Temperature Effects on Phase Composition and Strength of Partially-Frozen Soil

C. W. LOVELL, JR., Research Engineer
Purdue University, Lafayette, Indiana

The primary objective of this study was the determination of the relative amounts of frozen and unfrozen moisture in several fine-grained soils over a range of below freezing temperatures. A secondary goal was the definition of the importance of subzero temperature (and phase composition) on the strengths of the same test soils.

Three soils were utilized—a silt of glacial origin, a silty clay of the Wisconsin drift, and a clay derived in place from limestone. The soils were characterized in the usual manner, and in addition their specific heats and behaviors in a desorption process were defined.

The calorimetric method was used to determine the amount of ice in a molded specimen of known total moisture, density, and subzero temperature. The phase composition of the test soils was found to vary significantly between soils at a given temperature level, and to change significantly for a single soil with lowering of temperature. For example, comparing soils molded to standard Proctor peak conditions, the following approximate percentages of original moisture frozen obtained: at -3 C silt 73 percent, silty clay 42 percent, clay 16 percent; at -25 C, silt 83 percent, silty clay 62 percent, clay 50 percent.

Attempts to correlate the results of experimental desorption tests with the calorimetric data met with very limited quantitative success.

Unconfined compression tests were undertaken at controlled subzero temperatures with stress rates of loading of 160 or 200 psi per minute. Maximum compressive stress demonstrated a high temperature dependency for all test soils. For example, again comparing samples molded to standard Proctor peaks, the approximate ratio of compressive strength at -18 C to that at -5 C was more than 4 to 1 for the silty clay and almost 3 to 1 for the clay.

It was concluded that substantial proportions of the total moisture (defined by drying to constant weight at 105 C) of fine-grained soils may remain unfrozen at temperatures as cold as -25 C and that the changes in strength accompanying change in temperature within this range emphasize the practical significance of relative phase composition.

● THE FACT THAT soil moisture commonly remains unfrozen at temperature below 0 C is a widely recognized one. It is further conceded that there are important implications or consequences of this phenomenon. For example, the very process of ice segregation in freezing soils is dependent upon the feeding moisture in the smaller pores remaining unfrozen. Also, accurate estimates of depth of freeze or depth of thaw of soil require good knowledge of the temperature at which phase changes will take place in the soil water. Finally, in the perma-frost regions of the world the high capacities of frozen ground to support loads may be utilized more rationally if the phase composition of the ground at various subzero temperatures (-C) is reasonably defined.

The primary purpose of the research reported herein then was to determine the freezing behavior of certain fine-grained soils—specifically to ascertain the relationships between temperature, and percentages of soil moisture unfrozen (or frozen) at such temperature. A secondary purpose of the research was to relate the above data to some measure of soil strength—specifically, compressive strength.

The number of variables that can be involved in a study of this purpose are understandably quite large. Temperature was an obviously critical variable, and the effects of it were studied from values just below 0 C to nearly -25 C. Soil texture was a second obvious variable, and three fine-grained soils of significantly different characteristics

were chosen—a clayey silt, a silty clay, and a clay.

The factors of moisture content and density (or unit weight) are very important, but due to physical limitations neither was studied as a primary variable.

Direction, rate, and type of freezing are also obviously important. However, all test samples were given the same primary treatment of rather rapid cooling from all sides without access to additional water during the cooling process (closed—system freezing). This meant that the moisture was frozen substantially in place, and that the moisture content and distribution, and density of the test samples were "controlled" to the highest degree believed practicable.

Strength evaluation of partially-frozen samples was achieved by means of the most simple type of test, undrained cylindrical compression in an unconfined condition. Loading was achieved at controlled stress rates apparently most descriptive and desirable for partially-frozen soil, approximately 200 psi per minute.

SOIL MOISTURE

The total amount of soil moisture present in a given quantity of soil is ordinarily defined arbitrarily with references to a condition achieved by oven-drying to constant weight at 105 C. Even more important than the total amount of moisture present is the distribution of the moisture within the solid—voids system of the soil mass. Understandably, the definition of soil moisture distribution is a complex problem, and rather imperfectly answered by the present state of knowledge.

Classification

Soil moisture is ordinarily classified in an engineering sense on the basis of difficulty of removal from the soil mass by gravity drainage. On the most general scale, the breakdown is into "free" and "held" moisture. The free water may be removed from the soil by ordinary drains. The held water may not be removed directly by gravity because of the force magnitude by which it is held in soil pores or around the soil particles. These forces in the ultimate may be complex combinations of attractions that are intermolecular, electrical, magnetic and gravitational in nature.

A further subdivision on the basis of drainability may be envisioned as indicated in Figure 1.

A somewhat different approach to the classification of soil moisture may be made

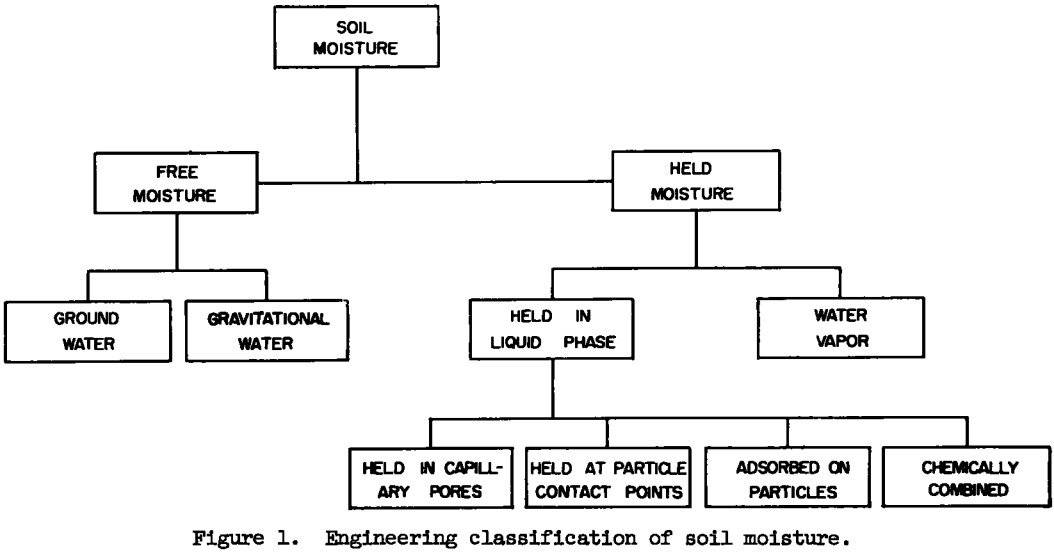


Figure 1. Engineering classification of soil moisture.

on the basis of relative position of the moisture within the soil pores, and on the relative magnitude of force holding the water within the system. For example, Michaels (1) suggests that four types of water may exist in a wet soil mass: pore water, solvation water, absorbed water and structural water.

Suction

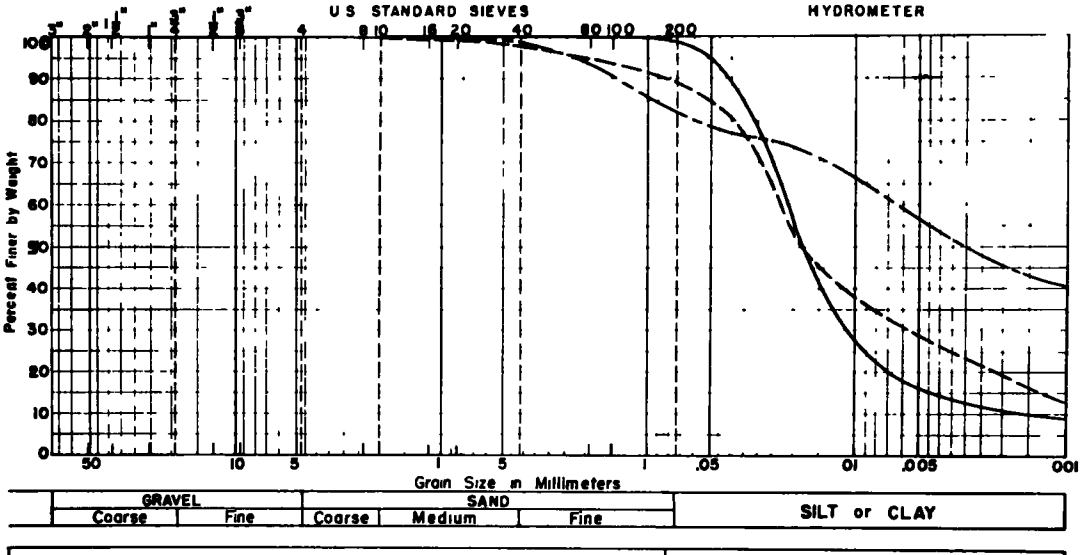
Because of the attractive forces exerted by the soil on the held water, this water is considered to be in a state of negative pressure, tension, or suction. Thus in a relatively wet soil mass all air-water interfaces consist of menisci, and the relative curvature at each of these menisci is indicative of the pressure difference across the meniscus, the suction of the liquid phase, and the equilibrium vapor pressure of the gas phase.

The vapor pressure of the soil air may be related to the saturation vapor pressure at that temperature, and expressed as a relative or percentage humidity. Such pressure or relative humidity may be measured directly, or calculated from a knowledge of the magnitude of soil water suction with which it exists in equilibrium.

A number of approaches have been utilized to express the magnitude of soil water suction. However, the range of values of possible interest is so large that a logarithmic rather than arithmetic scale of reference is commonly employed. Schofield (2) introduced the pF scale to meet the need for a convenient logarithmic scale of measure. If the soil water suction is expressed in terms of the length in centimeters of an equivalent water column, the common logarithm of this length is the pF value.

The use of suction (pF) or of vapor pressure (or relative humidity) allows a more rational approach to the problems of moisture retention and moisture movement. For example, moisture may or may not move from a location of high moisture content to one of lower moisture content, but will always move (within the limits imposed by gravity) from, (a) low suction (pF) to high suction, or (b) high vapor pressure (or relative humidity) to low vapor pressure.

As a further example, soil water existing in equilibrium at a high suction value will



Remarks	SOIL	PERCENTAGE OF SIZES				
		SAND	SILT	CLAY (< 002mm)	< NO 200	< 002mm
	SILTY CLAY	106	678	216	894	530
	CLAYEY SILT	12	871	117	988	560
	CLAY	182	360	458	818	735

GRAIN SIZE DISTRIBUTION

——— CLAYEY SILT ——— CLAY

- - - - - SILTY CLAY

Figure 2.

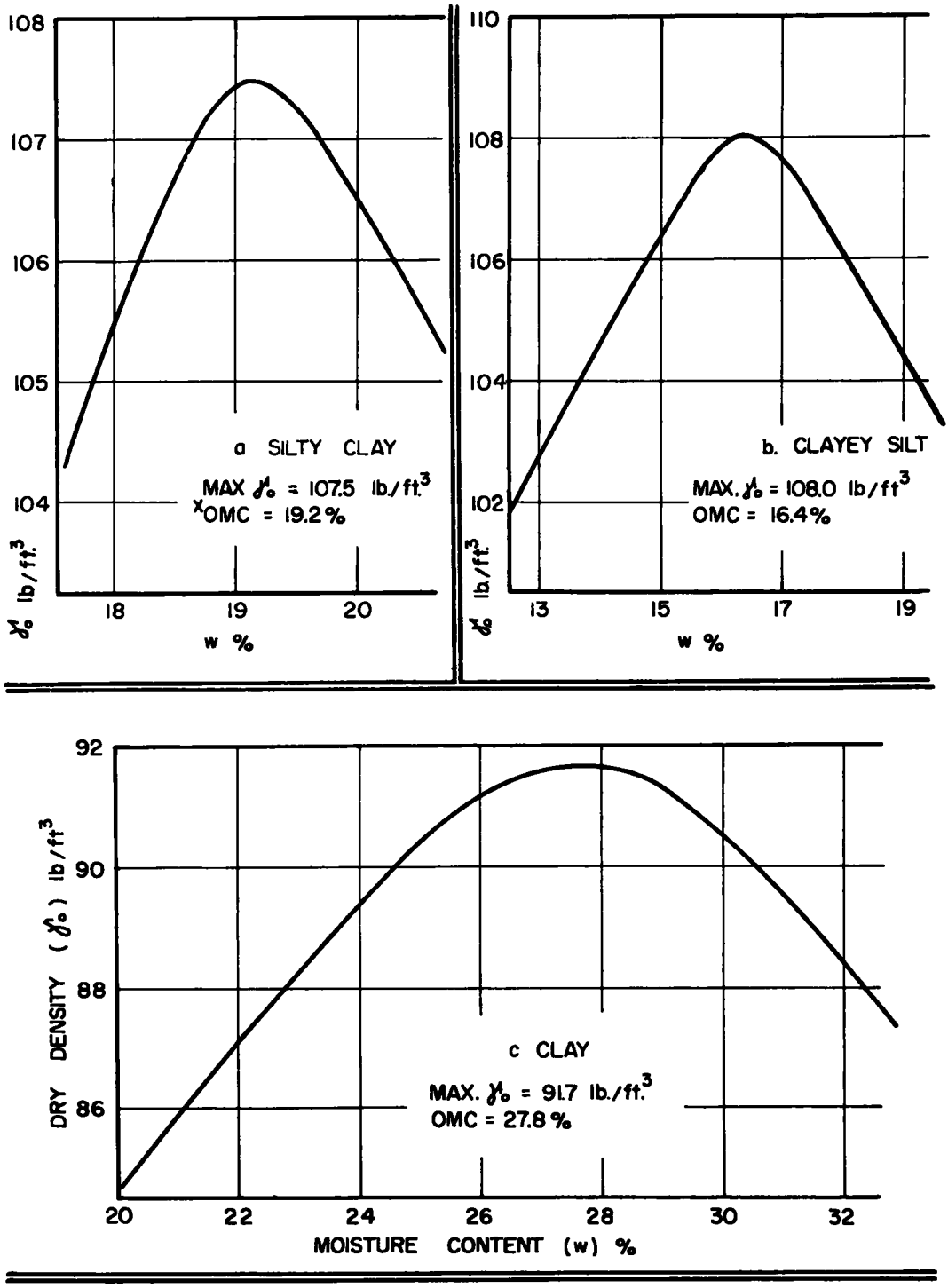


Figure 3. Moisture density relations at standard Proctor compactive effort.
*(OMC = optimum moisture content).

freeze much less readily with the lowering of temperature than would the same soil water under lower suction. Indeed, the suction value may be used to calculate theoretical freezing point depression, all soil water having the same theoretical depression at a given suction level. The quantities of unfrozen moisture in equilibrium at a given suction level and sub-zero temperature of course vary considerably from soil to soil.

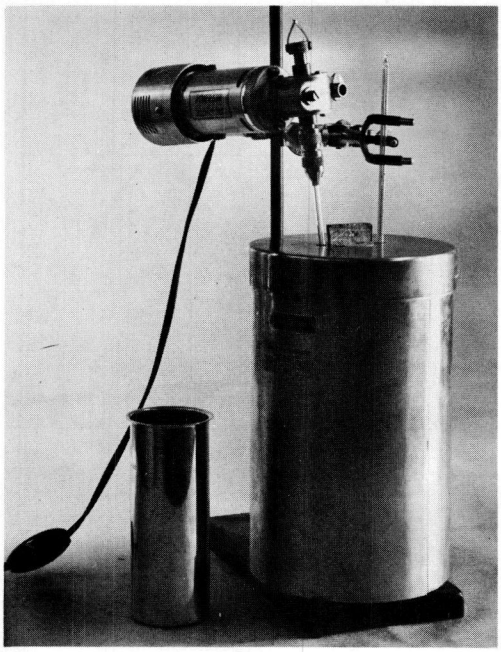


Figure 4. Calorimetric equipment.

Freezing of Soil Moisture

The lowered or depressed freezing point of the water in soil pores has been the object of much study. To briefly summarize, two general theories have been advanced to explain and describe this phenomenon:

1. Early investigations appear to have concentrated on the capacity of salt solutions to lower the freezing point. At high moisture contents the concentration of the salt solution in the soil water is relatively low, and the most free water in the system should freeze at only slightly depressed temperatures. However, as the moisture content is reduced, either as a result of desiccation by evaporation or by freezing process, the salt concentration of the re-

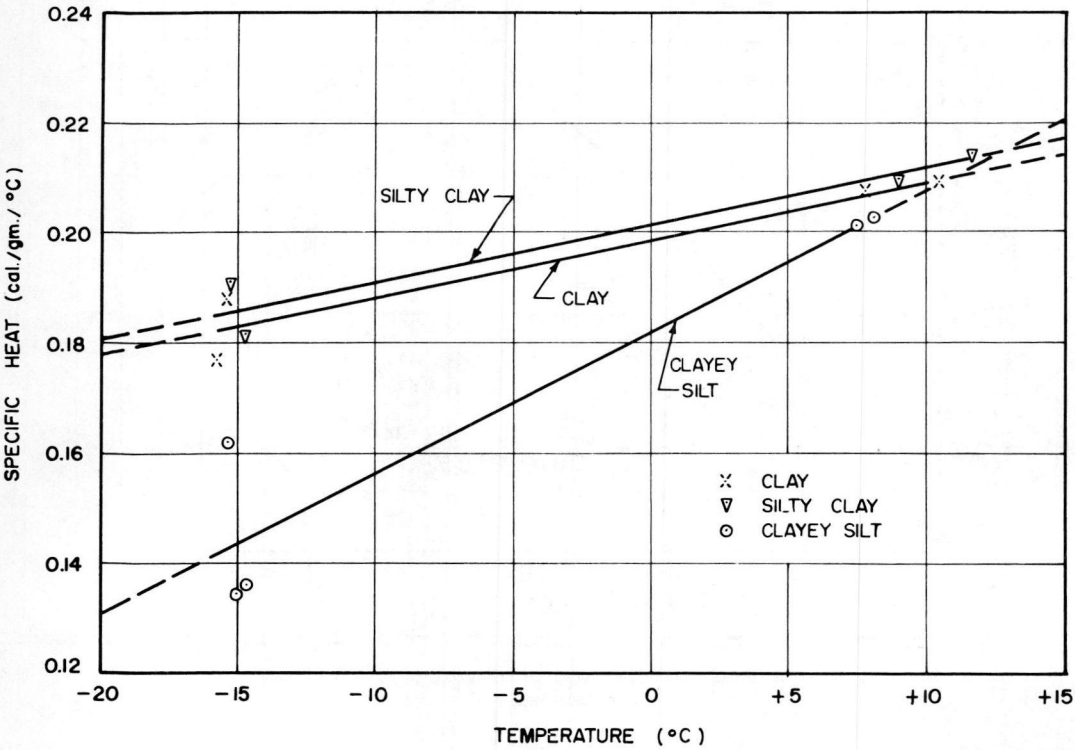


Figure 5. Variation of specific heat with temperature.

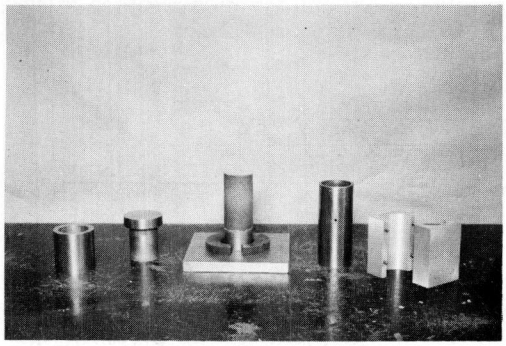


Figure 6. Molding cylinder and accessories.

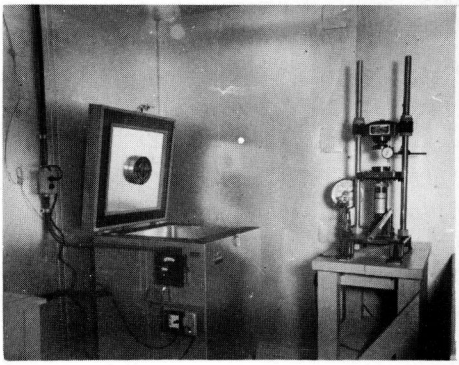


Figure 7. Controlled freezing cabinet (left). Hydraulic loading press (right).

maining liquid is increased, and progressively lower temperatures should be required to freeze this liquid. The contributions of Bouyoucos (3, 4, 5, 6, 7,) in development of this theory are prominent.

2. Later investigations have indicated that the dominant role of influence belongs not to the concentration of the salts, but to the relative magnitude of the negative pressure or suction forces with which the soil moisture is held within the soil system. The magnitude of these forces varies inversely and exponentially with the distance from the soil particle. Accordingly, the most free water in a wet soil mass exists under relatively small suction force, and freezes at only slightly depressed temperature. As such water is removed from the liquid phase by either evaporation or freezing, further freezing may occur only at significantly depressed freezing points because of the magnitude of the suction under which the solvation water and absorbed water exist (1, 8). Beskow (9) formulated such an hypothesis based upon the "adsorption power" of the soil particles.

Parker (10) compared the two causative effects and concluded that each contributed in about the following manner: (a) that the freezing point depression under very small suction was caused basically by the material in solution; (b) that the depression for water under intermediate suction was roughly additive of suction and solution effects; and (c) that the moisture at high suction had a depression controlled almost completely by the pressure. In addition, although the effect of the solution concentration increased with decreasing moisture content, at all but the very wet conditions of the soil the pressure or suction effect apparently had dominant influence in determining the soil water freezing point.

No formal hypothesis of freezing behavior was formulated as a result of the research reported herein. However, the belief that suction influence is dominant in all except the very wet soil conditions is shared by this writer.

DESCRIPTION OF TEST SOILS

Three soils were selected: (1) A red-colored clay derived from limestone; (2) a brown glacial silty clay, pedologically classified as Crosby, "B" horizon; and (3) a tan glacial clayey silt. The soils were selected partially on the basis of the difference in freezing behavior expected of them, and with the hope that these different behaviors would tend to "bracket" the fine-grained soil range. All soils are native to the state of Indiana.

Each soil was sampled in quantity, possessed, and subjected to the common simple characterization tests: Atterberg limits, grain size distribution, specific gravity, and Proctor compaction. Processing included disaggregation to pass the No. 4 sieve and air drying. Accordingly, the reported laboratory behavior of these soils is to some degree peculiar to this processed condition, and may differ significantly from the in-situ behavior.

Results of the Atterberg limits evaluation of plasticity, and the measurements of specific gravity of the soil solids are presented in Table 1.

TABLE 1

ATTERBERG LIMITS AND SPECIFIC GRAVITY

Soil	Liquid Limit	Plasticity Index	Sp. Gravity
Clayey Silt	26.8	5.3	2.75
Silty Clay	35.4	15.9	2.69
Clay	75.4	49.4	2.81

Grain size distributions are presented in Figure 2, where the textural scale shown is that of the Unified Soil Classification System (11). Also on this figure are tabulated percentages of the sand, clay and silt sizes (interposing a division between silt and clay sizes of 0.002 mm), as well as the amounts finer than the No. 200 sieve and 0.02 mm. The latter size is a familiar one in frost susceptibility ratings (12).

Moisture-density relations at the standard Proctor level of dynamic compactive effort are presented in Figure 3.

SPECIFIC HEAT DETERMINATIONS

Since a thermal approach to the problem of determination of relative phase composition (ice and water) of soils at subzero temperatures was adopted for this study, it was necessary to ascertain specific heat[1] values for the test soils.

As might be expected, specific heats of the various inorganic soil constituents are very similar, and have in many cases been approximated by a single average value such as 0.19 or 0.20[2] (13, 14, 15, 16). However, Kersten (17) measured a small but definite decrease in specific heat with temperature, and concluded that values of 0.15 to 0.17 were more reasonable for temperatures of soil freezing. These values are for the dry soil solids.

Apparatus and Procedure

The use of calorimetric equipment and the general method of mixtures for determination of specific heats of soils is reported in detail by Kersten (17, 18). The specific equipment utilized in this study is illustrated in Figure 4.

The calorimeter consists of an outer metal jacket within which a large Dewar vessel with silvered surfaces is mounted, an insulated cover with suitable openings for stirrer, thermometer and introduction of sample, and two aluminum cups of approximate 250 and 500-ml. capacity.

Stirring was accomplished with a glass rod powered by a variable-speed electric motor. The thermometers used had a range of -35 to +25 C, a least graduation of 0.1 C, and were checked for calibration at the ice point.

The procedure employed was somewhat different than that reported by Kersten. Rather than introducing the soil into the calorimetric liquid and observing the temperature change that resulted, the test run was started with the soil inside the calorimeter and in equilibrium with liquid partially filling the cup. To effect the temperature change, additional liquid of known temperature was added to the cup. This method appeared to minimize experimental difficulties, and did not require evaluation of the heat of wetting of the soil solids.

Heat exchange between the calorimeter cup contents and surroundings during test required the customary small correction on the plot of time vs. temperature to obtain the true temperature change. For these tests, the simple procedure of extending the

[1] Specific heat is defined as the quantity of heat required to change the temperature of a unit mass of a substance by one degree.

[2] Units are either cal./gm./C or Btu's/lb/F.

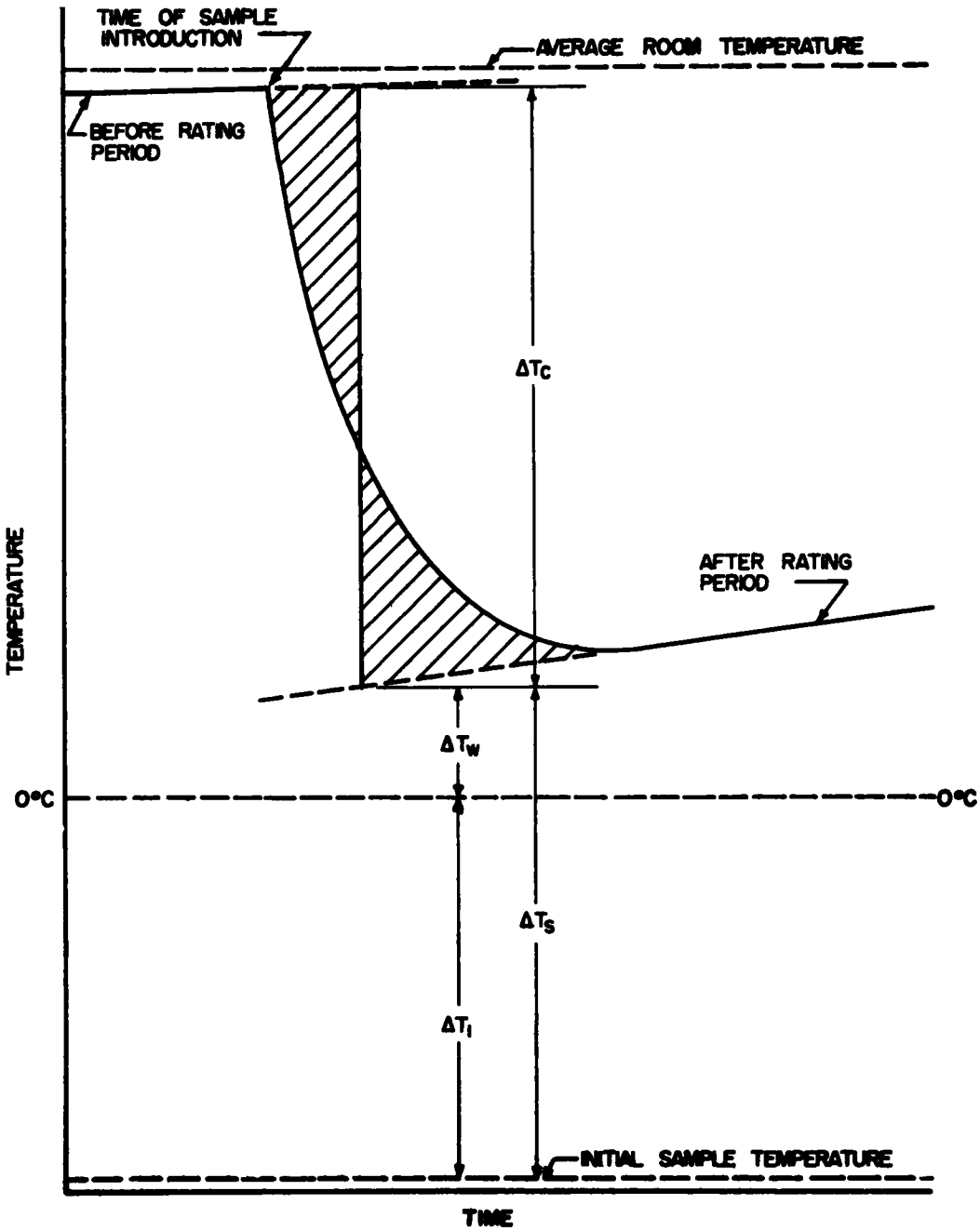


Figure 8. Schematic calorimeter curve.

linear "before" and "after" rating curves to the mid-point time of liquid introduction was used to define the true change.

Since heat gained by the calorimeter and its contents equalled heat lost by the liquid added:

$$C_S = \frac{W_{LA}\, C_{LA}\, \Delta T_{LA} - W_{LC}\, C_{LC}\, \Delta T_C - E \Delta T_C}{W_S\, \Delta T_C}$$

Where, C_S = specific heat of soil solids

W_{LC} = weight of liquid in calorimeter

W_{LA} = weight of liquid added to calorimeter

W_S = weight of soil solids

C_{LC} = specific heat of liquid in calorimeter

C_{LA} = specific heat of liquid added to calorimeter

ΔT_C = temperature change of calorimeter and contents

ΔT_{LA} = temperature change of liquid added to calorimeter

E = water equivalent of calorimeter

Results

Specific heats were determined at only two general temperature levels–10 C and -15 C. An interpolated plot of specific heat and temperature for all soils is presented as Figure 5.

Some temperature dependency of the specific heats is observed, and the absolute magnitudes of the specific heat values are in reasonable agreement with those previously reported. Additional experimental work would have undoubtedly allowed refinement of these results.

MOULDING AND FREEZING TEST SPECIMENS

Moulding

In preparation of test specimens it was considered quite important to exercise good control over the quantities of moisture content and density. Specifically, it was desired to: (a) achieve a given moisture-density combination to the greatest practical precision in a moulded sample; (b) achieve uniform moisture-density relations throughout the sample; and (c) reproduce a uniform moisture-density condition between a number of samples.

This is an old problem, yet one that has never been answered satisfactorily, to the knowledge of this writer. It is known that neither purely dynamic nor purely static type of compaction (as normally applied) achieves a uniform sample condition (19). Leonards (20) reports favorable results with the use of static compaction on both ends of a sample with large diameter-to-height ratio, with subsequent cutting and trimming of small specimens from the large compacted mass.

For a variety of reasons, it was decided to establish, by trial-and-error procedure, combined dynamic and static compaction techniques which would produce the desired levels of moisture content and density uniformly in individual cylindrical samples of size 1.4 (dia.) x 2.8 in. The usual moisture-density level for sample mounding was arbitrarily selected as that existing at the peak of the standard Proctor curve (Figure 3).

In such a trial-and-error approach to the attainment of a given moisture-density combination with a given soil and sample size, many details of procedure may be varied: distance of static displacement, top and bottom; timing of displacement, top and bottom; length of period static load applied; allowance for rebound; number of layers for dynamic compaction; weight of dynamic compaction hammer; height of hammer drop; number of hammer blows; etc. Nevertheless, compaction techniques were worked out for the standard Proctor optimum moisture content conditions for all test soils.

Molding proper was accomplished in stainless steel cylinders complete with collar, compaction head, and compaction base. These items are illustrated in Figure 6. All were machined to very close tolerances.

Samples were molded in small batches, and one sample from each batch was sliced into parts immediately after molding to ascertain that the desired moisture-density level and uniformity probably obtained in the other batch samples, which were used in

duplicate for phase relation or strength determinations. The results of this same physical slicing process of course constituted the original basis for selection of the appropriate compaction to be adopted for each desired soil-moisture-density combination. Such checks revealed that it was possible to control the molded moistures within one-half to one percentage points, and the dry densities within two to three lb per cu ft.

Thus, the molding procedures outlined above adequately served the purposes of

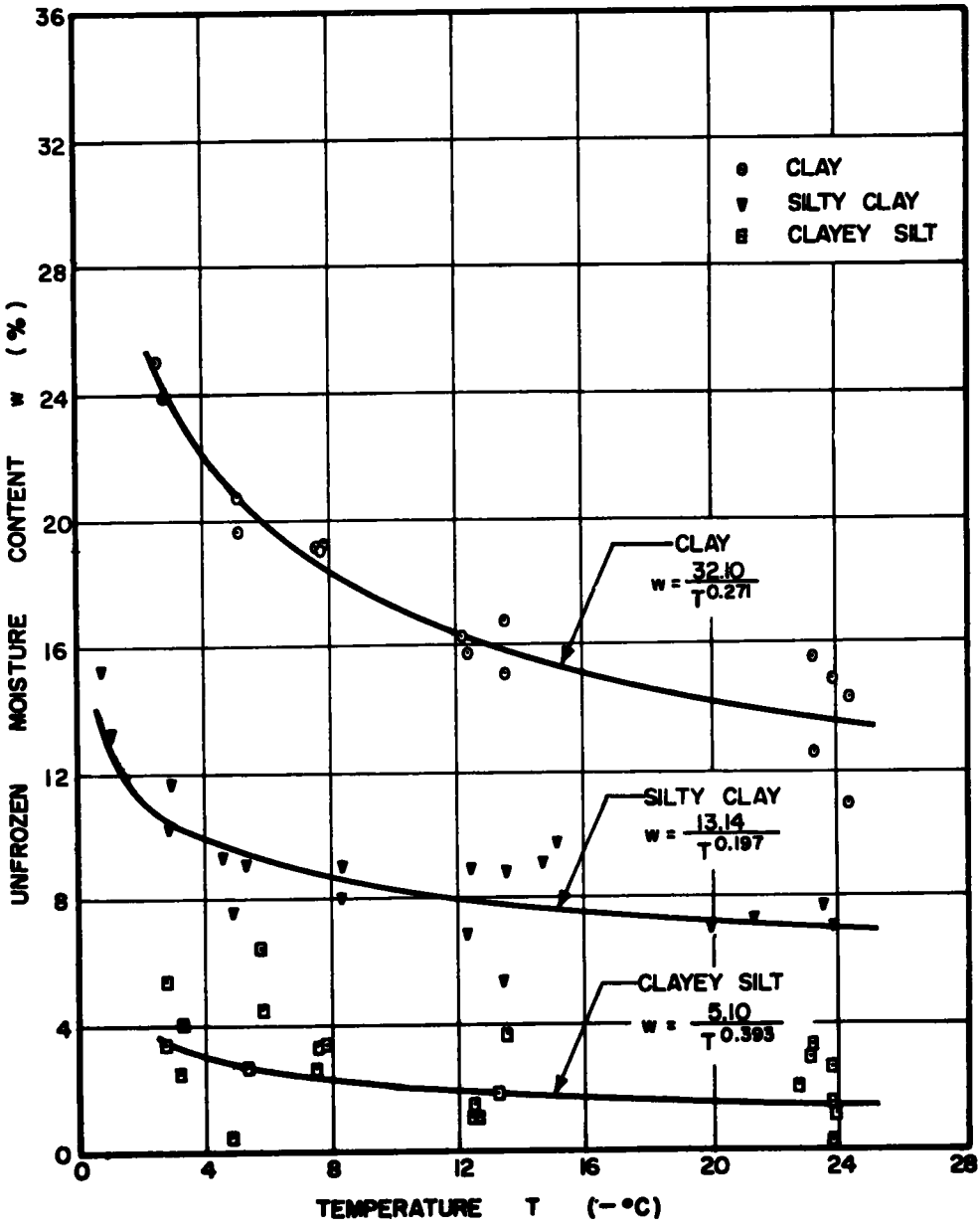


Figure 9. Unfrozen moisture content vs. temperature—all calorimetric points.

this study. However, the writer does not wish to particularly recommend them because of the great amount of care and effort involved in proper execution.

Freezing

Molded and extruded samples were brought to appropriate temperatures for phase relation or strength determinations within a freezer. In the early phases of the study an ordinary horizontal-type deep freeze was used for this purpose. Later, a special cabinet located within a walk-in cold room became available. This cabinet, shown in general view by Figure 7, has a range of ambient to -20 F, and a temperature controller with an on-off differential of 0.5 F. The cabinet also has forced circulation from a small fan in the lid.

Samples that were to be used for phase relation (calorimetric) tests had a 24-gage copper-constantan thermocouple inserted in their tops. The thermocouples not only provided good determination of initial temperature in the calorimetry, but also served as excellent "handles" for the partially-frozen samples.

The procedure for bringing soils to the appropriate subzero test temperature was to merely place them, exposed on all sides, within the freezer preset at this particular temperature. Samples remained in this position for a period sufficient to ensure equilibrium with the freezer ambient—some 18 to 24 hours. During this time the samples experienced some redistribution of moisture due to the established cooling gradients, and lost some moisture to the atmosphere of the freezer by process of limited evaporation and sublimation. Checks indicated that the magnitude of these chances was small. In any instance, the average moisture content of the sample used for either strength or calorimetric tests was determinate at the conclusion of such a test.

Since molded moisture contents were always measurably below saturation and conditions were not conducive to ice segregation, the samples did not exhibit significant volume increase on freezing.

DETERMINATIONS OF ICE IN PARTIALLY - FROZEN SOILS

The calorimetric technique has apparently had a little application to the specific problem of this study. Such technique has been used to determine the free water content of snow (21), and preliminary unpublished experiments on soils have been undertaken by the Arctic Construction and Frost Effects Laboratory[3], New England Division, Corps of Engineers.

Despite the limited knowledge available with regard to use of the calorimetric method for partially-frozen soils, it was decided to utilize this technique rather than the dilatometric (7, 22) or other method.

Briefly stated, the technique involves placing a sample of known subzero temperature, moisture content and density into a calorimetric cup of relatively warm liquid at known temperature. The heat required to melt the ice is indicated by the resultant temperature change within the calorimeter. By use of appropriate specific heats and the latent heat of phase change, it is possible to solve the thermal equation for the weight of ice present. An additional simple step permits calculation of the amount of unfrozen moisture at a given subzero temperature or of the percentage of total soil moisture that was frozen at this temperature.

Apparatus and Procedure

The calorimetric apparatus is described in the section "Specific Heat Determinations". The only alteration required for this test series was the substitution of a stainless steel stirrer for the glass one shown in Figure 4. The glass stirrer proved too fragile to withstand occasional contacts with the sample in the calorimeter cup.

The initial sample temperature (in the freezer) was obtained by means of a thermocouple embedded in the sample. A conventional potentiometric setup was utilized to obtain such readings.

[3] Information furnished by Mr. J. F. Haley, Assistant Chief of the Laboratory.

After the conventional "before" rating of the calorimeter and its liquid contents (water) had been established, and the temperature of the sample in the freezing cabinet determined, the sample was rapidly transferred, suspended by the thermocouple wire, from freezer to calorimeter. Then followed the usual procedure of stirring and observation of temperature change with time, until a final "after" rating period was defined.

Once within the calorimeter cup, the sample soon thawed, crumbled, and settled to the bottom. Stirring could not serve to keep any appreciable portion of the soil in suspension, but merely circulated the liquid within the cup and around the loose soil particles.

At the conclusion of the test the average moisture content and density of the tested sample could be determined by weight differences of the calorimeter cup contents, and checked against the nominal moulded values.

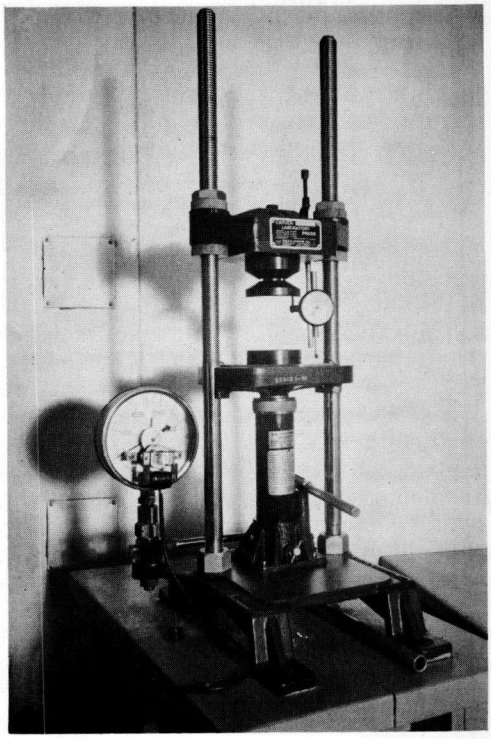


Figure 10. Details of hydraulic loading device.

Method of Calculation

The equality by means of which the amounts of ice present in the samples were determined is a simple thermal one which states that:

Heat lost by the calorimeter and its liquid contents = heat gained by the soil solids + heat gained by the unfrozen moisture in the sample + heat gained by the ice in the sample + heat of fusion of the ice + heat gained by the water derived from the melted ice.

Expressed symbolically, the equation reads,

$$E\Delta T_C + W_{WC}C_{WC}\Delta T_C = W_S C_S \Delta T_S + (W_W - W_I)\ C_{WU}\Delta T_I + W_I C_I \Delta T_I + W_I L_f + W_W C_W \Delta T_W$$

where E = water equivalent of calorimeter

W_{WC} = weight of original calorimeter water

W_S = weight of soil solids

W_W = weight of total soil moisture

W_I = weight of ice (frozen moisture)

$W_W - W_I$ = weight of unfrozen moisture

C_{WC} = specific heat of original calorimeter water

C_S = specific heat of soil solids

C_{WU} = specific heat of unfrozen (undercooled) water (below 0 C)

C_I = specific heat of ice

C_W = specific heat of water (above 0 C)

L_f = latent heat of fusion of ice (at 0 C)

ΔT_C = temperature change of calorimeter and contents

ΔT_S = temperature change of soil solids

ΔT_I = temperature change of ice and unfrozen (undercooled) moisture (below 0 C)

ΔT_W = temperature change of soil moisture (above 0 C)

A solution for W_I or $(W_W - W_I)$ is required.

Specific heats for normal water, undercooled water, and ice were taken from handbook tables (23, 24) for appropriate "average" or midpoint range temperature. Specific heat values for the soil solids were determined experimentally as previously described. The values used were, again, those at the midpoint soil temperature.

The latent heat of fusion of ice used in these calculations was that at 0 C. In other words, it was assumed that the ice was warmed to 0 C prior to melting. This may or may not be the actual occurrence. However, use of the assumption considerably simplifies the thermal equation and probably introduces only a very small error under the given test conditions[4]. Considering the over-all precision of the test series, further refinements here were not considered justified.

The temperature changes to be used in the calorimetric equation were determined from a plot of the time-temperature values. Such a plot is presented schematically in Figure 8. To compensate for the effect of heat losses to the surroundings, a somewhat more refined technique than that employed for the specific heat determinations was employed. The rating portions of the time-temperature plot were extended, and by trial and error with an ordinary polar planimeter the time value which defined equal areas on either side of the curve (shown as shaded portions of Figure 8) was defined. The temperature intercept between the extrapolated rating curves at this time was considered to be the temperature change that would have occurred in the calorimeter without any external thermal influence (25).

To ascertain the adequacy of the calorimetric technique, a substance of known thermal characteristics and phase composition - ice - was melted in the calorimeter. Two test runs for initial sample temperature of -6.4 and -6.3 C showed calculated percentages of moisture frozen of 99.3 and 99.7 percent, respectively (as compared to the actual 100 percent). This evidence supports the basic validity of the calorimetric technique.

Results

Test results are summarized in Table 2. The dry densities shown are the average values for the samples, and were obtained by the product of molded sample volume (V) and weight of solids (W_S) in the calorimeter cup. The original moisture content (w_1) is also an average value for the entire sample, and equals the quotient[5] of total weight of soil moisture (W_W)—frozen and unfrozen, at the time of introduction into the calorimeter cup—by W_S.

The fraction of soil moisture frozen is obtained by dividing the weight of ice (W_I) by W_W. The unfrozen moisture content (w) is the quotient of the weight of unfrozen moisture ($W_W - W_I$) by W_S.

Certain samples of each soil were molded to an average moisture-density combination different than that approximating standard Proctor optimum values. These samples appear in Table 2 under grouping 2. Average values and ranges[6] of values are shown for each grouping in the table.

The relation between subzero temperature (T) and unfrozen moisture content (w) may apparently be most closely approximated by a parabolic expression of the form $w = cT^m$, where c and m are constants. This relationship is linear on a log-log scale.

[4] The difference in specific heats of ice and undercooled water is approximately ½ calorie/gram/C, as contrasted to the latent heat effect of about 80 calories/gram.

[5] Multiplied by 100 to give moisture content as a percentage.

[6] Only a portion of the range indicated is unintentional variation.

TABLE 2

SUMMARY OF CALORIMETIC RESULTS

Soil and Group	Run No.	Original % (lb/ft^3)	Original w_1 (%)	Test Temperature (-C)	% Original Moisture Frozen	Unfrozen w % at Test Temperature
Silty Clay Group 1	51G	105.2	19.1	21 3	61.6	7.3
	52G	106.4	18.6	22.0	62.4	7 0
	69G	108.0	18.4	8.3	52.7	8.7
	70G	106.7	19.1	8.3	57.9	8.1
	71G	108.2	18.2	8.3	50.8	9.0
	79G	105.0	21.3	12.4	58.2	8.9
	80G	106.3	19.3	12.2	64 9	6.8
	83G	105.3	20.9	0.8	27.0	15.3
	84G	106.5	19 5	1.1	32.5	13.2
	103G	107.7	18.7	3.0	38 2	11.6
	104G	108.3	16.8	2.95	39 2	10.2
	109G	106.8	18.4	14.7	50.3	9.1
	110G	106 6	18.9	15.2	48.7	9.7
Average		106.7	19.0			
Range		105.0 to 108.3	16.8 to 21.3			
Silty Clay Group 2	112L	111.1	10.9	4.55	14.85	9.3
	119L	112.2	11.5	13.4	53.3	5.4
	120L	111.8	13.4	13.55	34.3	8.8
	123L	110.6	13.7	23 5	43.9	7.7
	124L	111.6	13.1	23.8	45.7	7.1
	131L	110.3	11.8	5.35	22.7	9.1
	132L	112.0	10.6	4.85	28.3	7.6
Average		111.4	12.1			
Range		110.3 to 112.2	10.6 to 13.7			
Clay Group 1	54G	90.8	27 8	23 9	48 1	14 9
	72G	91.4	28 0	7 8	32 2	19 0
	73G	91.7	27 4	7 8	30 0	19.2
	74G	91 9	27 7	7 65	31 1	19 1
	81G	90 1	29 2	12 3	44 4	16 2
	82G	90.7	28.4	12.15	44.8	15 7
	85G	89.8	29 1	2 5	13 8	25 1
	86G	90.7	28.0	2 8	24 8	23 9
	90G	91 0	28 1	23 25	44.4	15 6
	91G	91 4	27 5	23 3	54 1	12 6
	101G	90 7	28 6	5 1	27 7	20 7
	102G	91 4	27 7	5 2	29 3	19 6
Average		91 0	28.2			
Range		89 8 to 91.9	27.4 to 29 2			
Clay Group 2	115L	91.1	26.2	13.55	35.9	16.8
	116L	91.7	24.85	13.55	39.05	15.1
	125L	91.3	26.6	24 35	46.3	14.3
	126L	91.4	25 5	24.3	56.9	11.0
Average		91.4	25.8			
Range		91.1 to 91 7	24 85 to 26.6			
Clayey Silt Group 1	49G	108 8	16 0	22 65	86 9	2 0
	66G	107.8	16.2	7 7	79 3	3.4
	67G	107 6	15 9	7 5	79.2	3.3
	76G	107.1	15 9	3 25	74 8	4 0
	87G	107 6	17.1	23 05	82 0	3 1
	88G	106.8	17 0	23 1	80.6	3 3
	96G	107 5	16.8	3 1	85 4	2.5
	97G	108.0	16 4	2.8	67.3	5 4
	99G	107 5	16 4	5 8	72.7	4.5
	100G	107.2	16.5	5.65	61.4	6.4
Average		107.6	16.4			
Range		106.8 to 108.8	15.9 to 17.1			
Clayey Silt Group 2	77G	108.8	14.7	12.4	90.8	1.4
	68G	108.7	15.0	7.4	82 4	2.6
	75G	107.0	15.0	3.35	82.5	2.6
	78G	108.6	15.0	12.4	92.4	1 1
	114L	107.6	14.0	13.2	86.3	1.9
	117L	107.7	15.0	13.5	75.1	3.7
	118L	107.0	13.5	12.55	91.6	1.1
	121L	107.3	15.4	23.75	83.2	2.6
	122L	107.6	14.6	23.75	90.3	1.4
	127L	108.3	14.2	23.7	92.3	1.1
	128L	108.8	13.4	23.7	98.7	0.2
	129L	107.9	12.8	4.75	96.6	0.4
	130L	107.6	12.6	5.25	79.6	2.6
Average		107.9	14.25			
Range		107.0 to 108.8	12.6 to 15.4			

Figure 9 illustrates the sum total of experimental determinations. By the method of least squares (26) the equation of the straight line which best fitted the total data for each soil was determined. The scattering of points is considerable, particularly for the clayey silt. However, this figure does clearly illustrate that the curves follow the qualitative pattern that would have been predicted from a knowledge of the soil texture, plasticity index, or quantity of clay sizes—namely that with exposure to a given sub-freezing temperature the clay will contain more moisture in an unfrozen condition than the silty clay, which will in turn contain more than the clayey silt.

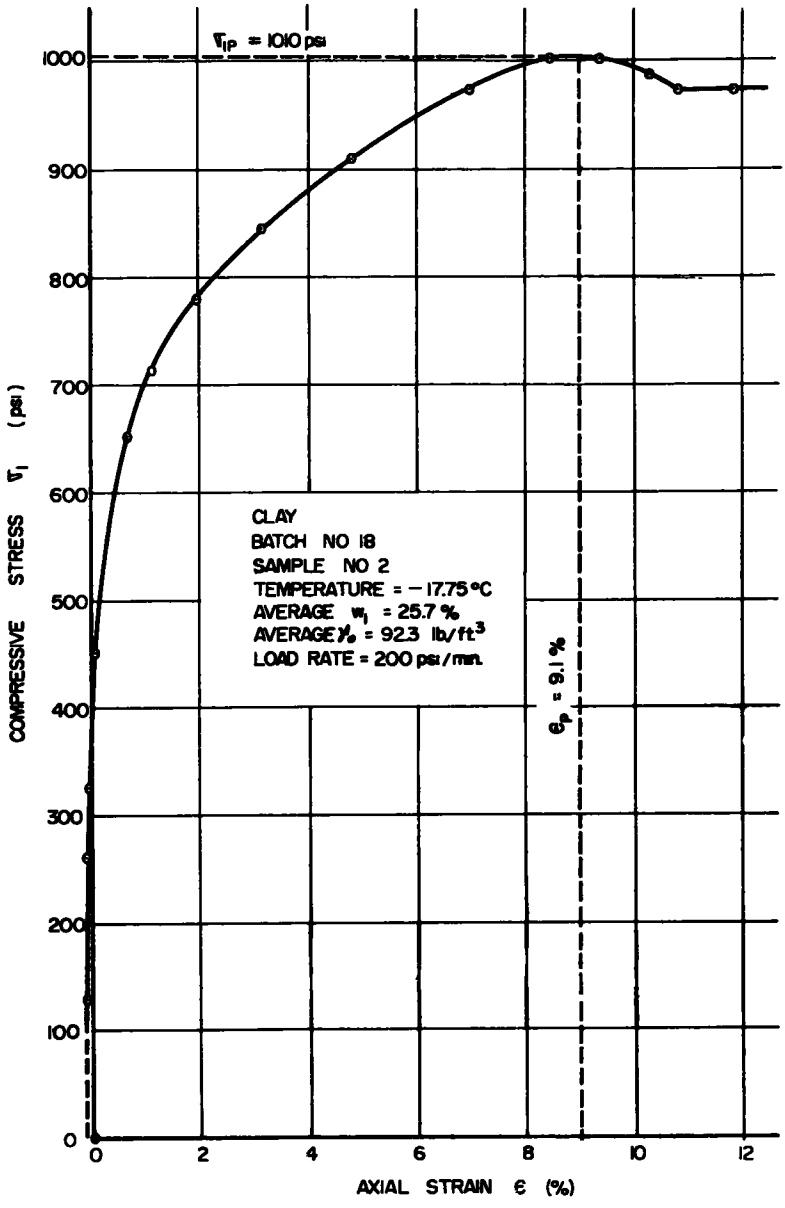


Figure 11. Sample stress-strain curve.

Other analyses were made breaking the data into groups as indicated in Table 2. A comparison of group 1 data, for which the average initial moisture contents and dry

densities are very closely those of the standard Proctor compaction peak, is made at selected temperatures in Table 3.

TABLE 3

COMPARATIVE PHASE COMPOSITION AT SELECTED TEMPERATURES

Soil	Unfrozen Moisture Content w (percent)			
	at -3 C	at -15 C	at -25 C	Ratio $\frac{-3\ C}{-25\ C}$
Clayey Silt	4.4	3.1	2.8	1.55
Silty Clay	11.05	8.0	7.2	1.53
Clay	23.6	15.8	13.9	1.70
	Percentage Moisture Frozen $(\frac{w_1-w}{w_1}100)$			
	at -3 C	at -15 C	at -25 C	Ratio $\frac{-25\ C}{-3\ C}$
Clayey Silt	73.4	81.0	82.9	1.13
Silty Clay	41.8	58.0	62.1	1.48
Clay	16.3	44.0	50.6	3.11

DETERMINATIONS OF PARTIALLY-FROZEN STRENGTHS

It was proposed to show by means of these tests the relative effect of the phase composition (ice and water) peculiar to a given soil and particular test condition on compressive strength. Commensurate with the purpose of the strength determinations, the test procedures used were selected for: (a) simplicity, and (b) adherence to generally accepted methods.

The type of strength test selected for this study was simple undrained unconfined cylindrical compression. Sample size was 1.4 in. (dia) x 2.8 in. The advantages of simplicity for this type of test are of course even stronger for partially-frozen materials.

Until very recently, the only source of data relative to strengths of partially-frozen soils was that described in the foreign literature. Summaries of this data appear in Muller (27), Herrin (28) and in particularly good detail in Corps of Engineers (29). The work of American investigators is now beginning to appear, for example, Kersten and Cox (30) and Corps of Engineers (29)[7].

Stress-controlled rates of loading are most common for partially-frozen soils (29), as contrasted to the strain rates popularly employed for unfrozen materials. In addition, partially frozen materials are usually loaded at what would constitute a very rapid rate for unfrozen soils. In this particular test series, samples were loaded at stress rates of either 162 or 200 psi per minute.

Apparatus and Procedure

Loading was accomplished at controlled temperatures by means of a standard laboratory model hydraulic press (Figures 7 and 10). Load was applied manually and read by calibrated load gages. The two gages used had load capacities of 2,500 and 5,000 lb, with respective least divisions of 25 and 50 lb.

Good loading-rate control was achieved by attaching a small synchronous motor (of the electric clock variety) to the maximum hand of the load gage. By means of interchangeable plastic gear combinations, various speeds of movement of the maximum hand could be achieved. This hand thus became a pacing hand for the manual operation of the hydraulic jack. Strain was recorded to 0.001 in. by means of an ordinary 1-in. capacity dial.

[7]Studies of strength properties of partially-frozen soils by the Arctic Construction and Frost Effects Laboratory, New England Division are continuing.

TABLE 4

SUMMARY OF PARTIALLY-FROZEN STRENGTH DATA

Soil and Group	Batch - Sample No.	Test Temp (-C)	Average w_1 (%)	Average γ_s (lb/ft³)	Rate of Loading (psi/min)	ϵ_p (%)	Max. Stress σ_{1P} (psi)
Silty Clay Group A	26-1	5.15	15.3	106.5	162	5 35	424
	26-2	5.1	16.4	106.5	162	4 6	443
	27-1	10 25	16.7	107.1	162	9.0	645
	27-2	10 3	16.9	107 1	162	7 7	796
	28-1	17 7	17 2	106 4	162	12.7	1700
	28-2	17 7	17.2	106.4	162	8 5	1655
Average			16 6	106.7			
Range			15 3 to 17 2	106.4 to 107.1			
Group B	23-1[1]	13.5	12.45	112.0	162	7 3	909
	23-5[1]	13 5	12 45	112.0	162	5 5	974
	25-1[1]	5.1	11 2	111.2	162	3 6	558
	25-5[2]	5 1	11.2	111.2	200	2.3	527
	24-1[2]	23 65	13.4	111.1	200	5 4	1728
Average			12.1	111.5			
Range			11.2 to 13 4	111 1 to 112.0			
Clayey Silt Group A	19-1	5 4	8.3	116.8	162	1.7	487
	19-2	5 4	8.1	116.8	162	1 95	491
	20-1	9 5	6.6	113.5	162	0.85	620
	20-2	9.45	7.6	113.5	162	1.6	715
	21-1	17.7	8.5	-	162	1 7	1210
	21-1	17.7	8.5	-	162	1 0	1185
Average			7.9	115.15			
Range			6 6 to 8.5	113 5 to 116.8			
Clayey Silt Group B	15-1[3]	13.0	14 25	107 4	162	4 2	1295
	15-5[3]	13 0	14.25	107 4	162	4 1	1300
	16-1[3]	23.75	15.0	107 4	162	2 1	1624
	16-5[3]	23.75	15.0	107 4	162	3 1	1624
	17-1[4]	23 7	13.8	108 6	200	8 0	2516
	17-5[4]	23.7	13 8	108 6	200	7.0	2390
	18-1[4]	5 0	12 7	107 8	200	4.45	747
	18-5[4]	5 0	12 7	107.8	200	4.4	682
Average			13 9	107 8			
Range			12.7 to 15.0	107.4 to 108 6			
Clay Group A	16-1[5]	5 15	25 2	91 7	162	8.5	367
	16-2[5]	5 3	25.5	91 7	162	14 2	390
	17-1[5]	10.3	24.9	92 7	162	10 1	590
	17-2[5]	10 35	24 95	992 7	162	7.8	568
	18-1[6]	17.7	26.2	92 3	200	10 6	1007
	18-2[6]	17 75	25.7	92 3	200	9 1	1010
Average			25.4	92 2			
Range			24.9 to 26.2	91 7 to 92 7			
Group B	14-1[5]	13.55	25 5	91 4	162	16 6	812
	14-5[5]	13 55	25 5	91 4	162	7 9	649
	15-5[6]	24.3	26 05	91.3	200	6.0	1250
Average			25 7	91 4			
Range			25.5 to 26.05	91 3 to 91.4			

[1] Group A1 Avg w_1 = 12 0 Avg γ_s = 111 7 Range of w_1 = 11.2 to 12.45 Range of γ_s = 111.2 to 112.0
[2] Group A2 Avg w_1 = 12 3 Avg γ_s = 111 15 Range of w_1 = 11.2 to 13.4 Range of γ_s = 111 1 to 111.2
[3] Group A1 Avg w_1 = 14 6 Avg γ_s = 107.4 Range of w_1 = 14.25 to 15.0 Range of γ_s = 107 4 to 107.4
[4] Group A2 Avg w_1 = 13 25 Avg γ_s = 108 2 Range of w_1 = 12.7 to 13.8 Range of γ_s = 107 6 to 108.6
[5] Group 1 Avg w_1 = 25.3 Avg γ_s = 91 9 Range of w_1 = 24.9 to 25.5 Range of γ_s = 91.4 to 92.7
[6] Group 2 Avg w_1 = 26 0 Avg γ_s = 92 0 Range of w_1 = 25 7 to 26 2 Range of γ_s = 91.3 to 92.3

Strength samples were exposed on all sides to the selected test temperature within the freezing cabinet for a period of 18 to 24 hours. The loading press was also located in the cold room, which had an ambient closely equal to that of the freezer. The sample temperature was considered to be the mean within the freezer, and the test was conducted in a manner to strictly minimize change of this sample temperature. For example, the sample was touched only by objects of essentially the same temperature.

The test was carried sufficiently far to define a peak compressive stress (σ_{1P}). As no corrected area formula was considered applicable, the molded or nominal sample area was used to convert load to stress. Figure 11 is a reasonably typical stress-strain plot[8].

RESULTS

All strength data are summarized in Table 4. The average moisture contents (w_1) listed include all moisture, unfrozen and frozen, in the sample at the time of test.

[8] The failure of the curve to pass through the origin was due to minor physical difficulty in correlating zero stress and zero strain.

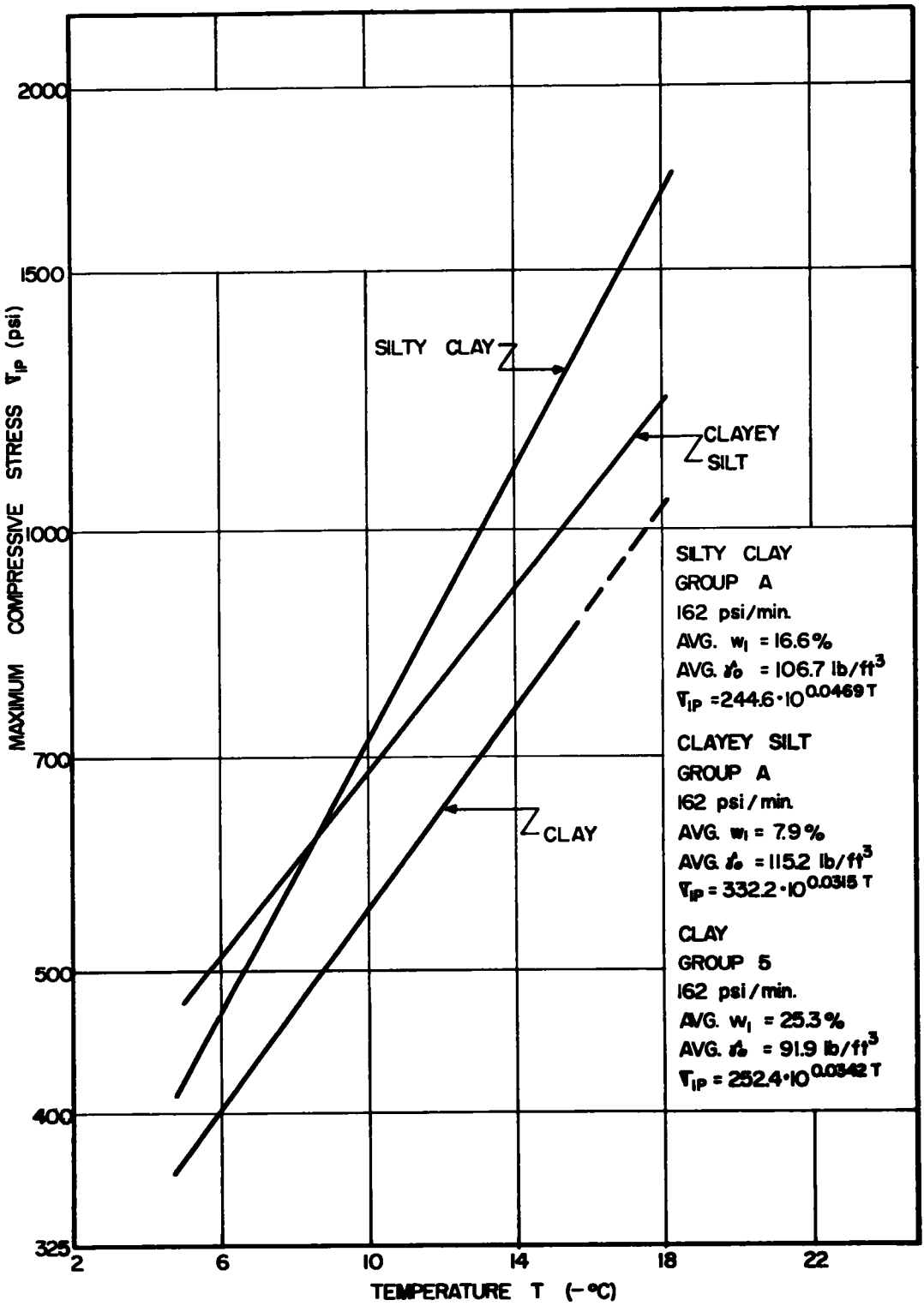


Figure 12. Variation of compressive strength with temperature—all test soils.

Average dry density values are those of "duplicate" check samples in the same soil batch. The primary breakdown of the data into groups A and B represents slight differences in the test procedures which apparently were of only minor influence and are not discussed herein. However, within these groupings significant variations occurred in (a) speed of loading and (b) magnitude of initial moisture-density, necessitating subgroupings for purposes of data analysis. These subgroupings are also indicated in Table 4. Within a given subgrouping, speed of loading is constant and the moisture-density combinations which existed at the time of testing show a rather small range of variation.

Most of the tested samples demonstrated definite failure surfaces with an average approximate angle of 60 deg with the major principal plane. A few samples bulged at top or bottom under load. With a few other samples the upper swiveled loading head tilted considerably before peak load was reached. These difficulties were encountered most frequently with the silty clay. In only one sample (clay) did failure appear to be definitely attributable to weakness along a compaction plane.

All tested samples were later broken apart and examined for evidence of macroscopic concentrations of ice. In only the clay samples at temperatures of -10 C or lower were ice crystals visible. In the case of all other samples, the only ready evidence that they were partially frozen was afforded by their coldness and by extreme hardness. Even very small fragments of the partially-frozen soils could not be crushed between the fingers, until heat from the hand effectively thawed them.

What is believed to be the most significant portion of the strength data is collected in Figure 12, which constitutes a graphical comparison of strengths between the three test soils. The comparison is most valid between the silty clay and clay, which at the time of compression tests existed at approximately standard Proctor optimum moisture content (ice and water) and maximum dry density.

The linear variations shown are the results of least squares analysis. Equations of these lines in the exponential form, $\sigma 1P = c \times 10^{mT}$, are presented on the figure[9]. As was the case with the phase composition equations, these equations are valid for subfreezing temperatures within the test range, and only for soils that have been exposed to sufficient undercooling to initiate freezing.

Since the strength tests were not rational, the strength values presented are intended for use only in a comparative or relative sense.

Large increases in strength with decrease in subzero temperature are shown by Figure 12. Comparisons at selected temperatures are tabled below.

TABLE 5

COMPARATIVE STRENGTHS AT SELECTED TEMPERATURES

Soil	Maximum Compressive Stress $\sigma 1P$ (psi)			
	at -5 C	at -12 C	at -18 C	Ratio $\frac{-18\ C}{-5\ C}$
Clayey Silt	477	794	1227	2.57
Silty Clay	420	894	1708	4.07
Clay	374	649	1042	2.79

The group 1 calorimetric data show that for the silty clay and clay soils at slightly higher but comparable moisture contents and at very nearly equal densities, the following percentages of moisture frozen obtained at the previously tabled temperature values:

[9] Where T is the numerical value of the subzero temperature, and c and m are evaluated contents.

TABLE 6

Soil	Percentage Moisture Frozen			
	at -5 C	at -12 C	at -18 C	Ratio $\frac{-18\ C}{-5\ C}$
Silty Clay	47.6	56.3	59.5	1.25
Clay	26.6	40.8	46.5	1.75

Strictly comparable data is not available for the clayey silt.

It is seen in comparing two temperature levels such as -5 C and -18 C, that the unconfined compressive strength increases exponentially with the relative percentage of moisture frozen. For the silty clay for example, the amount of moisture frozen at -18 C is only 1¼ times that frozen at -5 C, but the compressive strength at the colder temperature is over 4 times that at the warmer level.

Summary of Results and Conclusions

Determinations of Ice in Partially-Frozen Soils. In Table 2 are summarized the results of 59 separate calorimetric determinations of the phase compositions of the three test soils at temperatures from -0.8 C to -24.35 C. The variation of unfrozen moisture content (w) with subzero temperature (T) was found to assume the form $w = cT^m$, where c and m are constants.

The test soils were found to differ significantly from each other in phase composition at a given subzero temperature, and to change appreciably in individual phase composition with lowering of temperature. For example, comparing soils molded to standard Proctor peaks, the following approximate percentages of original moisture frozen obtained: at -3 C, clayey silt 73 percent, silty clay 42 percent, clay 16 percent; at -25 C, clayey silt 83 percent, silty clay 62 percent, clay 50 percent.

It was concluded that very substantial proportions of the total soil moisture of fine-grained materials (defined by drying to constant weight at 105 C) remains unfrozen at temperatures as cold as -25 C. Apparently the more clayey the soil, the greater the quantity of unfrozen moisture.

The calorimetric approach to the solution of phase composition of partially-frozen soils (as utilized in this study) required some simplifying assumptions, but was judged reasonably accurate and workable. Reproducibility of results for the clayey silt soil was poor.

Estimation of phase composition of partially-frozen soils from experimental sorption data for these soils was given detailed consideration. An attempted correlation of such data with "converted" calorimetric and cooling curve data met with little quantitative success, and is not reported in this paper.

Determination of Partially-Frozen Strengths. Unconfined compressive strengths of samples of known moisture, density and temperature were obtained by means of a hydraulic press located within a cold room. Tests were of the stress rate type, at speeds of 162 or 200 psi per minute.

Compressive strengths demonstrated a strong temperature dependency. For example, again considering soils molded at approximately standard Proctor peaks, the approximate ratio of compressive strength at -18 C to that at -5 C was 4.1 to 1 for the silty clay and 2.8 to 1 for the clay. The changes in phase composition, expressed as a ratio of percentage of original moisture frozen at -18 C to that at -5 C, were 1.25 to 1 for the silty clay and 1.75 to 1 for the clay.

It was concluded that the changes in phase composition of partially-frozen fine-grained soils which can take place at temperatures of natural occurrence apparently are responsible for large and important changes in unconfined compressive strength. The practical implications of the changes in strength coincident with change in subzero temperature are of considerable significance.

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