil again suitable for compaction. It follows, therefore, that in situations where early use of the compacted soil is imperative, it would be highly desirable to be able to obtain suitable compacted densities under freezing conditions by some modified but yet practicable method, such as a reasonable increase in compaction pressure. Such compaction of frozen material might not be practicable at all at the higher moisture contents because of the excessive compactive effort required. Even at moderate moisture contents, the density obtainable at practicable higher pressures may yet be too low to provide a minimum of stability after thawing and saturation.

It is possible that the range of moisture (ice) contents in which this increased compactive effort would be effective might be small. It is also possible that the densities obtainable generally by compacting frozen soil might be appreciably lower than those obtained at ordinary temperatures. However, it is believed that in certain situations, such as military operations, or emergency civilian construction, the somewhat lower compacted densities obtained using frozen material and heavier pressures may provide a minimum standard of density which would insure a degree of stability adequate for the particular need.

C. VARIABLES

1. Variable Elements

In soil compaction under freezing conditions the variables are considered to be as follows:

(a) Gradation of the soil (including both size and shape of particle)

(b) Moisture content of the soil

(c) Rate at which freezing progresses

(d) Temperature of soil and moisture

(e) Compactive effort applied

2. Range of Variation

Given a particular soil gradation, it is assumed that there will be a range of temperature (at or below 0° C or 32° F) and a range of moisture contents for that temperature range at which it will be practicable to compact the soil in the field to a suitable density. Such compaction would be that obtainable with practicable sheepsfoot or other roller pressure for such work as roadbeds and airfield runways and taxiways. The compaction should produce soil densities and bearing strengths in both frozen and thawed state which would be suitable for use in roadways and air-field runways and taxiways.

3. <u>Control of the Variables</u>

(a) <u>Gradation</u> -- Several different types of soils, typical of certain soil classifications, can be selected and grading analysis made. However, it is considered possible that both freezing and compaction may alter the granular structure somewhat and thereby affect subsequent tests made with the same material.

(b) <u>Moisture</u> -- This can be relatively easily varied and con-trolled, except for possible changes in distribution of moisture due to ice crystal growth during freezing. Any change in distri-bution could probably be minimized by freezing in thin sections.

(c) <u>Rate of Freezing</u> -- It was not expected that this could be readily controlled or varied, since the equipment available would not permit variation. The rate provided by the equipment although practically uniform or constant, was expected to be considerably more rapid than would occur in nature, and therefore relatively little change in moisture distribution would be expected.

(d) <u>Temperature of Soil and Moisture</u> -- This also would be difficult to control at temperatures below freezing, unless very elaborate equipment were available. However, it was not expected that variation within about 10° F below 32° F would appreciably affect the results and therefore attempt at control would be made only to this extent.

(e) Compactive Effort -- Practicable field compaction pressures can be approximated in the laboratory by using standard compaction test methods and equipment with variation obtained by varying the number of blows and weight and fall of the rammer. While the variations are probably not equivalent to increased weight of roller, they are assumed to be equivalent to increased number of passes and thereby a measure of compactive effort.

D. SCOPE OF PROPOSED INVESTIGATIONS

In brief, after research of any existing pertinent literature, it was proposed that laboratory investigation be made of several typical soils, to determine for each the compacted density obtainable through a range of moisture contents, under both room temperature conditions and with frozen soil, and to measure stability or penetration resistance under each condition by some suitable means. From study of the results it is expected that for a given soil a range of moisture contents will be indicated beyond which the density resulting from compaction of frozen soil will be too low to provide satisfactory stability after thawing and saturation.

It is assumed that compacted density and percent voids, for ordinary soils, constitute a measure of structural stability, sufficiently accurate for the scope of this investigation. Compaction methods and equipment as in laboratory use generally would be used, and results should therefore be more easily comparable to those of standard practice.

The work is reported under Part I and Part II, a 5-1/2 lb. rammer having been used for compaction in Part I, and a 10 lb. rammer in Part II. Other variations in the work under Parts I and II will be apparent in the detailed comments below.

INVESTIGATION: PART I

A. PLAN AND SCOPE

1. Limiting Considerations

Initially the laboratory work was confined to compaction of soils in frozen or freezing condition, and measuring penetration resistance prior to thawing (with such measurements occasionally after thawing). With time and facilities available, it was considered impracticable to conduct adequate tests subsequent to thawing concurrently but that such tests would be conducted later as time was available. (In Part II)

2. Variables to be Considered

In order to arrive more quickly at a qualitative confirmation of the basic premise on moisture-density relation in compaction of frozen soil, preliminary work was limited to only two relatively sandy materials for ease of handling and to only one degree of compaction. Temperature variation consisted of only the two conditions, room temperature (70° F approximately) and (32° F or below). Moisture was varied through the usual range used in compaction tests. These limitations to the variables also permitted the investigators to become familiar more quickly with the testing procedures, technique, and equipment.

3. Outline of Method

On any particular soil sample, work was contemplated as follows:

(a) Make mechanical analysis (gradation)

(b) Determine specific gravity

(c) Prepare moisture-density and penetration resistance curves at room temperature as under normal laboratory and field conditions, using standard compaction testing equipment and procedure.

(d) Prepare same as (c) for freezing or frozen samples of same soil.

(e) Based upon results of (d) compact occasional representative sample of freezing or frozen soil, thaw, and measure penetration resistance.

(f) Compare moisture-density relations obtained in (c) and (d) using same compactive effort.

B. MATERIALS USED

1. Preliminary Work

In order to develop the required laboratory technique and familiarize the investigators with standard procedures, some preliminary compaction tests were made using a local sand clay loam from the campus area of the Institute and also a sandy loam from the site of "Manhattan Village" near Manhattan Beach. The amount of these soils available at the time was not adequate to make complete tests.

2. Comparative Test

The two soils used for the compaction tests in this investigation are:

(a) Sand -- a grey sand from vicinity of Glendale

(b) Sandy loam -- a fine yellow sandy loam from Pasadena area (Robertson property)

Mechanical analyses in Figure 4 show gradation of each of these soils.

C. EQUIPMENT USED

1. Compaction Equipment (Figure 1)

(a) Cylinder was 4.6 inches in height and 4.18 inches in diameter or volume of 0.0365 cu. ft., with circular base and collar.

(b) Rammer weighed 5-1/2 lbs., had 2 inch diameter striking face, and was equipped with a tubular guide for controlling a free fall of 12 inches.

(c) Support under cylinder while compacting was concrete basement floor.

2. Stability Testing Equipment (Figure 2)

(a) Penetration needles were from the standard type of penetrometer and varied from 0.05 to 0.2 sq. in. in point area.

(b) Penetration resistance measurement was made by direct reading from bathroom type scales placed under the cylinder.

(c) Penetration pressure was applied by drill press or by compression testing machine.

3. Freezing Equipment (Figure 3)

(a) Refrigerating compartment was 25" x 25" x 14" deep with two access doors on top.

(b) Power was supplied by two 2 HP induction motors, each driving a compressor working in series.

(c) Temperature range possible extended to -20° to -30° F, and was measured by mercury thermometer.

(d) Soil containers during freezing were shallow rectangular

Figure 1

COMPACTION EQUIPMENT USED IN PART I

Note: Cylinder shown is type used in Part II. Cylinder used in Part I was not available for photographing, but differed only slightly in volume (0.0365 cu.ft. instead of 0.0338 cu. ft. for the one shown) and in shape of base and method of bolting.

Figure 2

PENETRATION RESISTANCE MEASURING EQUIPMENT

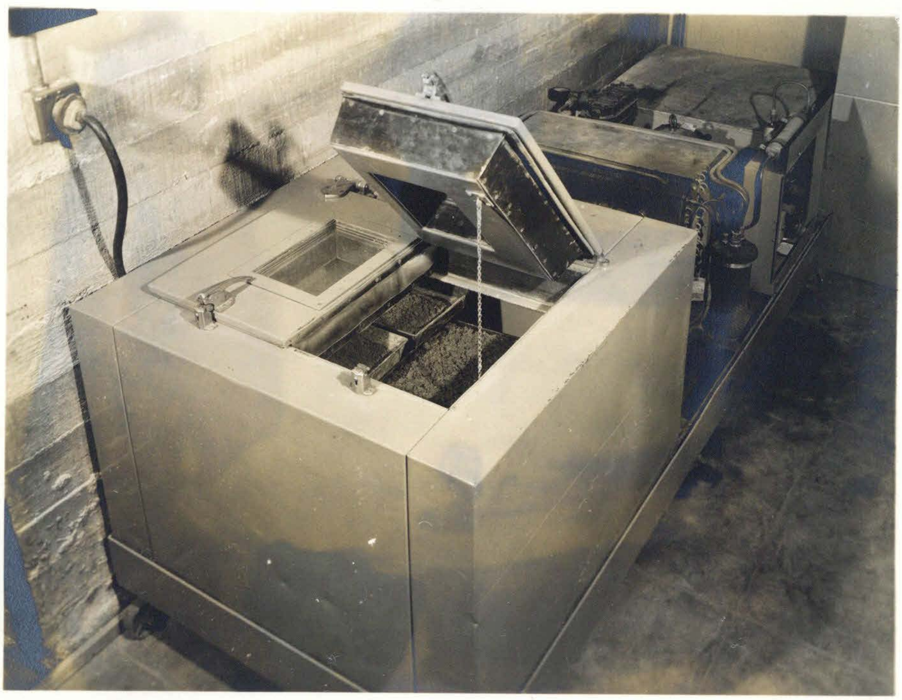


Figure 3

FREEZING EQUIPMENT

metal pans averaging 10" x 16" x 1" or 2" deep.

4. Weighing Equipment

Platform scales accurate to 0.01 pound, and laboratory balances accurate to 0.1 gram.

5. Mechanical Analysis

(a) Sieve test -- Tyler standard sieves, sizes No's. 8, 14, 28, 48, 100, 150, and 200.

(b) Hydrometer test -- Taylor (Bouyoucos type) No. 342081, 1000 ml graduate, and dispersing mixer.

D. PROCEDURE

1. General

As outlined above in general plan for the project, compaction tests were made on each of the two soils, both at room temperature and frozen. Density and penetration resistance were determined for various moisture contents.

2. Compaction

Soil was placed in the cylinder in three layers, and rammed with twenty-five 12" free-fall blows to each layer. Duplicate batches of soil were prepared for each moisture content, one batch being compacted at room temperature, and the other batch frozen, and then compacted.

3. Stability

Penetration resistance was measured by the smaller Proctor needles (.05, 0.1, or 0.2 sq. in., depending on range of resistance). In order to obtain a uniform rate of penetration and direct reading of resistance, the compacted sample in cylinder was placed on a bathroom scale, the scale placed under the head of compression machine or drill press, and the needle held vertically against the bottom of the head of the machine, and pressure applied by moving the head downward at constant speed, at the standard rate of 1/2 inch per second to a depth of 3 inches.

4. Density

By weighing struck cylinder on platform scales.

5. Specific Gravity

Pycnometer method, exhausting entrained air with 20 pounds per sq. in. vacuum.

6. Mechanical Analysis

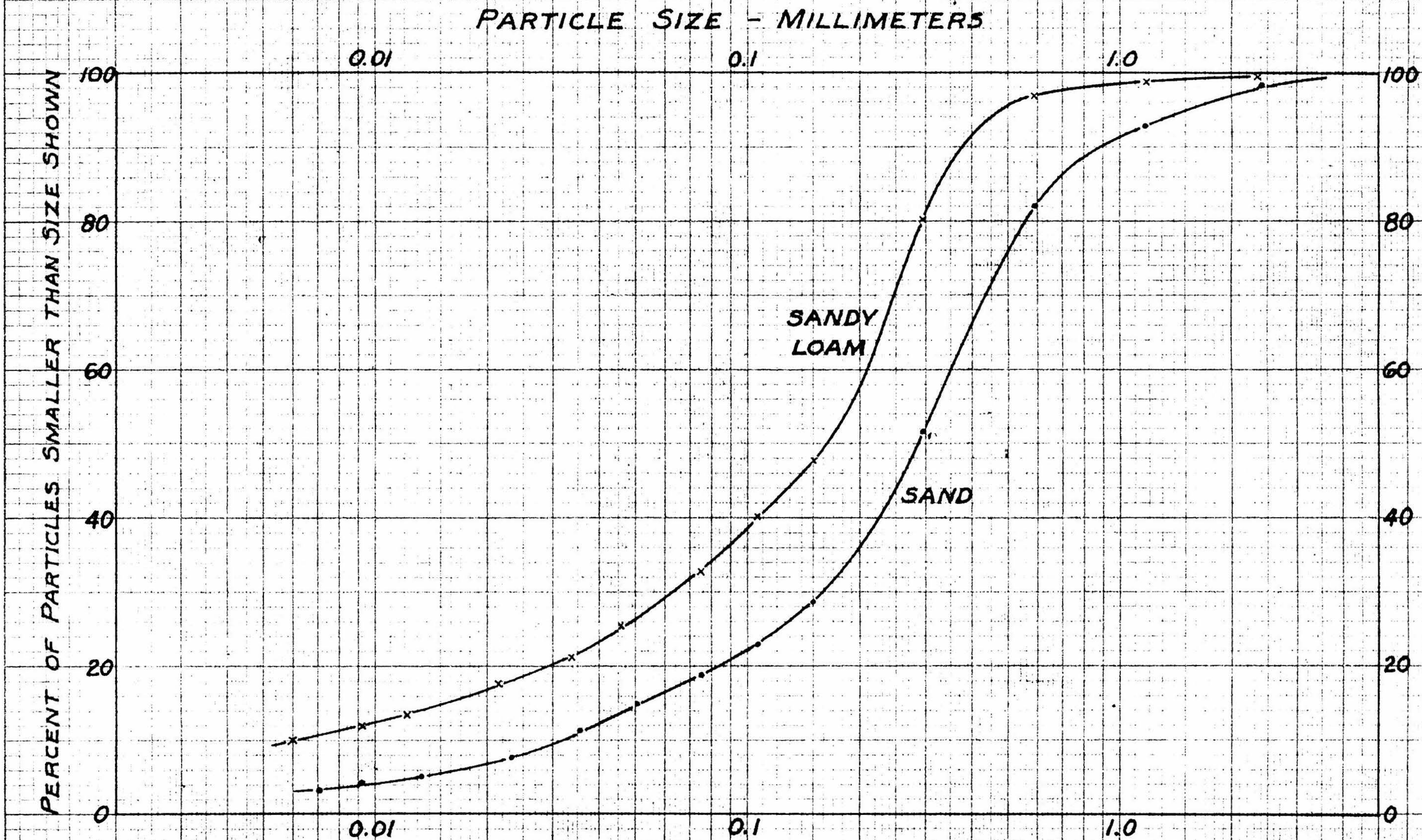
Conventional test methods. (ASTM Designation, D 422-39)

7. Moisture Content

Conventional test methods. (ASTM Designation D 698-42T)

E. DATA

Curves have been plotted from data accumulated in the laboratory and are attached hereto (Figure 5). Only significant data are considered. Two soils classified as sand and sandy loam respectively were investigated (see attached mechanical analysis curves, Figure 4). A number of penetration tests were made on samples which had been compacted frozen and then allowed to thaw before penetration testing, but the principal part of the work was with compacted samples before thawing.



MECHANICAL ANALYSIS OF SOILS

USED IN COMPACTION TESTS - PART I

FIG. 4

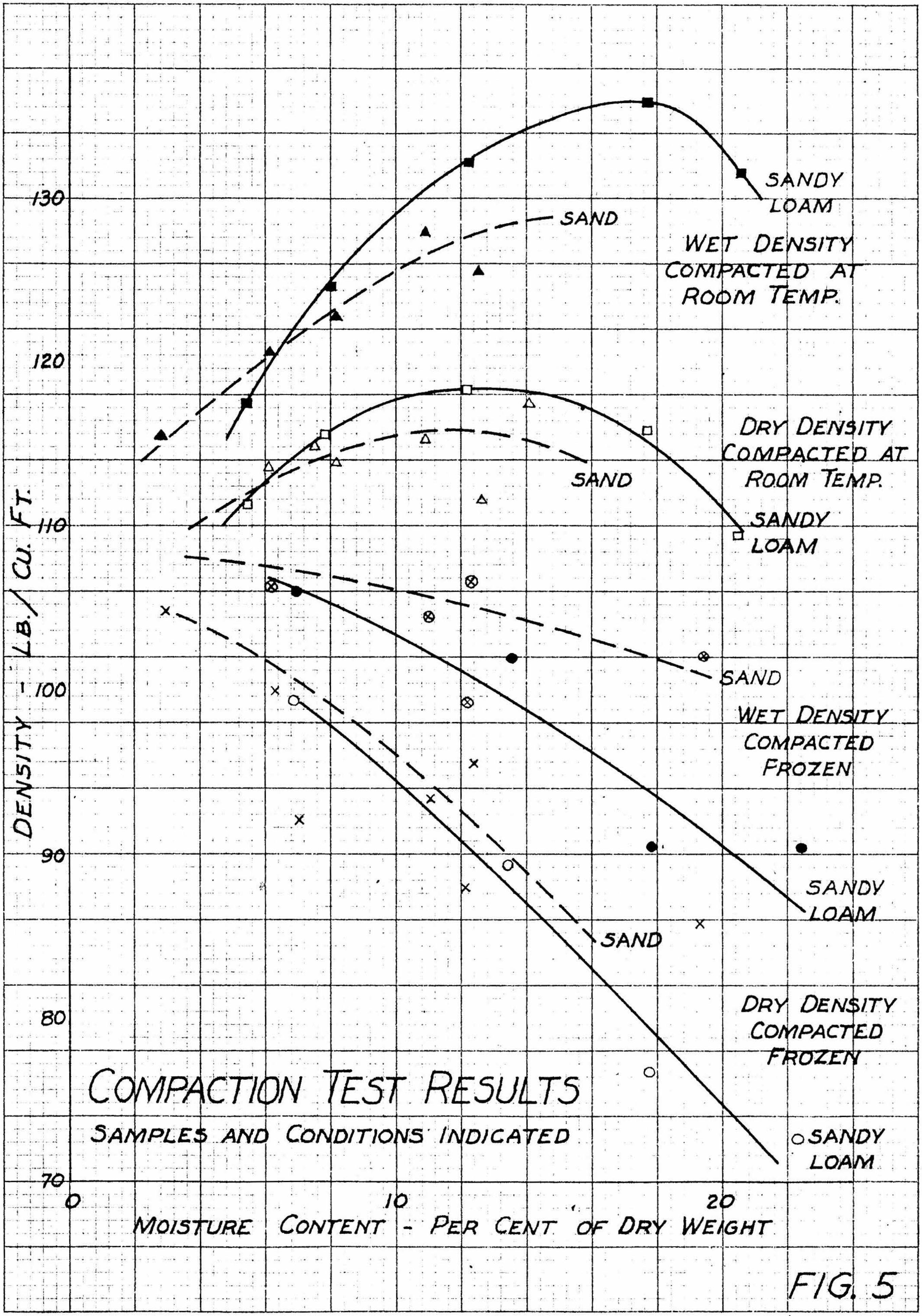

SANDY LOAM
SAND
WET DENSITY COMPACTED AT ROOM TEMP.
DRY DENSITY COMPACTED AT ROOM TEMP.
SAND
SANDY LOAM
SAND
WET DENSITY COMPACTED FROZEN
SANDY LOAM
SAND
DRY DENSITY COMPACTED FROZEN
SANDY LOAM
COMPACTION TEST RESULTS
SAMPLES AND CONDITIONS INDICATED
130
120
110
100
90
80
70
0
10
20
DENSITY - LB./CU. FT.
MOISTURE CONTENT - PER CENT OF DRY WEIGHT

FIG. 5

F. OBSERVATIONS

1. Gradation (Figure 4)

The grey sand was composed of about equal parts coarse and fine sand, and about 15% silt. The sandy loam has approximately the same characteristics with the addition of about 10% clay, and a somewhat smaller maximum size.

2. Compaction

Results are plotted in Figure 5. There was nothing unusual about compaction of the material at room temperature. However, the frozen samples were extremely difficult to handle. Where the moisture content was more than a few (2 or 3) percent, ice formation caused the soil in the metal trays to freeze as hard as set mortar, requiring considerable breaking up before it could be put into the cylinder for compaction. Even then compaction was relatively ineffective, and large voids remained. Some attempt was made to keep the compaction equipment as cold as possible by putting it in the cold box between compactions; but some thawing at the edges of the compacted soil occurred, nevertheless, during the handling, since the ambient temperature was about 70° F (a cold room was not available for the work).

3. Freezing

The time required to freeze a sample uniformly appeared to increase with the moisture content. About three to four hours continuous operation of the freezer was found to be necessary for the wetter samples. Soil temperatures went as low as -20° F in some cases but there was little uniformity and control of temperature was not practicable with the equipment as available, beyond physical evidence as to when the soil was frozen.

4. Penetration Resistance

Because of the high penetration resistance of the sandy material, the readings obtained were erratic, even in the soil compacted at room temperature. The frozen samples were even more erratic in readings observed, even using the smallest proctor needle (1/20 sq. in.).

A few random samples of compacted frozen material were allowed to thaw and were then tested for penetration resistance. Where the moisture content was above approximately hygroscopic (2 or 3%) the resistance was invariably practically zero.

G. INTERIM CONCLUSIONS

1. General Approach

Work done at this stage had not been sufficiently exhaustive to justify abandoning the method of approach outlined in the statement of purpose of this investigation. However, the work done did indicate that the limiting boundaries of variation of some of the factors may be considerably narrowed from the concept under which the work was initiated. These will be described below.

2. Freezing Process

The lack of completely controlled conditions during freezing and during compaction of frozen material prevented evaluation of the effect of temperature on compactive effort required and densities obtainable. About all that could be done was to insure that the samples were visibly frozen. The effect of latent heat of fusion on time required for freezing (see Figure 9 in Reference No. 13) was indicated by the fact that the inner moist parts of a sample remained at 32° F for a considerable time while freezing progressed inward from the outer edges. When freezing was completed, it was assumed that all the sample was at or below 32° F. The actual temperature of the frozen soil may have gone as low as the box air temperature, i.e., -20° to -30° F, but was not measurable with the mercury thermometer used (due to solid nature of frozen material). This variation in temperature below freezing may have some effect on compacted density and resulting stability, in view of the already established relation between shear strength of frozen soil and temperature (Reference No. 13). However, for the conditions dictated by equipment available, further tests on this investigation will probably have to be made on the assumption that the frozen soil is at or below 32° F.

3. Compaction of Frozen Soil

(a) Compaction Temperature -- As stated above, little or no control of temperature while compacting is possible with available equipment. In fact, since thawing unavoidably begins during the compaction operation or the penetration test, the assumption made above that the testing temperature is at or immediately below 32° F is believed reasonably correct.

(b) Moisture Content at Compaction -- Increased moisture content resulted in lower compacted density, due apparently to the fact that the added moisture became solid (ice), hence could not be distributed to lubricate the soil particles, and may have increased voids. With low or near zero moisture content, the density is very nearly that obtainable at room temperature with the same moisture. Compaction at moisture contents greater than order of 2 or 3% would probably require abnormally high compaction pressures to obtain a density which would provide adequate stability at saturation.

(c) Compaction Pressures -- Since only one pressure standard was used, no data was obtained on effect of variation of compaction effort. However, observation of action of the frozen soil at higher moisture contents clearly indicated that a relatively large increase in pressure would be necessary if suitable densities were to be obtained in frozen soil with moisture (ice) content greater than, say, 2 or 3%. It is probable that such pressures required may rapidly exceed practicable field equipment limits and thereby limit practicable moisture content for compaction to something like 3 to 5%.

4. Stability

(a) General -- This was directly measured only by penetrometer needle measuring penetration resistance. This method is inherently of little value in sandy material because of lack of plasticity and consequent high penetration resistance even with the smallest needle.

(b) Frozen and Compacted -- The shortcoming of the penetrometer was even more apparent with frozen material. Some other means should be determined for measuring stability of the frozen material.

(c) Frozen, Compacted, and Thawed -- The penetrometer needle was of no value here either because of the practically zero penetration resistance after thawing. In tests to be made on thawed material, the measure of stability used for frozen samples should also be applicable to thawed samples. It is believed that some stability will exist, even though small, in thawed material if compacted frozen at relatively low moisture content. Tests at this stage had not yet indicated that moisture content, however.

INVESTIGATION: PART II

A. PLAN AND SCOPE

1. General

Based on the results of investigation described in Part I, in which was established the general trend of the moisture density relation for frozen soil compacted under a given compactive effort, it appeared desirable to introduce a variation in compactive effort for a given moisture content and determine its effect on density and stability. For the compaction, the "modified AASHO" (American Association of State Highway Officials) method was adopted since records of recent investigations and current practice seem to indicate that it produces compaction which is more nearly comparable to that obtainable with present-day field compaction equipment than the earlier, or "Proctor" test method. It was further apparent from results obtained in Part I that possibilities of producing a satisfactory density by compaction of frozen soil was more promising in the lower range of moisture contents, that is below the normal optimum moisture content.

This, then, was to be the general plan for the remainder of the investigation.

2. Outline of Plan

The introduction of the new variable, compactive effort, would modify the method somewhat, as follows:

(a) Make mechanical analysis and determine specific gravity (if not already available).

(b) Prepare moisture-density and penetration resistance curves for soil at room temperature, using standard compaction testing equipment and methods.

(c) Prepare same as (b) for frozen samples of same soil (omitting penetration test).

(d) Prepare same as (c) except increase compactive effort by some arbitrary amount above standard test procedure.

(e) Thaw compacted samples from (c) and (d), preventing evaporation, and test for penetration.

(f) Compare moisture-density curves obtained in (b), (c), and (d) and note effect of increased compactive effort.

(g) Repeat (a), to (f) on one or more additional representative soils.

B. MATERIALS

(See Figure 7 for mechanical analysis)

1. Sandy Loam

A fine yellow sandy loam from Pasadena area (same as in Part I).

2. Sand

A relatively coarse reddish sand from "Manhattan Village" area (same as used in preliminary tests, Part I).

C. EQUIPMENT

For the remainder of the investigation some modifications in equipment were considered desirable. The principal changes were the result of adoption of the modified AASHO standard compaction test procedure.

1. Compaction Equipment (Figure 6)

(a) Cylinders -- Six additional cylinders were made available. They were slightly modified in design of assembly bolting arrangement but provided compacted sample 4.0 inches diameter and 4.6 inches high, and of volume 0.0338 cu. ft.

(b) Rammer -- A previously constructed but incomplete improvised power driven compacting machine was modified to permit manual operation in raising the rammer, yet utilizing the supporting frame and guide arrangement of the machine. The rammer weighed 10 pounds, and the height of free-fall was 18 inches, as required in the modified AASHO method, instead of the 5-1/2 pound rammer and 12 inch fall used in Part I. Provision was also made in the equipment for adjusting the level of the upper stop on the rammer shaft to insure 18 inch fall above each of the successive layers during compaction.

(c) Supporting Base -- The cylinder base rested on a 3 inch thick wooden base, built integral with the rammer frame, and resting on a substantial wooden table, all on a concrete basement floor.

2. Temperature

For random check of actual temperature of frozen soil during compaction, a potentiometer and copper-constantin thermocouple were used.

3. Other Equipment

No change.

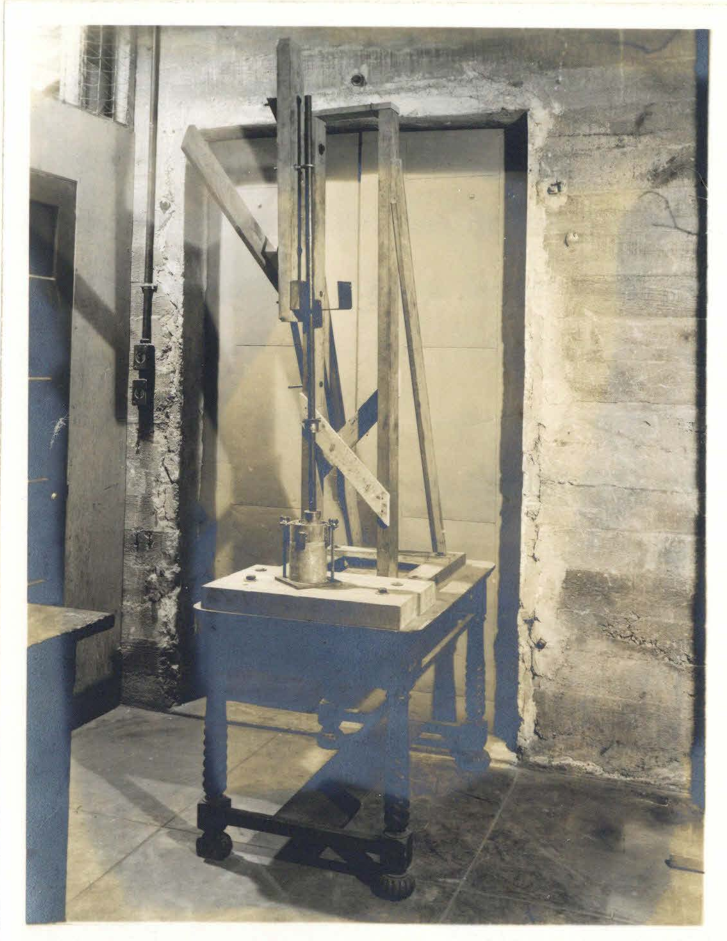


Figure 6

COMPACTION EQUIPMENT USED IN PART II

D. PROCEDURE USED

1. General

As outlined above in the general plan for Part II, the procedure herein differed from that used earlier principally in that the frozen material at each moisture content was compacted under two different degrees of total effort, one being a standard and the other an arbitrarily increased amount.

2. Compaction

In accordance with the modified AASHO standard, soil was placed in the cylinder in five equal layers and, for the normal or standard test, rammed with twenty-five blows to each layer. This procedure was used for preparing moisture-density curve for soil at room temperature. For compaction of frozen soil, duplicate batches of soil were prepared for each moisture content, both batches were frozen, and then one batch compacted using the standard number of blows (twenty-five) per layer, and the other batch compacted using fifty blows per layer.

3. Freezing

In order to increase the rate of freezing and to reduce the possibility of changes in the distribution of moisture in the freezing soil due to ice crystal growth, the soil was placed in shallow metal pans in layers approximately 1/2 inch thick, and the pans stacked in the box with separators between each to insure circulation of cold air and more equalized rate of freezing. The samples were kept in the cold box until by their appearance and feel they were considered to be frozen throughout, and until the box temperature became practically stable at or near 0° F (15° F approximately for Manhattan Village sand). The freezing time required increased with the moisture content and quantity of soil in the box, the time varying from three to five hours.

4. Temperature Measurement

In general, this was only approximated as mentioned under the description of the freezing procedure above. However, as a check against this approximation, the temperature of two samples was measured during compaction while in the cylinder by means of a thermocouple inserted between the intermediate layers.

5. Densities

These were determined by standard methods, weighing the struck-off compacted cylinder of soil on the platform scales to the nearest 0.01 pound, and determining the moisture content by over drying a sample of approximately 100 grams taken from the interior of the compacted cylinder.

6. Stability Measurement

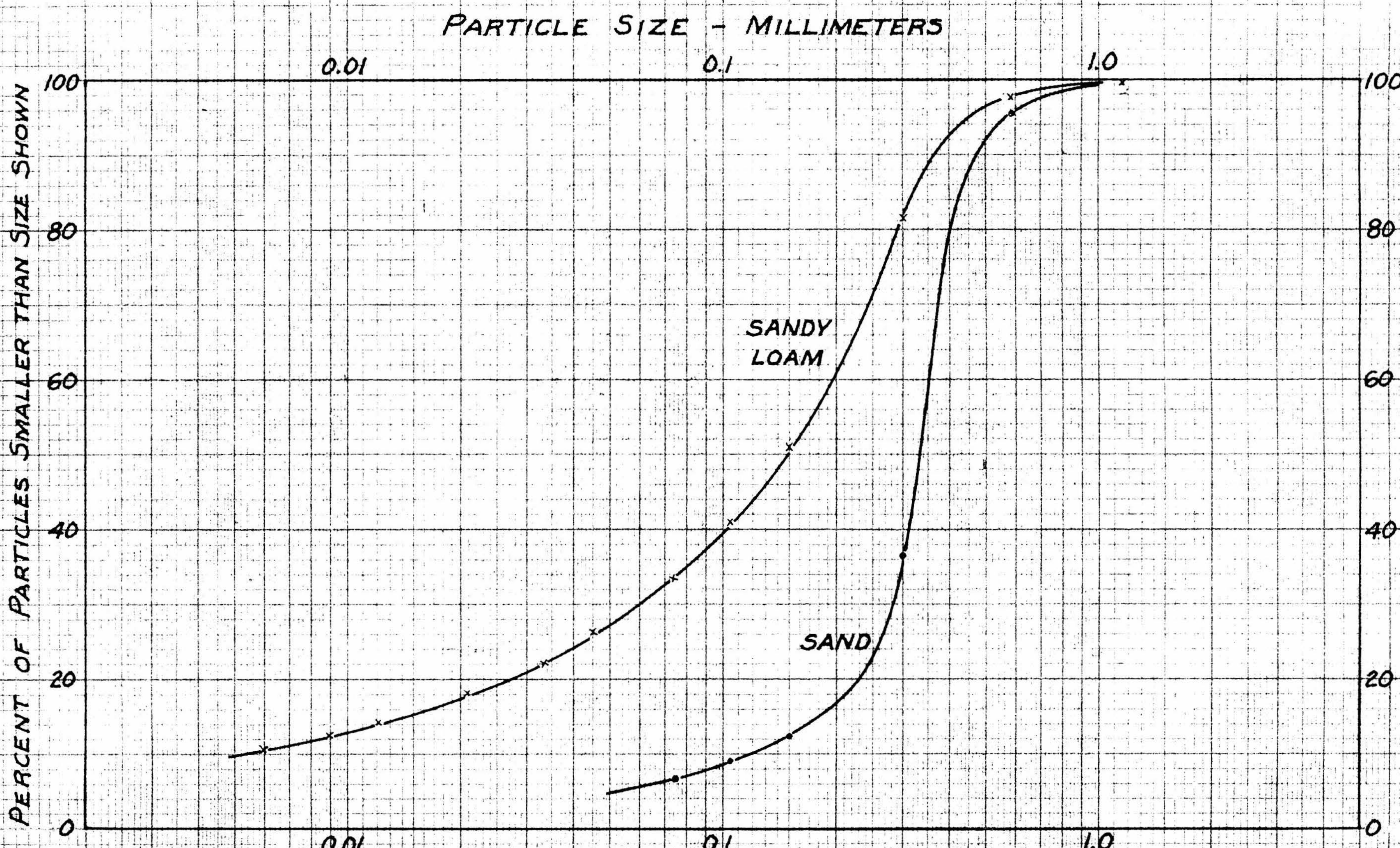
The only direct measurement made was that of penetration resistance by standard penetrometer needles. Samples compacted at room temperature were tested immediately after density determination, but the samples compacted frozen were tested only after thawing for at least twenty-four hours. Tests made in Part I had indicated that penetration resistance of frozen soil was above the measurable range of the smaller penetrometer needles and therefore such test had little significance.

7. Other Procedures

No change from previous methods.

E. DATA

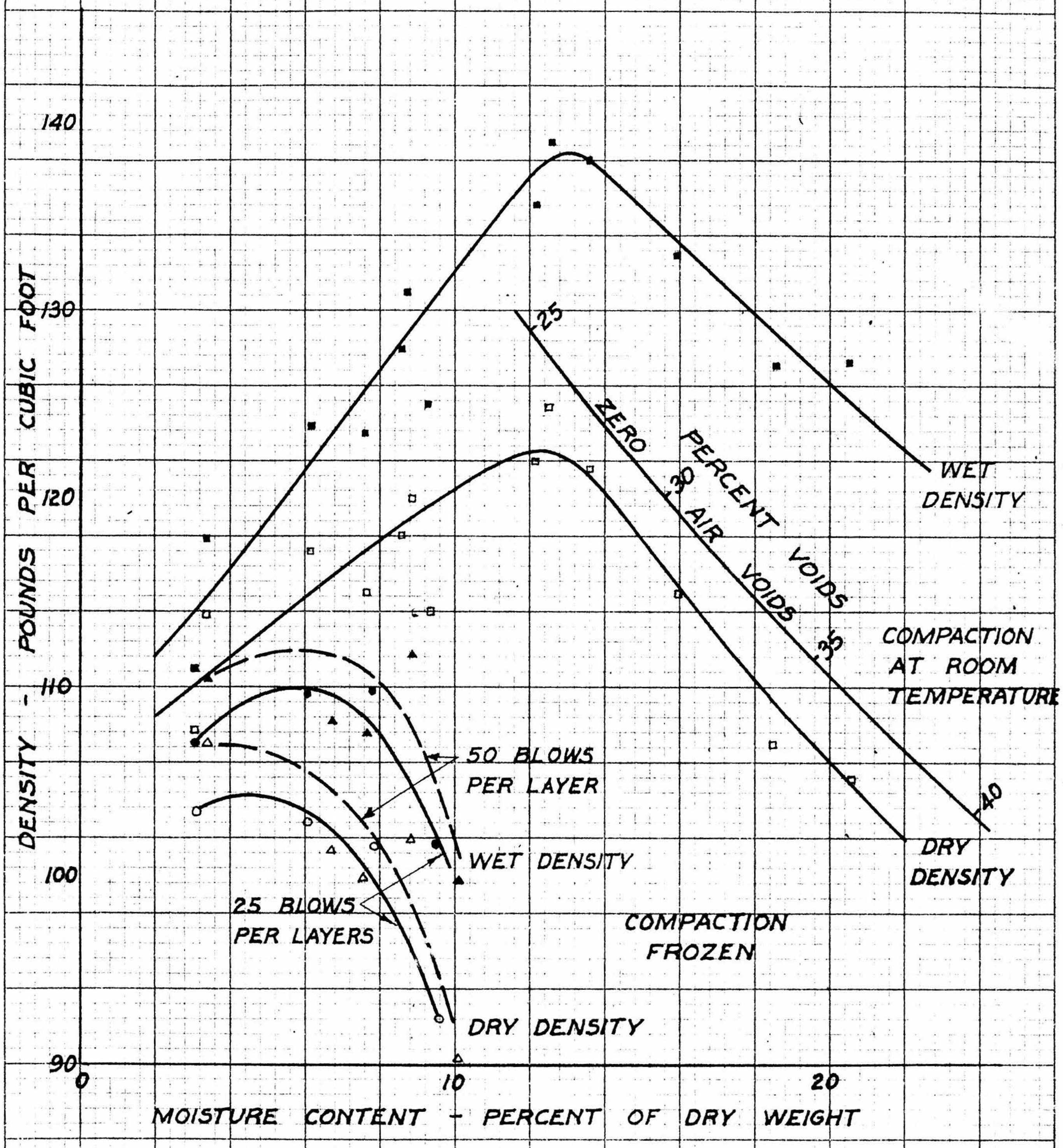
Results of the work done in Part II are shown in Figures 7 to 11 herewith. Figure 7 is the mechanical analysis of the additional sandy material tested. The sandy loam analysis is repeated from Figure 4 in Part I, for comparison. Figures 8 and 10 contain the combined results of the moisture-density relation tests at room temperature and frozen with normal and increased compactive effort, for the sand and sandy loam, respectively. Figures 9 and 11 show the penetration resistance for the two soils corresponding to the moisture-density and compaction conditions in Figures 4 and 6.



MECHANICAL ANALYSIS OF SOILS

USED IN COMPACTION TESTS - PART II

FIG. 7

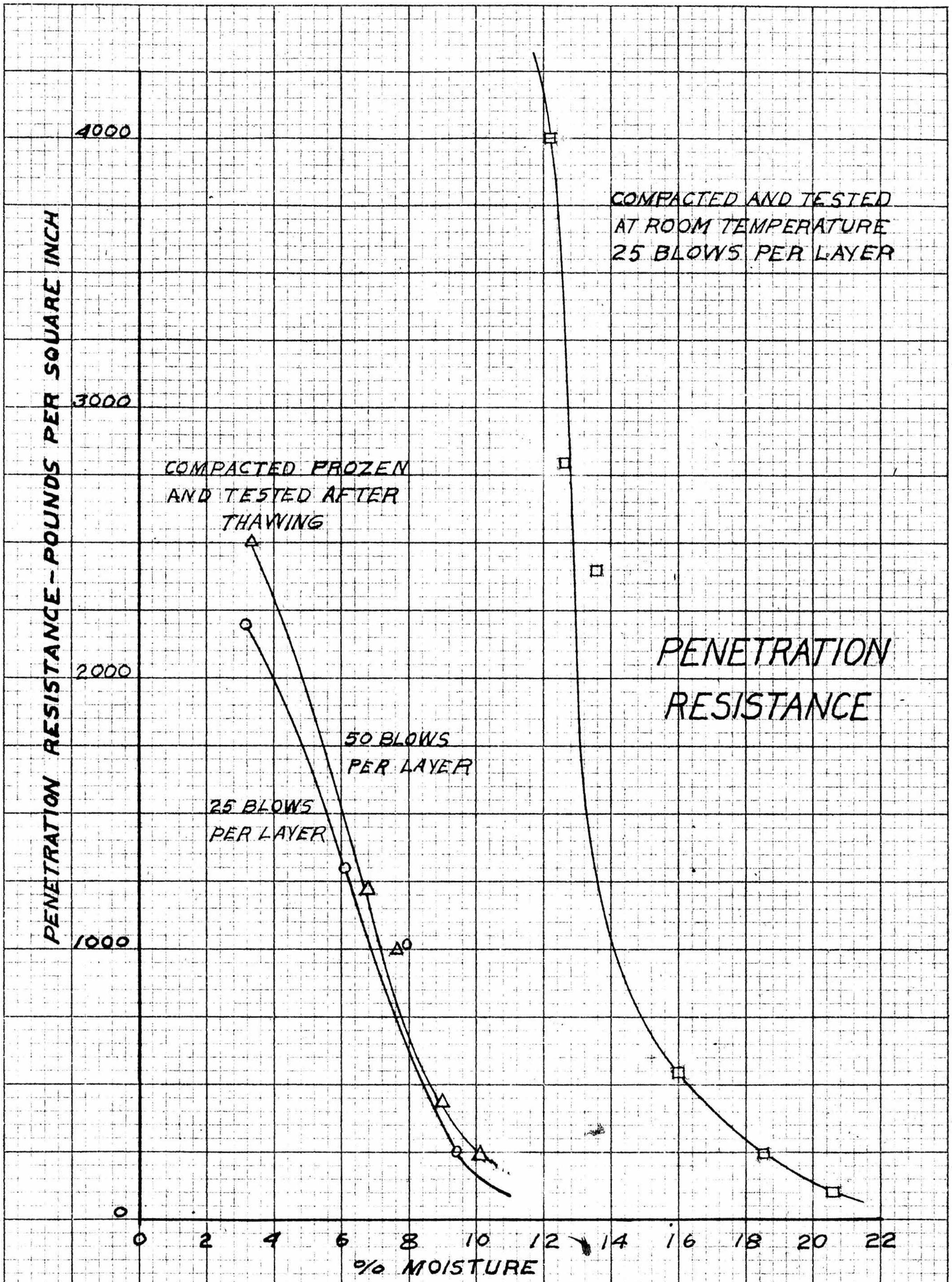


MOISTURE - DENSITY RELATION FOR A SANDY LOAM COMPACTED IN NORMAL AND IN FROZEN STATE

SANDY LOAM FROM ROBERTSON PROPERTY, L.A. COUNTY

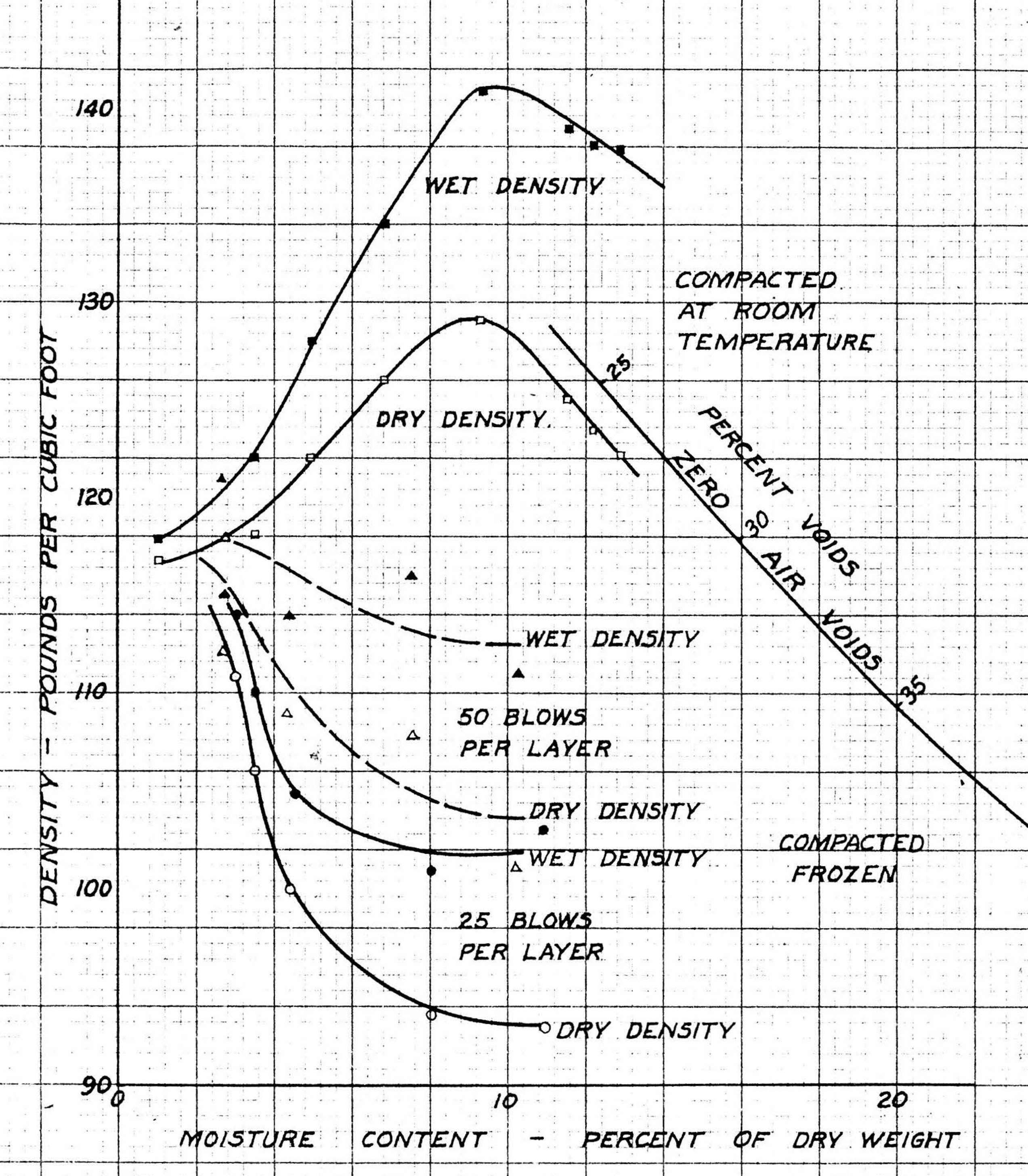
SPECIFIC GRAVITY 2.75

FIG. 8



SANDY LOAM (ROBERTSON)

FIG. 9

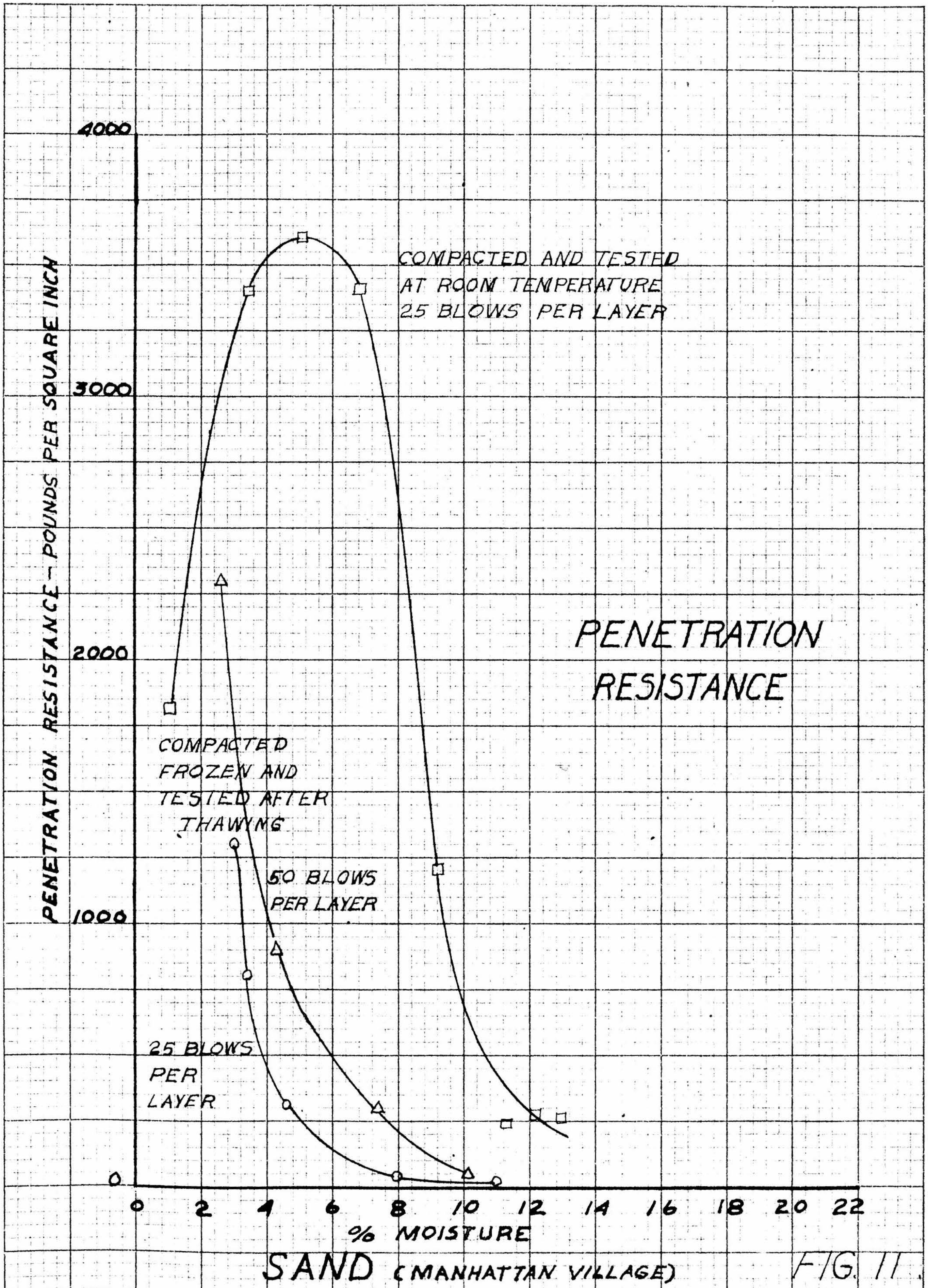


MOISTURE - DENSITY RELATIONS FOR SAND
COMPACTED IN NORMAL AND FROZEN STATE

SAND FROM MANHATTAN VILLAGE, LOS ANGELES COUNTY

SPECIFIC GRAVITY 2.69

FIG. 10



PENETRATION RESISTANCE - POUNDS PER SQUARE INCH
4000
3000
2000
1000
0
COMPACTED AND TESTED
AT ROOM TEMPERATURE
25 BLOWS PER LAYER
PENETRATION
RESISTANCE
COMPACTED
FROZEN AND
TESTED AFTER
THAWING
50 BLOWS
PER LAYER
25 BLOWS
PER
LAYER
0 2 4 6 8 10 12 14 16 18 20 22
% MOISTURE
SAND (MANHATTAN VILLAGE)

FIG. 11.

F. OBSERVATIONS

1. Gradation

The soils used were described under B above and analysis shown in Figure 7. They were typical of those found in the local Southern California area; but are possibly more sandy than average soils met in frost areas, and therefore probably more easily worked when frozen than those that would actually be encountered in field conditions.

2. Moisture-Density Relation (Figures 8 and 10)

(a) Normal Conditions -- Compaction at room temperature at various moisture contents gave the normal curve of moisture-density relation. The relatively sandy nature of both materials and the firm degree of compaction provided by the modified AASHO method combined to produce relatively high maximum dry densities. The sandy loam was 122 lb/cu.ft. at 14% moisture and the sand reached 129 lb/cu.ft. at 9% moisture. These densities were used as a basis for comparison of the effectiveness of compaction of the same soil in frozen condition.

(b) Frozen Conditions -- An increased degree of compaction was noted here also as a result of using the heavier rammer, greater height of fall, and thinner layers. However, the difference between compaction with twenty-five blows per layer and fifty blows per layer was less than anticipated. The difference in the case of the sand was from 4 to 6%, being greater with higher moisture content, whereas in the case of the sandy loam, there was only a slight increase in density (about 1%) for all moisture contents used. In all cases, the dry density at about 2% moisture appeared to be approximately equal to that under normal compaction at room temperature, and from that point dropped rapidly with increase in moisture content. The sand dry density was reduced to 100 lb/cu.ft. at 4-1/2% moisture for normal compaction (twenty-five blows per layer) and at about 10% for fifty blows. The sandy loam under both normal and heavier compaction had been reduced to 100 lb/cu.ft. at about 8% moisture.

3. Stability

(a) Normal Conditions --- The curves of penetration resistance resulting from compaction at room temperature are typical for the sand and sandy loam used.

(b) Frozen Conditions --- For the two soils in the frozen condition, under the two degrees of compaction, the penetration resistance after thawing appears in each case to bear the same relation to penetration resistance in normal conditions as existed between dry density under the same respective conditions. If 150 lb/sq. in. were considered a minimum allowable penetration resistance, it is seen that this limits the moisture content in the case of the sand to 5% for normal compaction and to about 7% for the heavier compaction (fifty blows per layer), and in the case of sandy loam, to about 10% for either degree of compaction. However, at the low densities obtained by compaction while frozen, it is apparent that the voids are not filled with moisture, even after thawing, and the further absorption of moisture up to saturation would obviously decrease the penetration resistance to a much lower figure.

G. CONCLUSIONS

1. General

The investigation in Part II further confirmed the earlier indications that, if any suitable densities were to be obtained by compaction of frozen soil at practicable pressures, it would be only at a relatively low moisture content.

2. Density

If a suitable density is considered to be approximately 90% of maximum obtainable with normal compaction at ordinary temperatures, the required density would be for the sand 90% of 129 of 116 lbs/cu.ft. and for the sandy loam 90% of 123 or 111 lb/cu.ft. This appears to be obtainable in the sand (see Figure 10) only with moisture contents below 3% and with the number of compactive blows doubled. In the sandy loam (see Figure 8) this assumed minimum allowable density was not obtainable at any moisture content even with the higher degree of compaction.

3. Stability

Inspection of the curves of penetration resistance (Figures 9 and 11) shows even more clearly the low degree of stability that would exist after thawing from the compacted frozen densities obtainable. When it is realized that these penetration resistance curves for the thawed material represent the stability of the thawed soil at the density and voids ratio to which compacted and at the moisture content at which compacted, it will be apparent that the voids are only in small part occupied by water and can readily absorb several times the percentage contained at the time of penetration test. The stability of the thawed material when subsequently saturated is assumed to be the same as that of a similar soil sample compacted at the same pressure, but at ordinary temperature, to the same dry density, and then saturated. If 150 lb/sq. in. is assumed to be the minimum penetration resistance allowable (Reference No. 18) in order to support loaded truck traffice, then it is evident from the penetration resistance and moisture-density data obtained herein that at any of the densities obtainable by compaction of frozen soil with the equipment used or its equivalent, the subsequently thawed and saturated stability will be below the minimum requirement.

DISCUSSION

A. GENERAL

The principal influence in this investigation was that of obtaining results of practical significance. War-time and peace-time airfield and road construction (particularly for military use) are frequently hampered or stopped by sub-freezing soil conditions. Specifications generally prohibit placing of frozen material or placing on frozen material. The problem in essence, then, is "Can frozen or freezing soils be compacted to usable stability for purposes such as airfields and roads?"

B. LIMITATIONS

It was realized at the outset or shortly thereafter that limitations as to time, equipment, and inexperience of the investigators would preclude anything but a few qualitative results. Such results would be obtained entirely within the laboratory but should "point up" the problem and perhaps establish trends in results to be obtained.

C. REFERENCES

A partial list of reference material is attached as Appendix hereto. While no references were found on the specific subject, information on related subjects such as frost-heave, "Perma-Frost" (i.e., permanently frozen soil), mechanical and physical characteristics of soils, compaction and testing practice, and procedures, and the formation and behavior of ice, were pertinent.

D. VARIABLES

Study of available data indicated that the probable major variable factors involved are as follows:

(a) Soil gradation (including particle size and shape)

(b) Moisture content

(c) Compaction pressures

(d) Temperature of soil (including that of moisture/ice)

(e) Rate of freezing

Additionally, as a reference point, density, percent voids, and resistance to penetration by plasticity needle were adopted as a measure of stability (i.e., load carrying capacity). It is granted that penetration resistance is not too indicative, particularly for non-plastic soils; however, it was obvious that when penetration resistance decreased rapidly, the degree of stability also went down rapidly (for instance, as moisture contents increased, samples in the thawed condition would obviously be sponge-like and offer little or negligible resistance to punching or compacting with the finger). Also, as verified by the results, stability in the thawed condition is more critical than in the frozen condition.

E. SOIL GRADATION

It was logical in view of known variation of soil bearing ability with variation in gradation under above freezing conditions to assume probable variation under freezing conditions. It was intended that three (3) fairly typical soils be investigated -- one in the sand range, one in the clay range, and one intermediate in the loam range, in order to establish the trend in results. However, time limited the work to two (2) sands and one (1) sandy loam. All soils were natural soils. Results for the soils used were inconclusive as to the assumption of variation in performance with change in gradation.

F. MOISTURE CONTENT

In view of known variation in soil performance at ordinary temperatures and variable moisture content, together with increased volume (and decreased density) of ice over that of water, variation in moisture should have pronounced effects. The work of Professor Stephen Taber and others on frost-heave, revealing the growth of ice crystals and formation of ice lenses in freezing of soils, posed the question of distribution of moisture. Accordingly, in order to make results more nearly comparable from test to test, it was decided to adopt a "closed system" (not admitting outside water during freezing) in lieu of the more normal "open system" existing in the field due to the availability of ground water during freezing. Also, to insure as uniform distribution as practicable, soil samples were frozen in layers of about one-half (1/2) inch in thickness (freezing progressing inward from top and bottom of layer). Admittedly, such control of moisture fails to correlate with the majority of field moisture conditions, but it facilitates determination of moisture limits in the laboratory and very probably correlates with actual or controlled field moistures for soils that may be usable when frozen (presupposing a relatively narrow range of usability restricted to the lower moisture contents in the field).

Results of the investigation verified the pronounced variation in stability for different moisture contents.

G. COMPACTION PRESSURES

Recent work under the advice and supervision of Mr. O. J. Porter (see Reference No. 17) in the field indicates the efficacy of increasingly heavy rolling compaction equipment under ordinary temperatures. Hence, in view of the known lowering of freezing point of water (or raising of melting point of ice) by application of pressure greater than atmospheric, it is reasonable to assume that higher compaction pressures (or perhaps greater compactive effort) would be effective on frozen soils. Also, work by Mr. H. C. Porter (see Reference No. 10) on clay soils indicated generally increased densities with increased number of blows of rammer (compactive effort). It was assumed in line with existing theory that increased compactive effort tends to expel soil air, redistribute (or expel) moisture, and key soil particles into a more dense mass, permitting more intense molecular attraction of soil particles and greater cohesion due to smaller capillary tubes.

In Part I, compaction was in three layers with twenty-five 12" free-fall blows per layer of a 5-1/2 lb. rammer. In Part II, the modified AASHO (twenty-five 18" free-fall blows per layer of 10 lb. rammer on five 1" layers) and further modification to fifty blows per layer apparently gave greater stability than Part I tests, although probably not as high in proportion as for the same difference in compactive effort at ordinary temperatures. The difference between twenty-five and fifty blows per layer was noticeable, but to obtain the equivalent of this compactive effort in the field possibly would require prohibitively heavy compaction equipment. As to melting of ice in soil by heavier pressures, the tests were inconclusive (see discussion of temperature below).

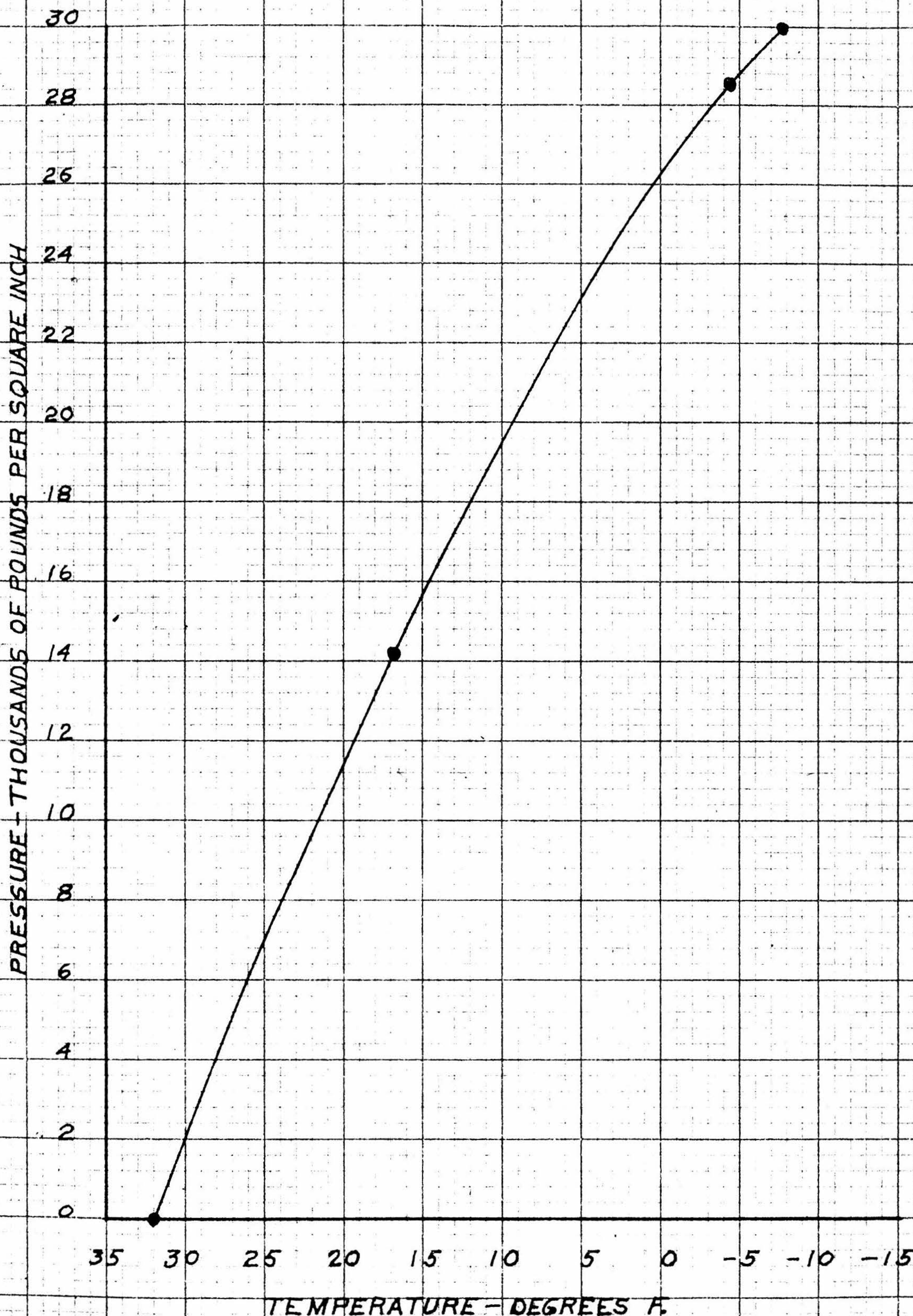
H. TEMPERATURE OF SOIL

Investigations by others (see Reference No. 13) indicate that frozen soil, as its moisture content increases, tends to take on the characteristics of ice, and also that compressive strength of ice increases tremendously with lowering of temperature (a fact which would limit the efficacy of heavier compaction in melting the ice by pressure application) (see Figure No. 12). Control of temperature was not possible with equipment at hand except that an effort was made to insure that soil samples were below 32° F and that handling was such as to make conditions approximately the same from test to test. Thermocouples imbedded in the center of several samples during compaction revealed that the soil was below 32° F; however, there was undoubtedly some thawing at boundaries of layers during compaction, as well as some raising of temperature for the soil as a whole.

The tests were not conclusive as to effect of temperature variation.

I. RATE OF FREEZING

Available information on "frost-heave" investigations (References No's. 1, 2, and 22) indicates that rate of freezing determines the rate and extent of growth of ice crystals and ice



RELATIONSHIP FREEZING POINT WATER VS PRESSURE
UNDER WHICH WATER EXISTS

(EXTRACT JUNE 1930 "PUBLIC ROADS")

FIG. 12

lenses in soils, and hence justifies the assumption as to effect of rate of freezing on behavior of frozen soils.

In this investigation, rate of freezing appeared to decrease with an increase in moisture content -- although close control for quantitative results was neither realized nor attempted. Three (3) to five (5) hours of continuous operation of the four (4) horsepower refrigerator used were required for lowering the temperature of soil samples from about 70° F to about 0° F. Freezing in the field would more probably be in an "open system" condition and at a much lower rate, tending to increase moisture contents undesirably.

J. EQUIPMENT

Variable factors could be controlled more positively and considerable time and labor could be saved by using a "cold room" and a powered compacting machine. Such equipment was not available at the time of the tests. Also, more adequate means than the penetrometer needle should be used in determination of stability. Lack of time precluded use of other means in this instance.

SUMMARY OF CONCLUSIONS

In summary, as to effectiveness of compaction (and resulting stability) of soils compacted while in the freezing or frozen state, it may be concluded from this investigation that:

1. Major factors to be considered are:
    (a) Moisture content
    (b) Compaction pressures and effort (i.e., number of applications)
2. Other probable major factors are:
    (a) Soil gradation
    (b) Rate of freezing
    (c) Temperature of frozen soil

3. Stability diminishes rapidly with increase in moisture (ice) content at compaction, for the sand and sandy loam tested, and probably for other soils.

4. Any practicable increase in compaction pressures (and also possibly in total compactive effort) will probably increase the range of moisture contents over which a given soil would be useable.

5. Stability will be inadequate unless:
    (a) Accretion of moisture after thawing is prohibited, and
    (b) Required unit soil bearing pressure is lowered.

RECOMMENDATIONS

Based on results of this investigation, it is recommended that:

1. Further investigations should be made in the laboratory and the results verified in the field.

2. A complete range of typical soils encountered in the field (under freezing or frozen conditions) should be tested.

3. The effects of chemical or other artificial means should be determined.

4. Temperature conditions in the laboratory should be controlled by a cold room.

5. An automatic compaction machine should be used for better control and to save time and labor.

6. An adequate method for testing frozen and thawed samples in bearing must be used.

Appendix

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