SOIL-ICE PROPERTIES OF FROST-SUSCEPTIBLE SOILS, MADE HYDROPHOBIC

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ABSTRACT

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By

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Almost every building, dam, road, airport, etc., must rest upon soil. Many of these structures employ soil in their construction, or support huge soil masses. The properties of existing soils, especially their bearing capacity, depend greatly on soil-water relations and their water contents at any given time. Water, in general, can move into the pores of a three phase soil system either by surface tension and capillary, or by hydrostatic pressure. Soil-water systems are further sensitive to other forms of applied potentials such as: temperature, electrical forces, or applied mechanical stresses. If any one of these constraints is applied to the soil, it will change the soil properties and bring about the problem of nonhomogeneous, unstable, or undefined material, which does not lend itself to any known method of evaluation or formulation. The effect of the constraints normally results in proportional

changes between solid, liquid, and gaseous parts of soil, or simply in phase proportion. This general deformation, in turn, alters the soil's response to the constraints and the entire soil system becomes interrelated. It is a known fact that all the soil properties and constraints are water dependent. To overcome the water-related problems, it is necessary to keep water away from the soil grain, or to render the soil waterproof.

This study is mainly concerned with chemically waterproofed soils. Chemical waterproofers are hydrophobic-hydrophilic materials, and if added to soil, the hydrophilic end of their molecule attaches to the surface of the soil particle and the opposite, or hydrophobic end, repels water.

For this investigation nine different soils were treated with a recently developed chemical waterproofer, known as TBC, and were then subjected to freezing conditions. TBC chemically is 4-tert-Butylprocatechol, and is effective over a considerable range of soils. As a part of this study, two common soils, a highly frost susceptible soil from Iowa (Iowa Silt) and a less susceptible native soil of Michigan, were used. The frost-moisture-related properties of these soils, water absorption, heave, shear strength, and water content for up to 20 cycles of freeze-thaw were determined. In addition, the extended time submerged water content and moisture retention of all the soils were determined.

The study was conducted on chemically treated and untreated soil sample pairs. Samples were molded using the Harvard method and equipment.

The study was carried out with both the open system and the closed system of freezing, employing a freezing temperature of -12°C. This temperature is equal to an average temperature gradient of about 0.6°C/CM across the soil samples. The study results indicate the waterproofer performs in two ways; the treated samples absorb less water when in contact with water or subjected to open system freezing, and treated samples retain more moisture than untreated samples when exposed to dry environment. The study indicates that although the chemical used is an additive of promise, concerning the strength results,it is doubtful if it can be used for frost-susceptible soils subject to direct load and severe weather conditions. TBC treated soils are not improved if not in contact with water, and a slight reduction in strength results. TBC is suggested to be used for certain problem soils for waterproofing and also to limit freezing problems.

It was observed that the water absorption of soil samples, with repeated cycles of freeze-thaw in an open system, could be represented by a mathematical model. The formulas were first derived for waterproofed soil samples, but it was later observed that the formulas were equally good for untreated soil samples. The formulas may be used

to estimate the maximum water content of soils with an unlimited number of freezing cycles, or for any desired number of cycles, once certain soil properties are known. A formula is presented which may be employed to estimate water retention properties of a soil versus time, once the moisture content of a given soil, at some boundary points, is known.

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NOTATIONS

A : identification name for a series of soil#1 samples.

a : constant coefficient.

B : identification name for a series of soils #1 and #2 samples

b : constant coefficient.

c : number of freezing cycles.

°C : temperature degrees, in Centigrade Units.

dm : infinitesimal mass of water.

e : natural logarithm base = 2.71828

°F : temperature degrees, in Fahrenheit units.

g : gravitational constant.

h : height of capillary rise, above water table.

i : variable identification number, for soil samples.

L : maximum saturation.

m, n : constant coefficients for "Welz and Eich" formula.

p : percent saturation.

r : radius of capillary surface.

r_1, r_2 : radius of capillary in different directions.

T : surface tension of water.

T_i : identification name for treated soil samples.

t : time.

U_i : identification name for untreated soil samples.

V : mean flow velocity in soil.

Y : water content in "Velz and Eich" formula.

Y_c : water content after c cycles of freezing.

α : angle of contact for water and soil.

γ_w : density of water.

ΔL : tube length.

ΔP : pressure difference between two points.

Δt : temperature difference across soil samples.

$\Delta \Psi$: potential difference between two points.

μ : viscosity of fluid.

Ψ : potential.

Ψ_c : capillary potential.

Ψ_g : gravitational potential.

CHAPTER I

INTRODUCTION

Soil, in general, is considered as a three-phase material consisting of solids, liquids, and gases. Engineering behavior of soil is greatly influenced by the variation of these three phases with respect to each other, and especially by the moisture variations. Homogeneity, elasticity, plasticity, and the intermediate states of material existence which lead to the simplification of properties and formulation of material behavior, are almost never directly applicable to soils. Only in a few cases,and with relatively rough approximations, has it been possible to introduce a coefficient to approximate the behavior of soil into a purely theoretical formula. Most of the existing mathematical or physical models for soil are empirical and have been found and formulated through laboratory and field studies. In general, research and development methods in the past have been progressing from theoretical to experimental and vice versa, or sometimes they have been used in connection with each other. For soils, the research and development have mainly relied upon experimental procedures and then mathematical tools were used to present the behavior of soil through an understandable model, which was done in this study, on modified three-phase soils.

The three-phase soil becomes further complicated by the existence of outside constraints. Application of any form of potential such as load, water, electric current, or heat may change the phase proportion which results in a change in soil properties. This property change is in turn interrelated with applied potential, and is time and rate dependent, which presents an ever changing, complex problem. Of the above-mentioned potentials, soil is most influenced by water or combinations of water and other variables. Load carrying and deformation rates, in addition to the rate of load, are dependent on the moisture and its movement in the soil. In a word, all outside constraints on a soil are moisture dependent.

When temperature depresses below zero (°C) over a soil, temperature will penetrate the soil body with some fixed rate. The temperature penetration supercools solid, liquid, and gas. Since the freezing point of free water is higher than that of moisture at the surface of soil particles, freezing starts at a single point, or many points, in capillary water and ice crystals start to grow. The freezing action converts part, or all, of the soil moisture into ice, causing a form of dryness and consequently, moisture from adjacent voids is drawn toward the freezing front.

The source of moisture and heat in the freezing soil is in the contained ground water. Moisture and heat transfer during freezing is a continuous process. Replacing the soil water with ice and adding continuously to the water and ice content of soil changes the soil, including its thermal conductivity, which changes rate of temperature penetration and changes the freezing system. It may be said that the entire soil-water-potential system is an unstable, nonhomogeneous mass. For freezing processes to take place, three conditions must exist: freezing temperature, available water supply, and a frost susceptible soil. Elimination of any of the three conditions may eliminate or limit soil freezing problems. Temperature penetration may be stopped or altered by using a layer of materials with very low thermal conductivity. The water table may be lowered by various methods, omitting the capillary water movement. The last soil freezing factor, frost-susceptibility, is a matter of soil structure, namely, the mineralogical composition, electrical properties, shape and orientation of particles with respect to each other, the nature and properties of soil water and its ionic composition, the interaction between soil particles, soil water, and other related factors.

Freezing in soils results in two major problems. When the soil freezes, the formation and growth of ice causes soil expansion, which may change the elevation of road or airport pavement, foundation, or any other object supported by, or adjacent to the soil. The second problem resulting from soil freezing is much more critical and occurs when the ice within the soil body melts. The strength loss due to water content may be agreed upon without further discussion, especially when ice expansion alters the state of soil compaction.

The technique of improving soil properties, or soil stabilization, is the art of giving the soil system a new, modified structure which may resist outside constraints. Among the available methods of stabilization, "chemical stabilization" has its own place and is gaining in importance. The increasing popularity of the chemical soil stabilizers is partially due to availability of new and more effective chemicals being offered and is also due to the demand for new methods providing soil engineers with inexpensive modified soils that may answer modern needs.

In general terms, chemical soil stabilizers may work as a bonding agent, a waterproofing agent, or a combination of both. This study is concerned solely with the waterproofing concept of improving the soil structure. Soil waterproofers may be hydrophilic-hydrophobic materials. The hydrophilic end of their molecules attaches to the soil particle surface, with the hydrophobic end repelling water and consequently saving a part of soil's dry strength when it is in contact with free or capillary water. A major

portion of this study examines the strength, water content, and expansion comparisons of two soils, a highly frost-susceptible and a relatively less frost-susceptible soil, with and without chemical treatment. In addition to the two soils mentioned above, seven other soils, ranging from silt to high clay fraction and organic sands, were utilized to determine the effect of waterproofing chemicals on a variety of soils and the soils' secondary properties. The experimental results indicate that the water retention of treated and untreated soils and their maximum water absorption under repeated cycles of freezing and thawing may be predicted with a reasonable degree of accuracy, once certain soil properties have been evaluated. The results indicat- that chemical soil waterproofers are valuable modern engineering materials.

CHAPTER II

LITERATURE REVIEW

1. Soil-water System

Soil particles and water almost always exist together in nature, and performance of the soil system and almost all of the physical properties of soil such as consistency, strength, compressibility, consolidation, permeability, and strength depend greatly on the properties of various combinations, and the interrelationship, of soil particles and water. These interrelationships, in turn, are determined by the form and forces holding soil particles together and the effect of variation of soil moisture on these forces.

An understanding or simulation of the forces that hold water in soil, as it is in nature, is difficult because of the complex interaction occurring between soil particles and various states of water within the soil body. Only with simplifying assumptions, has it been possible to calculate quantitatively how water is retained and how it moves in soil under selected conditions. This would, of course, vary for the cases of wetting or drying. In general, water surrounding the soil particles may exist in two forms:

a. Water absorbed by the soil particle, or oriented water; and

b. Free or bulk water.

For simplicity, but not quite accurately, it is usually assumed that the adsorbed water exists as layers of thin films around the flake-shaped soil particles. The first film of water is held by the surface of the soil particles with a great force, which in extreme cases may be as much as 10,000 atmosphere, or 142,000 PSI (15). This adsorptive force, however, diminishes rapidly as the distance from the surface of the particle becomes greater, and the total thickness of adsorbed film may be only a few molecule layers. It is agreed that the first two or three layers of water molecules are bonded to the soil particle surface and that the adsorbed water is extended to about 15 Angstrom from the particle surface (10). The stressed water has properties completely different from those of bulk water. The exact separation between the two waters, however, is not distinct and cannot be distinguished as a sharp line, but the characteristics change gradually and depend, non-linearly, on the distance from particle surface. The density of that part of water at the surface of the particle (adsorbed water) is higher than that of water filling soil pores (free water). Values up to 1.40 gr/cc have been measured for the first molecule closest to the particle surface. The density decreases for further layers, dropping to 0.97 gr/cc at about four water layers, and then increases to 1.00 gr/cc for free water (15). The dielectric constant near the surface is about one-tenth that of free water (10). Water adsorbed on the particle surface is not completely restricted from movement. Water molecules are relatively free to move in directions parallel to the particle surface but are restricted in their movement perpendicular to, or away from, the surface (15). The parallel water movement is a transfer from one bonded molecule to another, and in freezing is termed as film moisture transfer (8).

Forces holding soil particles together consist of forces bonding atoms to atoms forming molecules (Primary Valance bonds), atoms in one molecule bonding to atoms in another molecules (Van der Waals forces), and hydrogen bonds. The hydrogen bond is the result of attraction of one hydrogen atom by two other atoms. The hydrogen atom shares its bond with both of them, and causes some kind of connection between the two attracting atoms. Primary Valence bonds are sufficiently strong so that they are seldom broken in engineering work. Van der Waals forces are the weakest of all. The hydrogen bond is a relatively strong bond (10) and is very important in the structural bonding of water and ice crystals, bonding layers of clay minerals, holding water to clay surface, and in bonding water or organic molecules to clay mineral surfaces.

The forces holding water molecules to the soil particle surface are partly from the water molecule attracted by the charges on the clay surface, and partly from the hydrogen bond between water molecules and exposed oxygen atoms of mineral particles. For example, a hydrogen atom bonds the oxygen from a water molecule to an oxygen atom on the clay particle surface (10).

The first layer of water molecules is held to the particle surface by the hydrogen bond. The second water layer is held to the first layer, again by hydrogen bonding, but the bonding force is weaker and grows still weaker with further layers until it reaches the state of bulk water (15).

It has been attempted to find a mathematical or mechanical model for water retention and water movement in soil. In early soil literature the soil voids were assumed as tiny capillary tubes, holding water by surface tension forces (2). The height of water in the assumed capillary tube is given by

$$h = 2T \text{ COS. } \alpha \,/\, (r \,.\, \gamma_w) \qquad (1\text{-}1)$$

The angle of contact α for soil-water is assumed to be zero, except for hydrophobic soils (19). Choosing α equal to zero and working equation (1-1) with average r occurring in soils, heights up to several hundred feet will be obtained, while laboratory measurements have never yielded more than four feet of rise (15). The weakness with the above work is that the water in soil flows upward through very poorly defined flow paths, in a zigzag motion, and not in smooth capillary tubes. Buckingham (18) treated the water movement in soil by the energy concept. He defined the capillary potential as the work required to pull a unit weight of water away from a mass of soil. Considering a tube filled with uniformly compacted dry soil, with a free water level at the lower end, covered at the top, by equating the work done by capillary and gravitational forces, at moisture equilibrium, one may derive the expression for capillary rise as:

$$\Delta\Psi_c + \Delta\Psi_g = o \qquad (1\text{-}2)$$

or

$$[\Psi_c.dm - (\Psi_c + \frac{\partial\Psi_c}{\partial h}\,dh)\,dm\,] - [\,g.dm.dh\,] = o \quad (1\text{-}3)$$

and from the above

$$\Psi_c = -\,g.h + b \qquad (1\text{-}4)$$

using the boundary conditions, Ψ_c=o where h=o, then the integration constant b becomes zero and:

$$\Psi_c = -\,g.h \qquad (1.5)$$

Since capillary potential causes an inward pressure, it is assumed negative in sign, and is sometimes called capillary pressure. In addition to height h, capillary potential also depends on the water content. The relation between capillary potential and water content is governed by the equation:

$$\frac{\partial \Psi_c}{\partial w} = g \cdot \frac{\partial h}{\partial w} \qquad (1\text{-}6)$$

The above indicates that changes of capillary potential with moisture are equal to the constant g divided by the rate of change of moisture with height. Consequently, if the variation in moisture content with height is known, the relation of capillary potential to moisture content may be obtained.

The potential of soil-water is designated without reference to the forces by which water is retained in soil. The retaining forces, if known, will lead to a better understanding of the soil-water system. In sands, on wetting, no swelling occurs and the process may be compared to that of capillary tube. The angle of contact of soil-water is assumed to be zero. The pressure difference at the air-water interface is given by (19):

$$\Delta P = \Delta \Psi_c = - T \left(\frac{1}{r_1} + \frac{1}{r_2}\right) \qquad (1\text{-}7)$$

if radii of curvatures r_1 and r_2 are equal, this equation will be identical to equation (1-1).

It has been observed that at a given pressure a soil sample has a higher water content on drying than on wetting (19). This behavior which arises from the previous treatment of the soil is termed hysteresis. Since complete wetting in soil occurs when the largest pores are filled with water, and complete drying occurs when the smallest pores are emptied, the hysteresis phenomenon is understandable. Hemwal and Bozer (8) attempted to relate hysteresis to the shape of air-water interface. Approximating the interfaces as spherical and cylinderical, on desorption and absorption, respectively, they were able to obtain the following equations:

$$\Delta P_W = - T \left(\frac{1}{r_1} + \frac{1}{r_2}\right) \Bigg]_{r_2 = 0} = - T/r \qquad (1\text{-}9)$$

$$\Delta P_D = - T \left(\frac{1}{r_1} + \frac{1}{r_2}\right) \Bigg]_{r_1 = r_2} = - 2T/r \qquad (1\text{-}10)$$

which show the energy on drying is twice as much as on wetting. This phenomenon as well as soil porosity should be reported when investigating soil-water system.

Clays are more sensitive to water variation than sand. A decrease in water content of clays, up to their shrinkage limit, results in a decrease in soil volume. Air-water interfaces do not exist except at the boundaries of soil with air or at the cracks. On wetting, depending on the type of clay minerals, physical-chemical properties, salt concentrations, and cementing bond between soil particles, various amounts of swell may occur. In the limiting case, the wetting may be completely resultant of swelling forces.

For soils composed of varying particle sizes and minerals, the forces may be a combination of capillary and swelling forces, and hence the pressure difference cannot be calculated. However, equivalent capillary pore size may be calculated from the measured water retention curves (2).

2. Soil-ice System

When a moist soil is subjected to a low enough temperature for a sufficient length of time, the water within the soil voids freezes. Pore water in soil freezes at the same temperature as water in a container, but the freezing point for adsorbed soil moisture is much lower than the freezing point of free water, with first layer at soil particle surface never being frozen. This non-freezing film of water was first assumed by M. Faraday and J. Tendall (8). They presented the theory that ice is coated by a mobile noncrystalline film of water that is stable for temperatures below the freezing point. In later studies, Nakata and Matsumuto (8), working on adhesive forces between ice particles, observed a phenomenon that indicated a liquid water film surrounding small ice spheres. The water film on ice surface represents a gradual transition from the rigid structure of ice crystal to a double layer of soil moisture on the surface of soil particles.

Freezing in soil presents several engineering problems. Soil expansion dislocates structures in contact with it, raises highway and airfield pavements locally, breaks underground tunnels and pipes, may dislocate railway structure, and increases the pressure at adjacent sheeting, retaining wall, or water-impounding structures. The volume increase of soil with freezing is many times more than the expansion of soil moisture, which amounts to approximately 9 percent for water upon freezing. A simple computation indicates that heaves resultant of soil moisture freezing for most practical cases would amount to only a fraction of an inch, while heaves of many inches are commonly observed. The additional increase in soil volume is caused by migration of water to the freezing zone, resulting in higher water (ice) content for the soil. When the temperature depresses to the freezing point, or lower, the first ice particles start to form and grow in the bulk water. The freezing action dries the soil in the region of ice formation. Therefore, the necessary water to satisfy the attraction of soil would be supplied from adjacent soil moisture or any other available water reservoir, such as ground water, until an equilibrium of soil suction and gravitational forces on soil moisture is again reached. Ice nucleation may occur at one or several points in bulk water at the same time or gradually. Each ice nucleus works as a freezing front and attracts water from adjacent soil masses, and this may result in a very low water content in the intermediate soil regions.

The geometry and amount of ice in frozen systems of soil, in addition to soil porosity and ice nucleation, depends very much on the intensity and rate of freezing. If the soil freezes quickly (about 3 inches depth per day), although the water content of the soil will increase, no ice layer will be visible in the frozen soil and, depending on soil type and freezing rate, the final water content may be higher at the top, bottom, or mid/height of the soil. With slower freezing, visibly separated ice layers will form with thicknesses varying usually from 2 to 12 millimeters. The thickness of ice layers may even be much higher for soils with large voids or air gaps, and available water source.

Frozen soil as a structural material, and under constant load, is subjected to creep deformation. The property of ice changes with a change in the intensity of applied forces. Creep deformation for some soils has been determined (1) to be an exponential function of stresses. Water-ice transformation mechanisms and pressure-ice relations are under current research.

The loss of soil strength upon melting of ice is engineeringly important. The ice melting starts from the top, or top and bottom. The melt water cannot drain downward because of the underlying ice barrier; thus the thawed soil becomes saturated and loses practically all of its bearing strength.

Freezing, thawing, and the related problems in soil engineering have been termed frost action. For frost heave to occur in soils, three conditions must exist: a frost-susceptible soil, a freezing temperature, and a water source. Casagrande (18) states that for well-graded soils, if 3 percent or more of the soil particles are less than 0.02 mm. in particle size the probability of frost action exists and for uniformly graded soils if 10 percent or more of the soil particles are less than 0.02 mm. in size, then frost action is possible. These limits are based on laboratory, and some field studies, but recent works (10) have indicated that soils with smaller percentages of 0.02 mm. size particles, may be frost-susceptible. The U. S. Army Corps of Engineers classifies frost-susceptible soils as F_1, F_2, F_3, and F_4 groups (18). These soils are: Gravelly soils containing between 3 and 20 percent particles finer than 0.02 mm. by weight; Sands containing between 3 and 15 percent finer than 0.02 mm. by weight; Clays with plasticity index of more than 12; and all Silts, including sandy silts and very fine silty sands containing more than 15 percent particles finer than 0.02 mm. by weight.

In general, the weakest soils, from frost-heave point of view, are those which are sufficiently fine grained with relatively high capillary forces to lift water from a water table and at the same time sufficiently coarse grained to provide a high enough rate of capillarity to allow the water movement from the water table to the freezing front. Although most frost-susceptible soils are recognized by their silt fraction, any water-susceptible soil is a frost-susceptible soil if the rate of frost penetration is suited to the amount and nature of its porosity. For the temperature rates occurring in nature, the above-mentioned particle size limits serve as an engineering approximation, and from all the studies being made, no precise relation between frost-susceptibility and any other soil characteristics such as permeability, density, capillarity, composition, and specific surface has been found (18). The U. S. Army Corps of Engineers states that if the water table at any time of year can reach a level five feet below the grade line of a pavement, it should be assumed as an available water source for the freezing season.

The rate and depth of frost penetration depend on the thermal conductivity of a soil. The thermal conductivity of a soil, in addition to the soil texture and state of compaction, depends on soil-water and soil-ice-water systems, which are variables with the freezing process. On freezing, the pore water at any depth freezes at the same temperature as that of free water. The temperature required to freeze the water bonded to the soil particles will vary depending on the intensity of bonding forces (15). The amount of unfrozen water in soil also depends upon whether the unfrozen soil is being cooled, or a frozen soil is being warmed. The amount of unfrozen water in freezing soil is given as approximately 8 percent for clay soils and about 2 percent for silts at temperatures approaching 20 degrees centigrade below zero (18).

The entire freezing process in soil, heat, and moisture transfer from warm region to cold fronts, is a very complex phenomenon and is not completely understood (19). It is certain that a variation of any of the factors involved during the freezing process influences the other factors and, except for its simplest form, no simulation may be made to represent the actual occurring cases.

Means of rendering frost-susceptible soils non-frost-susceptible have been studied for some time. Some provisions would be treating the soil so that soil moisture can not migrate to form ice lenses, treating the soil such that freezing temperature cannot penetrate the soil, and finally, replacing the soil with a non-frost-susceptible soil.

3. Soil Improvement--Stabilization

The word stabilization is somewhat misused in soil literature. Stabilization is used to define any kind of improvement of soil properties, while an improvement may have an inverse effect on the permanency of soil characteristics. Over compaction, for example, may increase the soil strength but it weakens the soil with problems from capillary, or poor drainage (18). Freezing has recently been employed as a means of making soil a temporary high-strength material in mining, tunneling, temporary foundations, and open cuts while this, in fact, is not stabilization since if the temperature rises or when ice is melted the soil probably would be many times weaker than before freezing.

A soil can be said to be stable only if it shows constant characteristics against outside constraints, in dry or moist states, or with any other changes in the environmental conditions. Soil properties may be improved by many means, with the degree of stabilization depending on the type of soil, the method applied, and the environmental conditions to which the soil may be exposed. Each method of soil improvement is suitable with certain types of soils and under certain conditions while the selection of a method would be made by considering all the elements involved.

Soil properties may be improved, or stabilized, by mechanical, electrical, thermal, or chemical means. An improvement of engineering properties of soil, depending on the expected conditions, may or may not be stabilization. Stabilization, in turn, does not necessarily mean strength improvement, but reducing the sensitivity of soil to the environmental changes, especially moisture changes.

Mechanical stabilization methods alter soil properties either by rearrangement of soil particles by compacting, or by addition or removal of a portion of soil particles. Various methods of compaction have been employed on almost all the engineering soil types and all soils except those with very high organic matter content may be effectively compacted. Compaction effort changes soil permeability, compressibility, stress-strain characteristics, and strength of a soil, depending on the moisture content at compaction and the amount of effort employed. In part, the strength of a soil is dependent on the size distribution of particles. Addition of fine and very fine particles to coarse grained soils may increase the soil gradation and therefore increase strength and durability of the soil in service. The strength of fine grained soils may be increased by adding coarser materials. The addition or reduction of soil material also changes the soil-water property of soil, which again may or may not be in the direction of soil stabilization.

Electrical stabilization methods are used to remove water from saturated soils by introducing a direct electrical current into a saturated soil. Water moves toward the cathode and may be removed. Removal of water, if not replaced, decreases the volume of soil by consolidation, and consequently, increases soil strength. The electrical method may also cause other changes in soil particle and electrolyte properties. Electrical current has also been used by Casagrande (10) to increase load carrying capacity of friction piles.

Heating and cooling have both been used to improve soil properties. The desired temperatures are induced into the ground through a network of piles for a period of time producing a cylinder of solidified soil a few feet thick. Stabilization by heat has not been widely used in the United States. Thermal stabilization has been employed on a great number of projects (10), such as stabilizing saturated loessial soils, decreasing compressibility of cohesive soils, ice piles, ice cofferdams, construction of mine shafts in frozen soil, underpinning office buildings, temporary stabilizing of highway and dam embankments, and open pit mining up to depths of 500 meters. The problem with thermal stabilization, if economically acceptable, is that cooling of a soil drains adjacent soil masses and this action may cause settlement in the nearby area, or may cause undesirable heave.

Additives, such as Portland Cement and bitumens, have been employed extensively in recent years to improve properties of engineering soils. This, in fact, is production of new materials which are used where soil alone cannot be made suitable by other means.

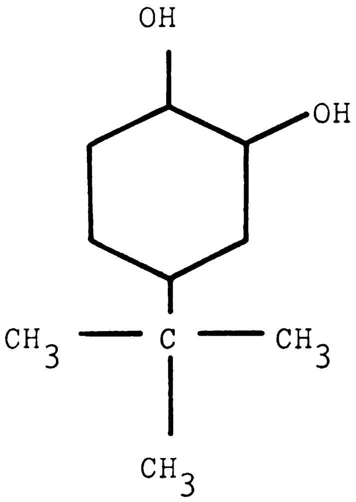
Soil stabilization by the use of chemicals probably is the most common method of stabilization. A great variety of chemicals are used, or proposed for soil treatment.

Chemical soil improvers are used both directly, and as secondary additives, or are used with other soil-improvers such as portland cement or bitumens. Chemical improvers are added to a soil in very small amounts and may improve soil properties by bonding soil particles together, by waterproofing them, or by a combination of bonding and waterproofing. Bonding agents work by cementing soil particles together and depending on whether bonding is formed between the soil and the matrix, or directly between soil particles, the effectiveness differs. Waterproofers are used to maintain the soil at a low moisture content, at which the soil has adequate strength for its purposes. No waterproofer has yet been found to serve this purpose completely, and their evaluation is based on how effective they are. Soil waterproofers usually indicate no bonding action, or a very small bonding action. The degree of stabilization depends on the stabilizer content in the soil with an optimum usually less than 2 percent by dry weight of the soil. Waterproofers may also improve other soil properties. Studies connected with construction of roads and airfields in the Sahara desert (15) have shown that waterproofers retard the evaporation of soil moisture and maintain soil strength for a longer period of time. Lamb (9), at Massachusetts Institute of Technology, studied 15 frost-susceptible soils and about 40 chemical additives for a period of 3 years in which chemical additives were classified as void pluggers, cements, aggregants, dispersants, and waterproofers. The conclusion was reached that although waterproofers show promising results, they are not economically compatible with other engineering stabilization methods. Since then, many new chemicals have been presented, with smaller required amounts to be used and many improvements and modifications have been made on chemicals previously tried. Waterproofers have received relatively more attention, and considerable effort has been made to produce, improve, and introduce them.

In the waterproofing mechanism the positively charged end of the organic molecule is attached to the negative surface of a fine soil particle, with the opposite end being hydrophobic, repelling water entering soil capillaries, thus making the soil particles nonwettable by water. Among the soil waterproofers which have been evaluated as soil stabilizers are Alkyl Chlorosilanes Soliconates and Quarternary ammonium salts having a cation-active nitrogen group and a long-chain aliphatic groups with 8 to 22 carbon atoms. Waterproofers have no beneficial effects on soil treated and cured but not subjected to water (10). Waterproofers provide soils no strength, but rather help them retain their dry strength in the presence of water (10).

4. The Chemical Used

The chemical used in this study is one of the most recently developed soil waterproofing agents, "4-terf-Butylpyrocatechol" or simply TBC as referred to henceforth in this study. It is a light brown to white solid and in 85-15 percent aqueous solution, with a phenolic odor, and has the following structural formula:



There has been some discussion on how TBC is adsorbed onto soil surface and the mechanics by which the soil is rendered waterproof (6). It is almost agreed that the adsorption is the result of a chemical reaction between TBC and materials presented in the soil. Studies indicate that the chemical is adsorbed on the surface of soil particles through aluminum complexing with the OH groups of TBC (6). The Carbon-Hydrogen group, at the opposite end of the TBC structure, then protrudes from the surface and is hydrophobic in nature, and repels water. Several other secondary reactions have also been reported (6).

The choice of using TBC in this study was not arbitrary. After extensive studies it was found that no other material presently available was effective over as wide a range of soils as TBC. A disadvantage of chemical waterproofers, as mentioned by Lamb (9), the economy, is completely compensated for by the very small required amount of TBC to be employed.

The basic function of TBC in soil is to limit water absorption by the soil. Generally, the most suitable soils for treatment with TBC are those that are silty in nature and contain less than about 40 percent clay. The amount of TBC to be used, depending on the type of soil, varies from 0.05 percent to 0.10 percent according to the dry weight of soil. Figure 2-1 gives these percentages, based on plactic index and unconfined compressive strength of the soil compacted at optimum moisture (5). Figure 2.1 may also be used to determine if a soil is suitable to be treated with TBC. The suggested method for treatment is to add a sufficient amount of TBC to the water and use the mixture to bring the soil to its optimum moisture. The soil should then immediately be compacted and allowed to cure for seven days. It is also suggested that the curing take place, preferably at 30 to 50 percent relative humidity and about 70°F temperature. These given conditions are not necessary but help to get slightly better results (5). In this study it has been attempted to employ the chemical TBC at optimum amounts, and work closely to required conditions of treatment as previously determined (5).

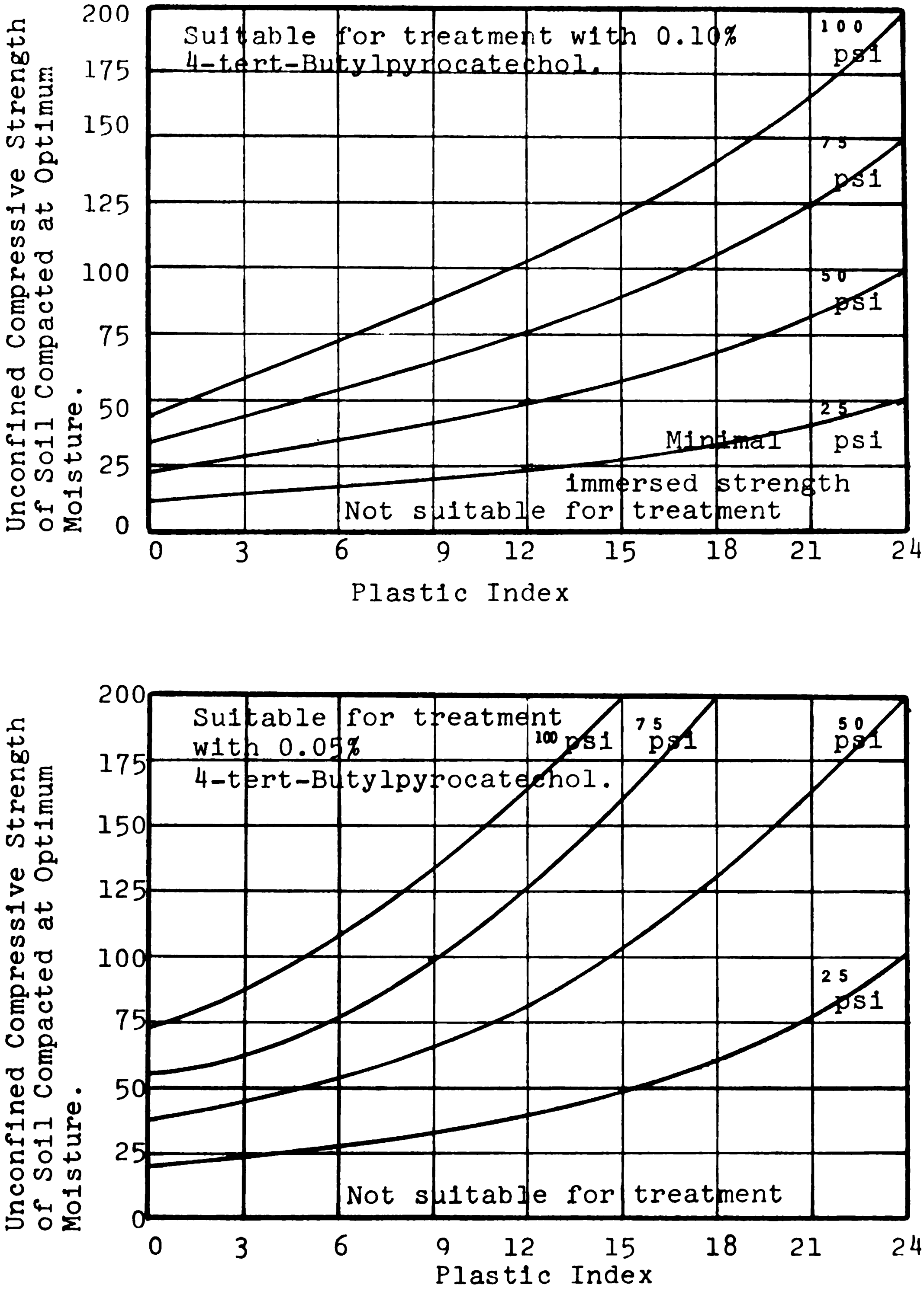


Figure 2.1.--Nomograph for Determination of Suitability of Soils for Treatment with 0.10% and 0.05% TBC.

CHAPTER III

SOILS USED AND SAMPLE PREPARATION

Two soils were used in the major portion of this study. The first, a highly frost-susceptible soil, Iowa Silt, was brought from Iowa. This soil will be referred to as Soil #1. The second, a less frost-susceptible soil with relatively higher clay content, was taken from the vicinity of East Lansing, Michigan, and will be called Soil #2. The properties of that portions of these soils passing #4, U. S. Standard Sieve, are given in Table 3.1.

TABLE 3.1.--Properties of Soil #1 and #2.

Properties	Soil #1	Soil #2
Sand Particle %	12	35
Silt Particle %	72	37
Clay Particle %	16	38
Max. Compact.density P.C.F.	126.5	134
Optimum water content %	14	15
Max. Dry Density P.C.F.	111	117
Liquid Limit %	25	27.3
Plastic Limit %	22.5	15.8
Plasticity Index %	2.5	11.5

Grain size distribution of these soils as determined by mechanical and hydrometer analysis (A.S.T.M. D-422-63) is shown in Figure 3.1.

Soil samples were prepared using the Harvard compaction equipment (17). The Harvard mold is 1.313 in. inside diameter and 2.816 inches long. Its volume is 1/454th of cubic foot, which makes the weight of a compacted sample in grams, numerically equal to its unit weight in pounds per cubic feet. Using the Harvard method, the optimum moisture and weight of each sample in grans (optimum unit weight in Pcf.) were determined. The samples then were molded at the optimum moisture. To insure uniformity of the soil-water, the mixture was thoroughly mixed and stored under a cover of aluminum foil for a period of eight hours. For treated samples 0.1 percent of TBC, based on the dry weight of soil, was used. The chemical was added to the water in sufficient amounts, and the optimum amount of chemical-water was added to the soil. The water used for all samples was distilled, deaered, and deionized standard.

In this study a total of 348 samples were prepared. To produce a few samples as control, the Harvard method was used. For molding samples in large numbers, the Harvard hammer was replaced with a known volume weight relationship. The exact amount of soil was placed into a collared mold and compacted from one end by downward motion of a brass cylinder, pushing the soil to the determined height in the

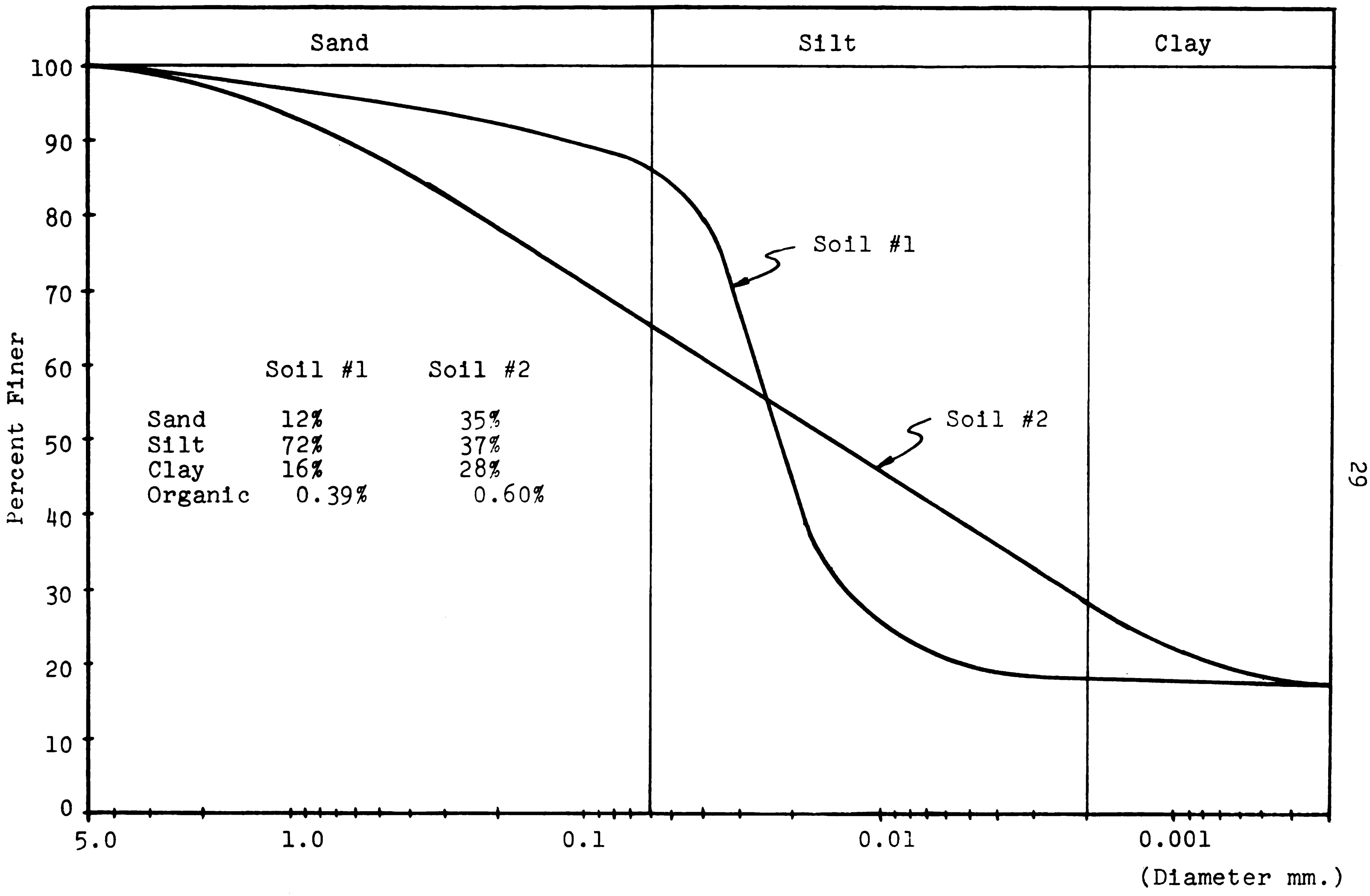


Figure 3.1.--Grain Size Distribution Curve for Soils #1 and #2.

mold. The motion of the cylinder and the required force were provided by a standard Marshall machine (A.S.T.M. D-1559) with the vertical speed of two inches per minute. To remove the samples from the mold, in either case, the Harvard extractor was employed. Compaction of soil from the top in the Harvard mold yields a compaction which is in very close agreement with that in field, using a sheepsfoot compactor (17). The molded specimens were placed in styrofoam boxes covered with plastic sheets. This was done to maintain uniformity in exposing the treated samples to the laboratory temperature and humidity. The entire duration of each sample preparation extended to as much as 10 hours, during which period the mixture of soil-water, and compacted samples were kept under similar conditions. For each treated sample, an untreated sample was made and kept under similar conditions. Following the sample preparation, all samples were placed in a moist room and exposed to the following conditions: 50 percent relative humidity and 70°F temperature for seven days. The humidity and temperature of the moist room were continuously recorded and attempted to be kept constant for the entire period of this study. Treated samples were marked as T_i and untreated samples as U_i; the varying indices i being the same for each pair of samples prepared and stored under similar conditions. At the end of the required period of seven days, part of the specimens were removed for the start of lengthy tests, with the additional specimens left for secondary tests on the soils and secondary properties of the chemical. Following sample molding a pair of samples, T_i and U_i, were wrapped in plastic sheets and aluminum foil to obtain a comparison base for the effect of a closed system of curing of the soil chemical.

In connection with these studies, seven additional soils were used to examine further properties of the chemical soil-waterproofer. These soils were referred to as soils #3 through #9. Their treatment was exactly like that of soils #1 and #2, and their properties are given in Table 3.2.

TABLE 3.2.--Properties of Soils #3 through #9.

	Soil						
Properties	#3	#4	#5	#6	#7	#8	#9
Sand %	24	48	14	42	6	5	61
Silt %	40	31	66	35	75	59	23
Clay %	36	21	20	23	19	36	16
Max. γ_w PCF.	130	142	133	143	120	129	127
Opt. w %	17	15	16	13	15	17	14
Max. γ_d PCF.	111	123	115	127	105	110	112
L.L. %	26	33	21	23	31	21	19
P.L. %	15	19	15	18	21	16	--
P.I. %	11	14	6	5	10	5	--

Soils #3 through #9 vary from well graded to poorly graded soils. Their grain size distributions are shown in Figure 3.2. Organic content of all soils used, except Soil #9, is relatively low and insignificant. The organic contents are given in Table 3.3.

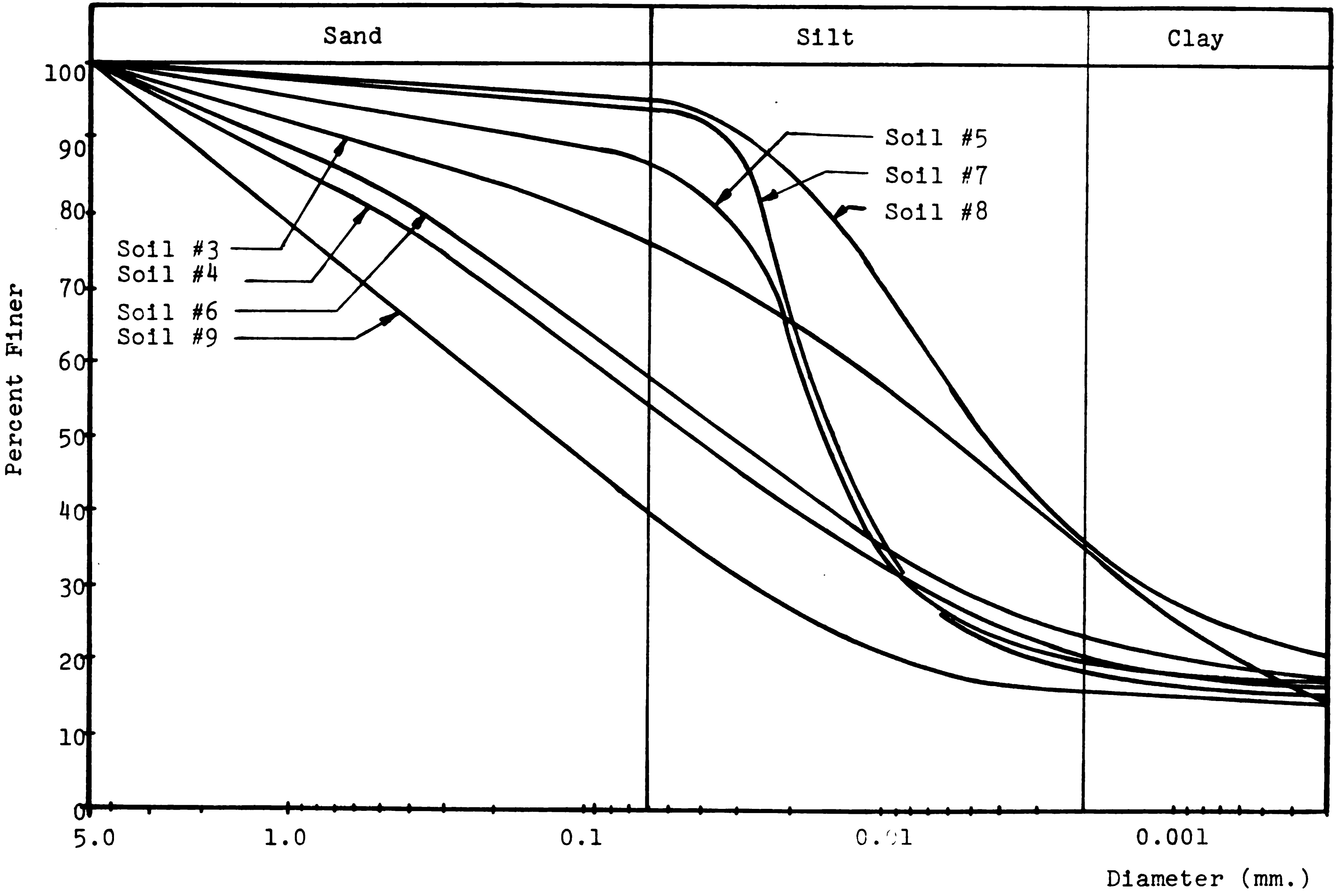


Figure 3.2.--Grain Size Distribution Curve of Soils #3 through #9.

TABLE 3.3.--Organic Content of the Soils Used.

Soil	#1	#2	#3	#4	#5	#6	#7	#8	#9
Organic Content %	0.39	0.60	0.80	0.24	0.32	0.24	0.31	0.25	1.67

CHAPTER IV

EQUIPMENT AND TEST PROCEDURE

1. Equipment

A great portion of this study was concentrated on the observation and measurement of the freeze-thaw-dependent properties of the soils under consideration. By the means of specially designed freezing chambers, and for up to 20 cycles of freeze-thaw, the water absorption, submerged and unsubmerged strength, and vertical expansion of soils due to ice lens growth were determined. To obtain comparative results, the entire study was carried out with treated and untreated soils, with emphasis on maintaining the procedure, conditions, and time of different stages of tests, exactly the same. Two types of tests, Open System and Closed System, were carried out. For each system of freezing a different freezing unit was designed.

For the Open System, as shown in Figure 4.1, the freezing unit consisted of a double-deck box, with outside dimensions of 22 by 16 and 12 inches high. Soil specimens were placed on the upper deck, with the lower deck serving as a water reservoir. To maintain water in the reservoir unfrozen for a desired temperature and length of time, a number

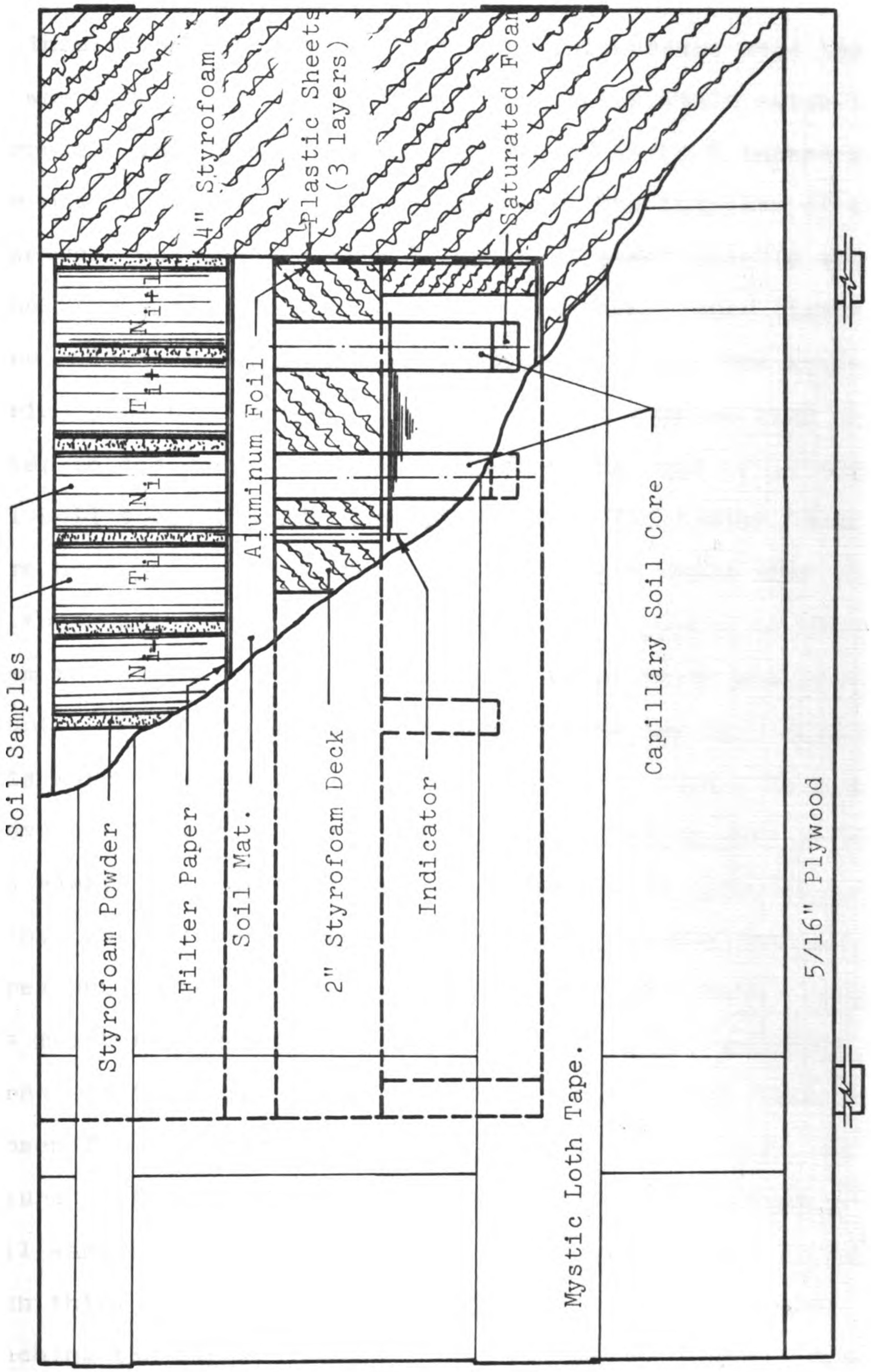


Figure 4.1.--Open System Freezing Unit.

of insulating materials with varied thicknesses were tested; it was found that styrofoam 4 inches thick would serve the purpose. This yielded a useful area of 14 by 8 inches with the maximum capacity of 66 specimens. The interior of the reservoir was covered with 3 layers of sheet plastic and a final layer made from aluminum foil. These cover liners were able to maintain the unit water-tight for the entire period of study. The connection of soil samples with the water in the reservoir was provided by the aid of 18 vertical soil cores placed in rubber tubes. The rubber tubes were hung inside the reservoir, with their upper ends fixed at the top and the lower ends capped with pieces of saturated foam to retain the soil cores. The water level was kept constant at 2-1/2 inches below the bottom of the soil samples. This water level provided a minimum of two inches free water above the bottom of the rubber tubes, insuring that water was always available for the soil samples by capillary suction. Water from the reservoir could penetrate the soil cores upward to the free water level by hydrostatic pressure. The moisture movement above this level was by capillary forces in the cores. The soil to be used in the cores was chosen from optimum available capillary soil (silt). To insure uniformity in moisture available at the bottom of soil samples, the samples were placed over a layer of 3/4 inch thick soil mat, covered with filter paper. Water reaching the top end of soil cores could move in all directions providing a uniformly moist mat for all the samples, treated or untreated. Moisture content was checked by taking water-content samples from different points of the soil mat, the water content being 28.5 ± 0.2 percent. The soil used in the mat was the same soil used in the cores, possessing capillarity and not interfering with or altering moisture movement to the specimens and/or freezing fronts. Since it was desired to introduce the top end of the soil samples only to the freezing temperature, all the seams of the freezing chamber were covered with impervious tape, making the unit air-tight from all directions except from the top. Measurements of the water level were made by means of a 10 in. long transparent tube, 3/32 in. inside diameter, dipped into the reservoir through a separate rubber tube installed in the upper deck. When the water level inside the tube became the same as that of the reservoir, the upper end of the tube was clamped, holding the water in the tube. The tube was then taken out and the water level could be checked with the reference on the tube. The hole was covered with filter paper and then covered with about three inches of styrofoam powder before being introduced to freezing temperature.

In the Closed System, the freezing unit was quite similar to that of the Open System, but without the water reservoir and soil mat. It was again made with a styrofoam sheet two inches thick. The outside dimensions of 18 by 16 in. and 5 in. high yielded a usable inside area of 14 by 12 in. and a maximum capacity of 108 specimens. Both units, Open and Closed Systems, were supported by strong wooden boards, standing on two transverse legs, for convenient handling and moving.

The freezing apparatus was a convenient model V-120 Kelvinator freezer, modified for this study. To maintain a constant temperature without movement of air mass, the freezer was divided into cells of desired sizes. This division was particularly important for introducing the specimens to the desired and steady conditions of individual cells, isolated from each other and from outside constraints. Horizontal dividers were standard freezer shelves but vertical dividers and front walls were constructed from 2 in. thick styrofoam. Brass wire handles and 3/16 in. holes were provided in the front walls to place thermometers on the freezing units. The entire freezer was defrosted and cleaned before each cycle of freezing. This was necessary to stop ice layer build ups and increases in air humidity.

Harvard compaction equipment, sometimes referred to as "miniature compaction device" devised at Harvard University, was utilized for sample compaction (17). This equipment is not standard equipment, but has many advantages over all standard compaction equipment, especially where large numbers of samples need to be prepared and tested. Considering the relatively small amount of material and time needed, in comparison with other methods, and the results in close agreement with field compactions, it can be believed that this equipment will become standard and widely popular in the near future. For the large number of samples needed for studies such as this, Harvard equipment was the only practical equipment.

The Marshal testing equipment is a standard device for determination of stability of asphaltic concrete (A.S.T.M. D-1559). In this study an AP-107 Model, Soil Test Marshal compression machine was employed. The vertical speed of the piston of this equipment is two inches per minute and may be compared to the speed of the moving roller in the field.

The moist room is a 8 1/2 x 17 x 8 foot space containing an air conditioning unit, heater, temperature relay, humidity relay, a controller unit, a hand-operated wet-bulb-dry-bulb, and a model R/4A Durham/Bush automatic recorder. The recorder prints both temperature and humidity continuously over a single card against the time. Cards have a maximum capacity of 30 hours and were replaced twice with each cycle of freezing.

For observation of rate and extent of ice lens formation, a chamber with a capacity of eight soil cores was used. This chamber was designed and used by Dr. G. H. Brandt (2) at Soil Laboratories of Dow Chemical Company. This chamber is shown in Figure 4.2. Temperature gradient in this chamber was imposed by two aluminum plates, the top one being below

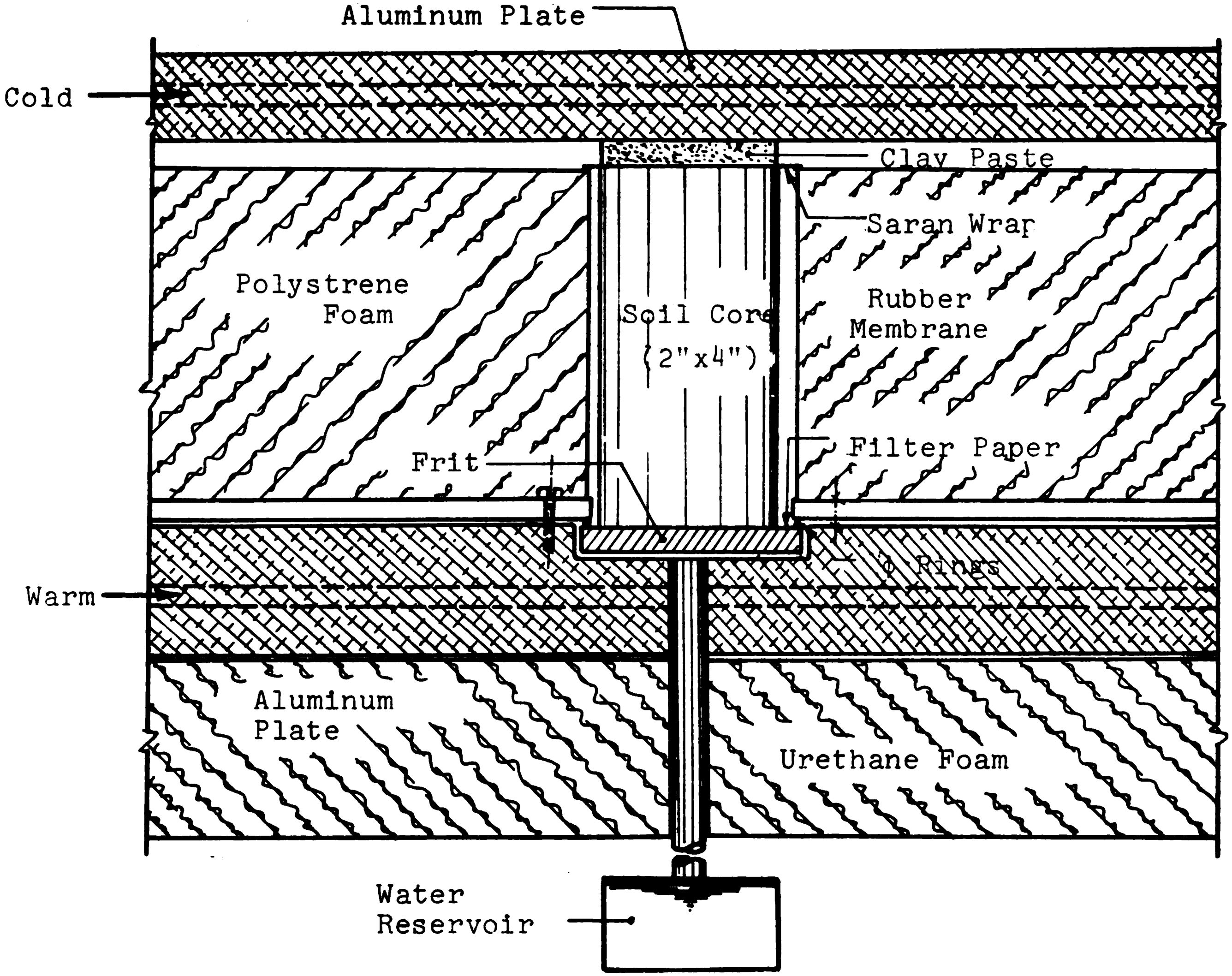


Figure 4.2.--Apparatus for Growing Ice Lens Growth Measurements.

zero. Samples were supported by frits (Figure 4.2), mounted in the bottom plate. Frits were connected to water reservoir. Soil Cores measuring 2" by 4" were jacketed by rubber membrane, surrounded by polystrene foam, styrofoam brand plastic foam, and capped with plastic wrap film to prevent moisture loss. To provide complete contact with the cold platens, clay paste was placed on the top of samples. Permeability of frits was sufficiently high to not limit water adsorption by soil cores. To assist water conduction, a filter paper was used underneath the soil cores. Temperature control units were Coleman coolers and Magna-set temperature control devices that activate coolant flow through the baths. The constant temperature refrigerant was then circulated continuously through the platens. The temperature of platens was controlled within about ± 0.15°C. Five thermocouples were placed within two centimeters of height of each core. After a test was run, the IBM 1130 computing system plotted temperature profiles and cumulative water absorption for each soil core. Changes in temperature profile were then compared and correlated with changes in water absorption rate. Soil #1 with 0.1 percent TBC by weight treatment was used, and the procedures for core preparations and tests were the same for treated and untreated samples.

2. Procedure

In the entire study, from the beginning of sample preparation to the last cycle of freezing and thawing, an attempt was made to duplicate the conditions occurring in nature. Samples were prepared from disturbed soil, compacted from the top only, and using Harvard compaction equipment and Harvard compaction methods. The Harvard compaction procedure is believed to yield a compaction very close to that obtained in field using a sheepsfoot roller (17). The molded samples were placed in the moist room for seven days. It was desired to expose the soil samples to a temperature of 68°F and 50 percent relative humidity. Curing of the TBC treated soil samples is not too sensitive to variation of relative humidity ranging from 35 to 55 percent and with temperature changes of wide range (5). The temperature and relative humidity of the moist room were continuously recorded. Pairs of treated and untreated soil samples were prepared and cured in groups under the same conditions. At the end of the proposed curing period, the samples were transferred to the freezing boxes. To avoid any horisontal moisture movement from one sample to the next, samples were separated with small gaps filled with styrofoam powder. The sample separation was especially important for the case of treated and untreated adjacent samples. Before placing the freezing boxes in the freezing cells, they were stored under the laboratory conditions for 24 hours, to absorb moisture by capillary action. From each group of soil samples a representative sample was taken for strength and water content tests and the remaining samples were placed in the cells for freeze-thaw studies.

Freezing temperature was chosen and applied as -12°C ± 0.10 (+10.4°F). The choice of the temperature was partially due to extensive studies and partially due to equipment limitations. The temperature was applied on the top surface of the molded specimens only, keeping the temperature of the water in the reservoir above freezing. The reservoir temperature was measured to be +22.5°C before freezing, and +3.5°C after the end of 24 hours of freezing periods. Placing of the freezing boxes in the freezer cells raised the established -12°C temperature to +16°C. It took about 11 hours until the freezer temperature was back to normal of -12°C. A temperature profile of this period is shown in Figure 4.3. At the end of each freezing period, the freezing units were taken out of the cells, covered with plastic sheets, and left under laboratory room conditions; ± 22.5°C temperature and ± 45 percent relative humidity. To obtain data on water absorbtion resultant of freezing, the samples to be tested were taken out of freezing boxes immediately upon removal from the freezer. The frozen samples were wrapped in at least three layers of plastic sheet and were left under laboratory room conditions until the ice melted. This action on frozen samples is equivalent to field conditions, in which the underlying ice layers have not melted, with temperature rising at the surface.

Test conditions were duplicated, with some variations, in the data for two different series of soil samples, Series A

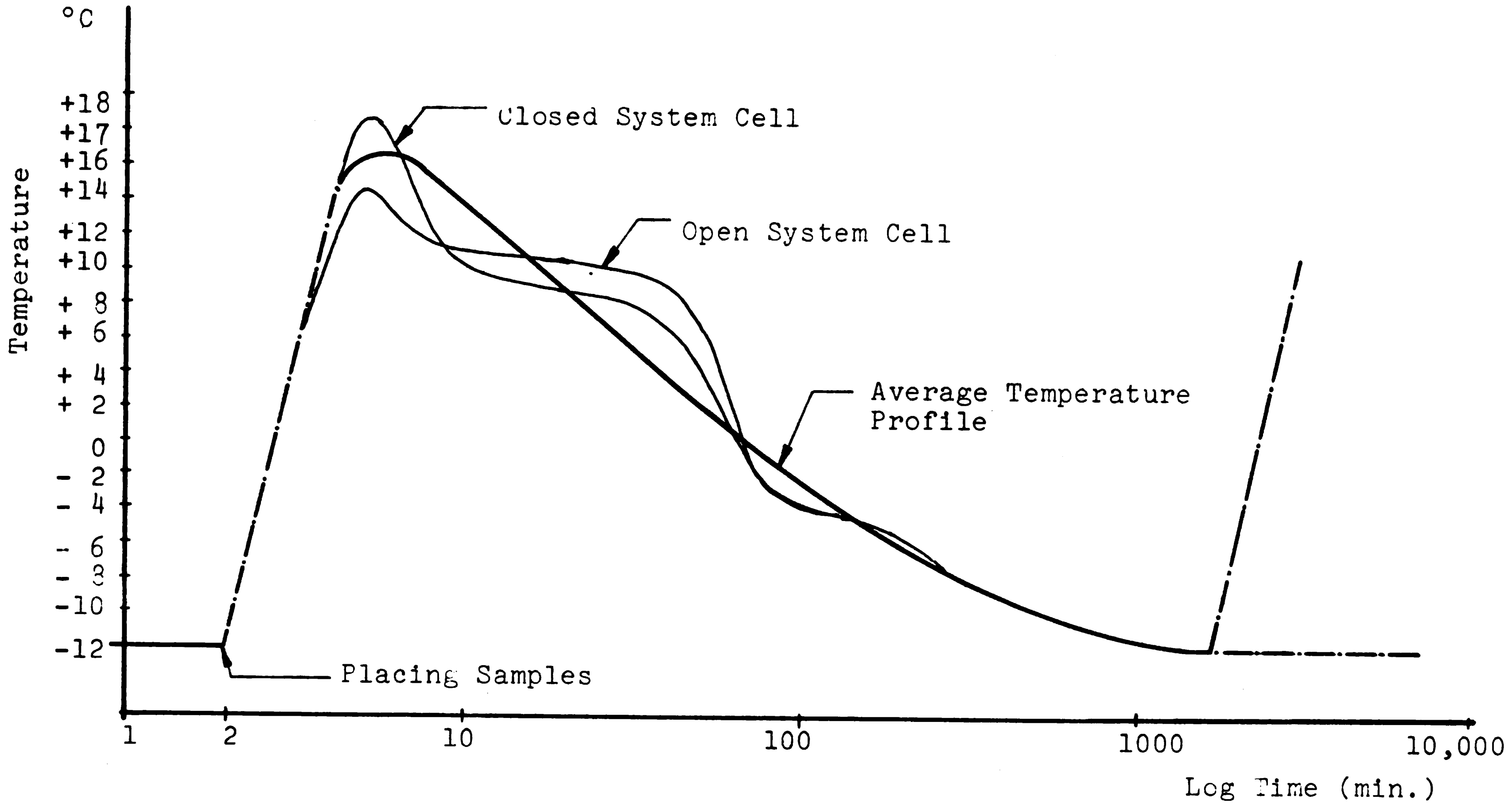


Figure 4.3.--Temperature Profile Across Soil Samples.

and Series B. For Series A, before the first cycle of freezing, untreated samples were exposed to capillary moisture for 24 hours, while the treated samples were submerged for the same period of time. This action brought the water content of all the samples to a limit at which complete freezing could occur in the first cycle. The reason for not submerging untreated samples was that they lost all their strength within very few minutes and disintegrated, while the treated samples retained their physical shapes completely. The water level in the reservoir for this series was once brought to the maximum level of two inches below the bottom of the samples, at the beginning of the test, and no water was added until the supply was exhausted following six cycles of freezing. For Series B of the study, samples were treated in the same manner as in Series A, mainly left for 24 hours to absorb water from the bottom by capillary action. The water table was measured after each cycle of freezing, and brought to the original level, by adding the necessary water to the reservoir. For Series B, the samples had varied water contents before freezing started but yielded comparable results for treated and untreated soils, being treated and introduced to exact conditions of moisture absorption and freezing.

Heave, or expansion of the samples, was measured after each cycle of freezing, from a fixed base established two inches above the top of freezing boxes. The amount of heave was negligible for samples frozen in Closed System. The expansion of the samples in Open System gave a good indication of ice lense growth in the treated and untreated samples of Soils #1 and #2.

As a preliminary study, measurement of heave and water content were made on all the nine soils, but only for two cycles of freeze-thaw.

Since the curing conditions for soil-chemicals may result in varied soil properties (5), a limited study was conducted to observe the effect of Open System curing and Closed System curing on treated soil samples. A pair of samples were prepared and cured differently, then submerged in distilled water for a period of six months. It was observed that a series of shrinkage cracks appeared on the surfaces of both samples following approximately three weeks' submergence. These cracks appeared very similar to those occurring on cut trees subjected to dry weather. To study the soil cracks, some time was spent on the variation of moisture content of soil samples when submerged under water.

Since some chemicals, when used with soil, show the property of retaining water, a limited study was carried out on the chemical used with all the nine soils. Water retention is a very helpful property for the soils used in arid areas in connection with construction of airports and highways.

In the computerized portion of the study, samples were subjected to capillary water action for 24 hours. Platens cooled rapidly but it took approximately six hours to establish the desired temperature across the soil cores. The temperature gradient was 0.6°C/Cm, with the upper plate at +3°C and the lower plate at +3°C. One-tenth percent chemical was used with frost-susceptible Soil #1 only. These treated samples were again paired with untreated samples. This set of soil samples was subjected to 10 Cm of tension (equivalent suction applied to the reservoir water) for approximately 240 hours freezing period. The purpose of this part of the study was to measure continuously the water migration to freezing front during a single freezing cycle. Water movement was measured up to ± 0.01 CC.

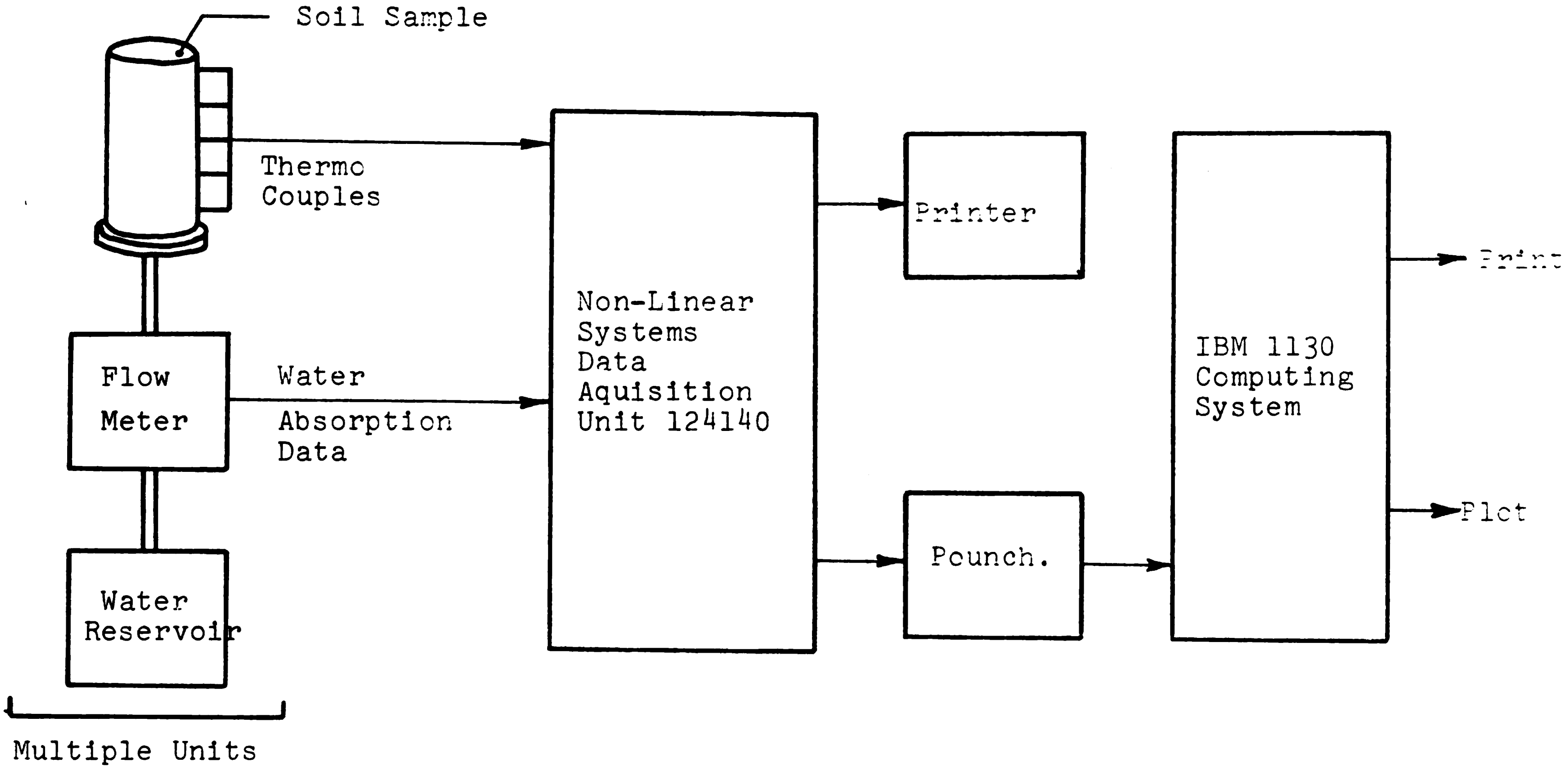


Figure 4.4.--Automatic System for Temperature - Water Flow Records.

CHAPTER V

EXPERIMENTAL RESULTS

1. Heave

Studies and measurements of heave for treated and untreated soils were conducted with two groups of samples. The first groups consisted of a pair of treated samples and one untreated sample of each of the nine different soils for two cycles of freeze-thaw. The second group included samples of Soils #1 and #2 and the study was carried out for as many as 20 cycles of freeze-thaw. The studies on Soils #1 and #2 were carried on with two series of soil samples. In the first series of samples, called Series A, before the start of the first cycle of freezing, untreated samples were subjected to capillary water with zero tension for a period of 24 hours but the treated samples were submerged in water for the same period, the main purpose being to bring the water content of all the samples to a limit at which freezing could take place on the first cycle of freezing. A similar test was conducted on another series of samples, called Series B, but with the difference that all treated and untreated soil samples were subjected to capillary moisture with zero tension. Studies on Series B, although started with varied water content of samples at first freezing cycle, yielded comparative results for treated and untreated soil samples. Heave studies included the above-mentioned group one and Series B of group two. The expansion of the soil samples upon freezing and their contraction following the thaw period were recorded twice for each cycle. The average duration of freezing period was 24 hours and thaw period was 12 hours, under laboratory conditions. Length changes were measured with a vernier caliper, with an accuracy of ± 0.016 inch from a base line set at five inches above the bottom of samples. The original height of samples being 2 26/32 inch yielded a free distance of 2 6/32 inch between the tops of samples and the base lines. Variations of sample heights were calculated by measuring variations of the free distance and subtracting from five inches total distance. The calculated sample heights are given in Tables 5.1 through 5.4. To simplify computations, all the values are multiplied by 32. The total, average, and cumulative values are computed and presented in the same tables. Table 5.1 gives these values for treated samples made of Soil #1. Results for untreated samples of Soil #1 are given in Table 5.2. The second column from the left of each table gives the length change of the samples after 24 hours exposure to free moisture in freezing boxes. This portion of the study was conducted for both Open and Closed Systems of freezing but expansion of the Closed system was not

TABLE 5.1.--Values of Heave of Treated Samples of Soil #1, in Open System.*

Sample	Soaked (24 hrs.)	Cycles of Freezing														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
O-T$_5$-1	0	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-2	0	+6	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-3	1	+1	+14	+ 4	---	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-4	0	0	+ 2	+ 4	+ 2	+ 5	+ 8	---	---	---	---	---	---	---	---	---
O-T$_5$-5	0	-1	+ 3	+ 2	+ 3	+ 5	+ 6	+11	+ 2	+ 9	+ 4	+ 1	+ 4	+ 4	+10	---
O-T$_5$-6	0	0	+ 2	+ 3	+ 1	+ 3	+ 6	+ 6	- 1	+10	+10	+ 4	+ 6	+ 7	+11	+ 3
O-T$_5$-7	0	0	0	+ 1	+ 2	+ 3	+ 5	+ 5	0	+ 6	+ 7	---	---	---	---	---
O-T$_5$-8	0	+1	+ 1	+ 5	+ 3	+ 3	+ 5	+ 4	+ 2	+ 7	+ 4	+ 4	+ 5	+ 5	+ 7	+ 4
O-T$_5$-9	0	+2	0	+ 8	+ 9	+ 4	+ 7	+ 4	+ 4	+ 7	+ 7	+ 3	+ 2	+ 4	+ 8	+ 9
Total	+1	+9	+22	+27	+20	+23	+37	+30	+ 7	+39	+32	+12	+17	+20	+36	+16
Average	0.00	1.13	3.14	3.28	3.34	3.84	6.17	6.00	1.40	7.80	6.40	3.00	4.25	5.00	9.00	4.00
Cumulate	0.00	1.13	4.27	7.55	10.69	14.53	20.70	26.70	28.10	35.90	42.30	45.30	49.55	54.55	63.55	67.55

*Values in 1/32 of inch.

TABLE 5.2.--Values of Heave of Untreated Samples of Soil #1, in Open System.*

Sample	Soaked (24 hrs.)	Cycles of Freezing 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$O-U_5-1$	+1	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_5-2$	0	20	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_5-3$	+1	16	4	1	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_5-4$	0	16	3	2	9	2	1	---	---	---	---	---	---	---	---	---
$O-U_5-5$	0	4	10	4	12	5	3	5	6	12	11	6	6	7	5	4
$O-U_5-6$	+1	10	10	3	9	0	4	19	7	12	7	10	10	7	5	0
$O-U_5-7$	0	0	6	3	6	3	4	7	6	12	9	---	---	---	---	---
$O-U_5-8$	0	10	1	1	5	1	4	9	10	12	10	0	4	7	6	1
$O-U_5-9$	0	14	0	1	7	0	10	10	5	11	10	8	1	9	5	5
Total	+3	90	34	15	48	11	17	50	34	59	47	24	21	30	21	10
Average	---	11.25	4.85	2.14	8.00	1.84	2.84	10.00	5.90	3.39	4.26	6.00	5.25	7.50	5.25	2.50
Cumulate	---	11.25	16.10	18.24	26.24	28.08	30.92	40.92	46.82	50.21	54.47	60.47	65.72	73.22	78.47	80.97

*Values in 1/32 of inch.

TABLE 5.3.--Values of Heave of Treated Samples Made of Soil #2, in Open System.*

Samples	Soaked (24 hrs.)	Cycles of Freezing														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$O\text{-}T_5\text{-}1$	0	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O\text{-}T_5\text{-}2$	0	4	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O\text{-}T_5\text{-}3$	0	2	4	2	---	---	---	---	---	---	---	---	---	---	---	---
$O\text{-}T_5\text{-}4$	0	2	3	3	3	6	7	---	---	---	---	---	---	---	---	---
$O\text{-}T_5\text{-}5$	0	2	2	3	3	9	7	8	3	7	11	11	5	3	10	9
$O\text{-}T_5\text{-}6$	0	6	2	3	4	8	5	7	3	4	7	7	6	4	10	9
$O\text{-}T_5\text{-}7$	0	3	3	3	4	5	8	8	7	7	10	---	---	---	---	---
$O\text{-}T_5\text{-}8$	0	3	4	3	4	3	6	6	6	9	11	8	8	6	7	11
$O\text{-}T_5\text{-}9$	0	6	5	4	6	4	4	5	5	9	15	8	7	6	6	11
Total	---	30	23	21	24	35	37	34	24	36	54	34	26	19	33	40
Average	---	3.75	3.29	3.00	4.00	5.84	6.17	6.80	4.80	7.20	10.80	8.50	6.50	4.75	8.25	10.00
Cumulate		3.75	7.04	10.04	14.04	19.88	26.05	32.85	37.65	44.85	55.65	64.15	70.65	75.40	83.65	93.65

*Values in 1/32 inch.

TABLE 5.4.--Values of Heave of Untreated Samples Made of Soil #[illegible], In Open System.

Samples	Soaked (24 hrs.)	Cycles of Freezing														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0-U_5-1	0	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
0-U_5-2	0	6	---	---	---	---	---	---	---	---	---	---	---	---	---	---
0-U_5-3	0	5	1	1	---	---	---	---	---	---	---	---	---	---	---	---
0-U_5-4	0	5	1	0	8	4	8	---	---	---	---	---	---	---	---	---
0-U_5-5	0	7	0	---	4	2	7	7	7	13	20	9	5	4	10	11
0-U_5-6	0	4	2	1	1	2	7	7	8	12	15	9	8	5	10	12
0-U_5-7	0	9	3	2	4	2	7	7	10	11	13	---	---	---	---	---
0-U_5-8	1	2	3	2	6	0	6	5	9	11	12	11	4	3	8	12
0-U_5-9	0	7	1	1	9	3	7	9	13	13	16	12	7	5	6	9
Total	---	45	11	7	32	13	42	35	47	60	76	41	24	17	34	44
Average	---	5.62	1.57	1.00	5.34	2.17	7.00	7.00	9.40	12.00	12.50	10.25	6.00	4.25	8.50	11.00
Cumulate		5.62	7.19	8.19	13.53	15.70	22.70	29.70	39.10	51.10	66.30	76.55	82.55	86.80	95.30	106.30

measurable and is not presented here. The cumulative values of these tables are shown graphically in Figure 5.1. It may be noted that the cumulate heaves of both treated and untreated groups assume the path of an S-shaped curve. This means that one can formulate the curves and use the formulas to compute total heave of a soil for any desired cycle of freezing.

Tables 5.3 and 5.4 with Figure 5.2 present similar data for Soil #2. Test procedure, measurements, and all the data for Soil #2 are similar to those of Soil #1 as described above for Series B samples. To explain the exact behavior of the soils, the expansion and settlement of all the samples were calculated and summarized in Tables 5.5 through 5.8. In these tables the length change of samples with growing ice lenses, melting of ice, and settlement of samples due to the failure caused by extensive water content are shown. The data in Table 5.5 through 5.8 are graphically illustrated in Figures 5.3 and 5.4. All of the values in the tables and figures have been multiplied by a factor of 32. Table 5.5 shows length change for treated samples of Soil #1. Data for untreated samples of Soil #1 are given in Table 5.6. The calculated average for each cycle in the above tables may be seen in Figure 5.3. Tables 5.7, 5.8, and Figure 5.4 show similar results for Soil #2. Pictures of frozen samples of some of the soils are shown in Figures 5.5 and 5.6.

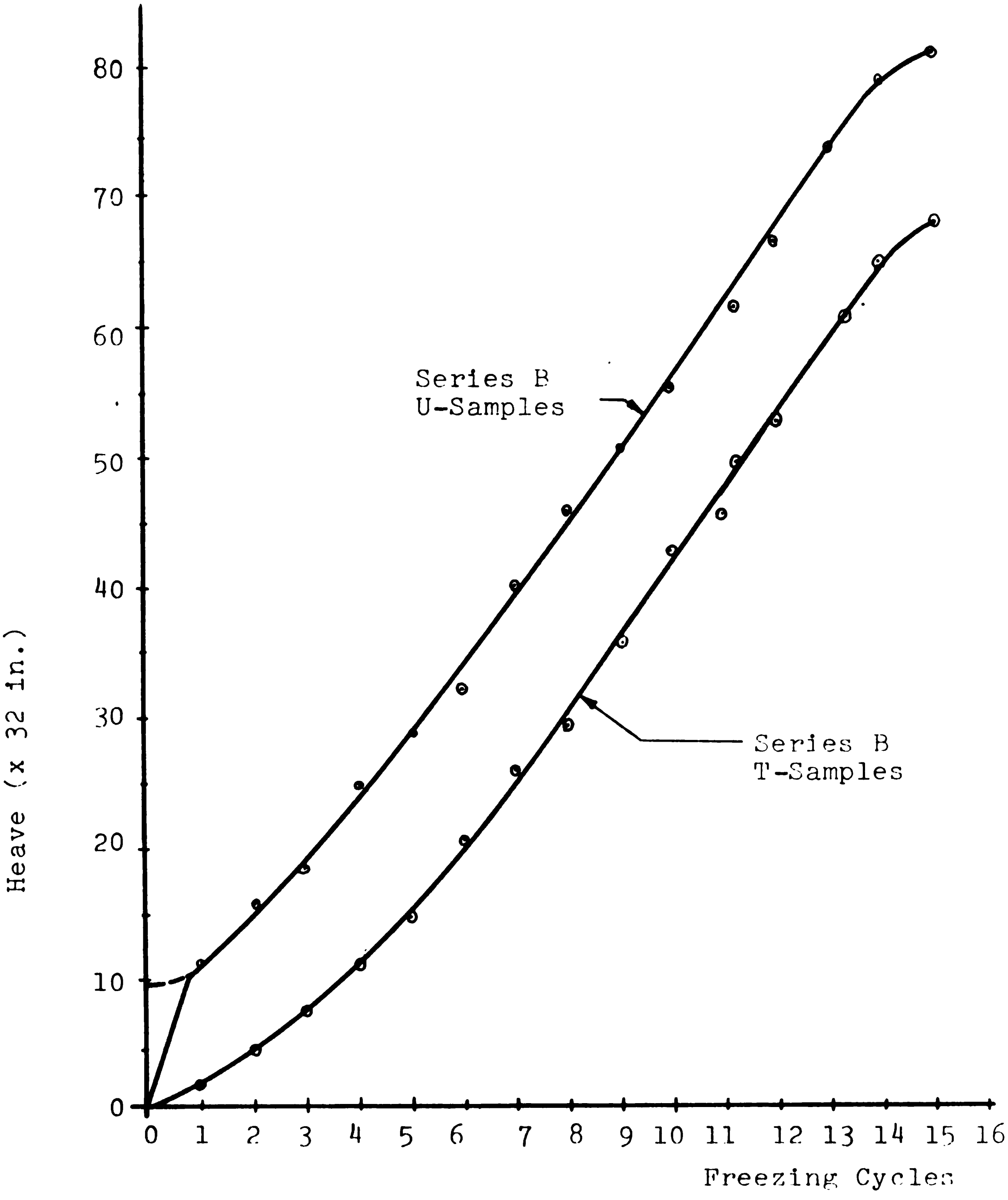


Figure 5.1.--Cumulative Heave Values of Frozen Soil #1

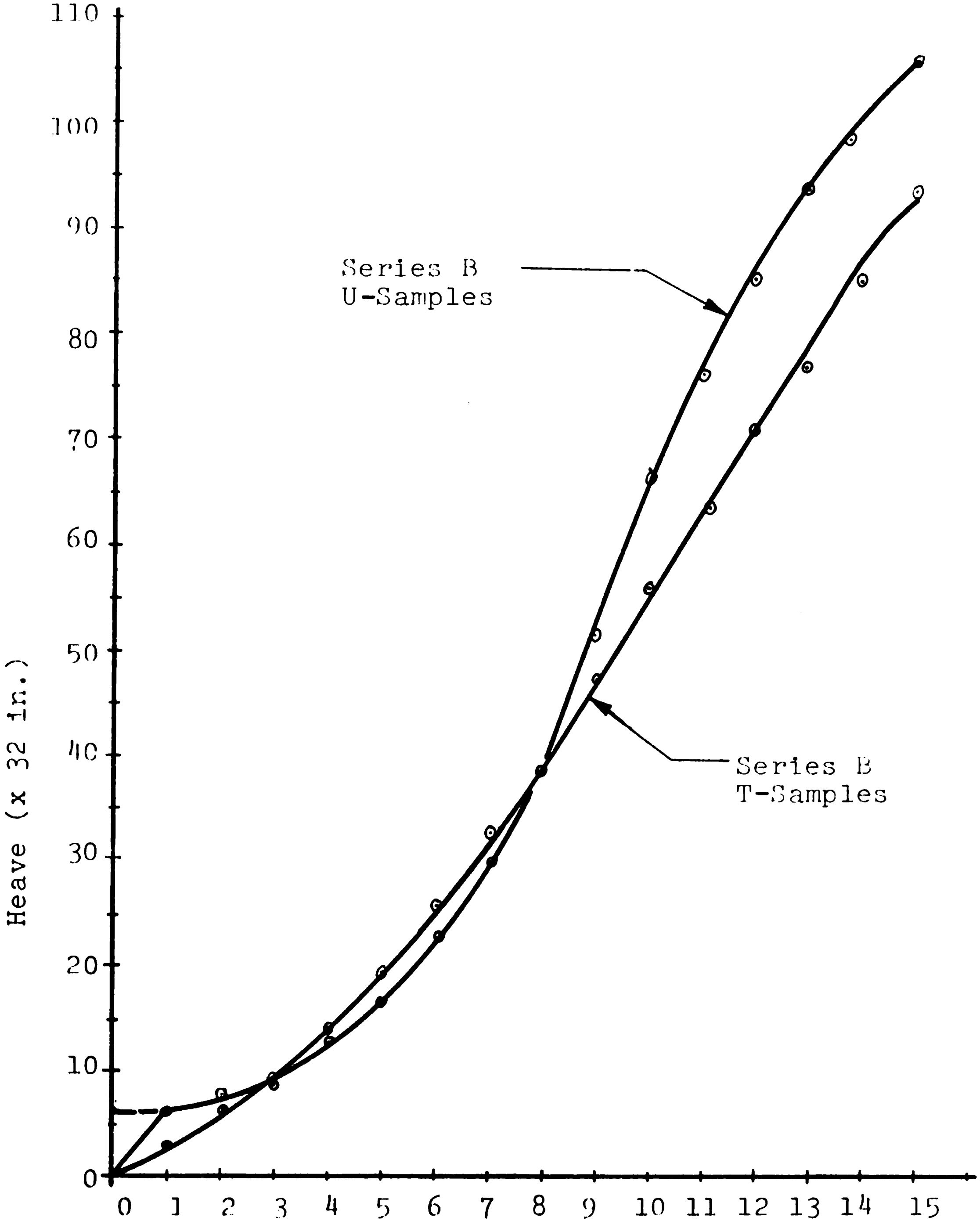


Figure 5.2.--Cumulative Heave Values of Frozen Soil #2.

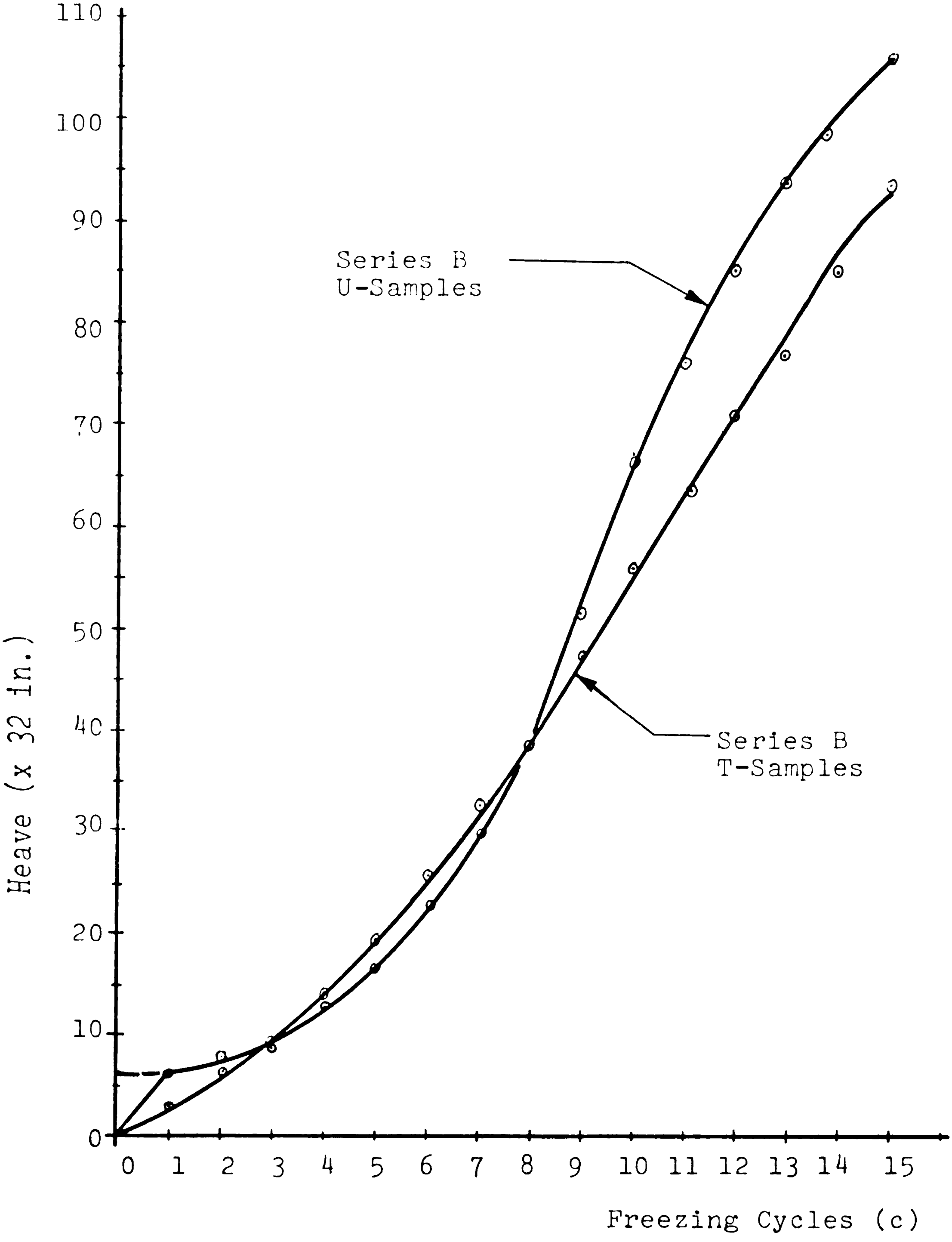


Figure 5.2.--Cumulative Heave Values of Frozen Soil #2.

TABLE 5.5.--Length Change of T-Samples of Soil #1, in Open System.*

Sample	Original Ht.	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
		Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.
O-T_5-1	1-26/32	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_5-2	1-26/32	+6	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_5-3	1-26/32	1	0	14	-15	4	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_5-4	1-26/32	0	0	2	- 4	4	- 2	2	- 2	5	- 6	8	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_5-5	1-26/32	-1	0	3	- 2	2	- 3	3	- 3	5	- 4	6	- 4	11	-13	2	- 6	9	-11	4	- 9	1	- 6	4	- 4	4	- 5	10	-12	0	
O-T_5-6	1-26/32	0	0	2	- 3	3	- 2	1	- 1	3	- 4	6	- 7	6	- 7	- 1	- 3	10	-11	10	-10	4	- 8	6	- 7	7	- 7	11	-11	3	
O-T_5-7	1-26/32	0	0	0	- 1	1	- 1	2	- 2	3	- 3	5	- 6	5	- 6	0	- 6	6	-11	7	---	---	---	---	---	---	---	---	---	---	
O-T_5-8	1-26/32	1	0	1	- 4	5	- 5	3	- 1	3	- 3	5	- 5	4	- 5	2	- 4	7	- 6	4	- 5	4	- 5	5	- 5	5	- 7	7	-10	4	
O-T_5-9	1-26/32	2	0	0	- 5	8	- 6	9	7	4	- 4	7	- 7	4	- 4	4	- 5	7	- 7	7	- 6	3	- 2	2	- 3	4	- 4	8	- 9	9	
Total		+9	0	+22	-34	+27	-19	+20	-16	+23	-34	+37	-29	+30	-35	+ 7	-22	+39	-46	+32	-30	+12	-21	+17	-19	+20	-23	+36	-42	+16	
Ave.	2.813	1.25	0	+ 3.14	- 4.85	+ 3.85	- 3.17	+ 3.34	- 2.67	+ 3.84	- 9.00	+ 6.17	- 5.80	+ 6.00	- 5.10	+ 1.40	- 4.40	+ 7.80	- 7.21	+ 6.40	- 7.50	+ 3.00	- 5.25	+ 4.25	- 4.75	+ 5.00	- 5.75	9.00	-1.0	+ 4.	
Cum.		1.25	+ 1.25	+ 4.39	- .46	+ 3.39	+ .22	+ 3.56	+ .89	+ 4.73	+ .73	+ 6.90	+ 1.10	+ 7.10	+ 2.00	+ 3.40	- 1.30	+ 6.80	- .41	+ 3.99	- 3.51	- .51	- 5.76	- 1.51	- 6.26	- 1.26	- 7.01	+ 1.99	- 8.51	- 4.51	

*Values are multiplied by 32.

TABLE 5.6.—Length Change of U-Samples of Soil #1 in Open System.*

Sample	Original Ht.	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
		Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.
O-U$_5$-1	1-26/32	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U$_5$-2	1-26/32	20	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U$_5$-3	1-26/32	16	-14	4	- 5	1	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U$_5$-4	1-26/32	16	-12	3	- 5	2	- 3	9	-12	2	- 7	1	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U$_5$-5	1-26/32	4	- 6	10	-10	4	- 8	12	- 14	5	- 8	3	-13	5	-10	6	- 8	12	-13	11	-12	6	- 8	6	- 6	7	- 8	5	- 9	4	
O-U$_5$-6	1-26/32	10	-16	10	-10	3	- 7	9	-11	0	- 5	4	- 4	19	-13	7	0	12	-12	10	-17	10	- 8	10	-10	7	- 6	5	-11	0	
O-U$_5$-7	1-26/32	10	- 3	6	- 3	3	- 5	6	- 6	3	- 4	4	- 9	7	- 8	6	- 9	12	-10	9	---	---	---	---	---	---	---	---	---	---	---
O-U$_5$-8	1-26/32	10	-16	1	- 3	1	- 5	5	- 9	1	- 5	4	-	9	-11	10	- 8	12	-10	7	-12	0	- 7	4	- 6	7	- 7	6	- 9	1	
O-U$_5$-9	1-26/32	14	-12	0	- 3	1	- 6	7	-13	0	- 2	1	- 1	10	- 4	5	- 8	11	- 9	7	-11	8	-10	1	- 4	9	- 8	5	- 9	5	
Total		+90	-79	+34	-39	+15	-34	+48	-65	+11	-31	+17	-27	+50	-46	+34	-33	+59	-54	+44	-52	+24	-33	+21	-36	+30	-29	+21	-38	+10	
Ave.	2.816	11.20	-11.30	+ 4.85	- 5.56	+ 2.14	- 5.66	+ 8.00	-10.84	+ 1.84	- 5.17	+ 2.84	- 5.41	+10.00	- 9.21	+ 5.90	- 6.61	+ 3.39	-10.80	+ 4.26	-14.30	+ 6.00	- 8.25	+ 5.25	- 9.00	+ 7.50	- 7.25	+ 5.25	- 9.50	+ 2.50	
Cum.		+11.20	- .10	+ 4.75	- .79	+ 1.35	- 4.31	+ 3.69	- 7.15	- 5.31	-10.48	- 7.64	-13.05	- 3.05	- 9.26	- 3.36	- 9.97	- 6.58	-17.38	-13.12	-27.42	-21.42	-29.67	-24.42	-31.42	-23.92	-31.17	-25.92	-35.42	-32.92	

* Values are in inches and are multiplied by 32.

TABLE 5.7.—Length Change of T-Samples of Soil #2, in Open System.

Sample	Original Ht. (in.)	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
		Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.
O-T$_5$-1	1-26/32	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-2	1-26/32	4	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-3	1-26/32	2	- 3	4	- 1	2	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-4	1-26/32	2	- 2	3	- 2	3	- 3	3	- 3	6	- 5	7	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-5	1-26/32	2	- 3	2	- 1	3	- 3	3	- 3	9	-10	7	- 5	8	-10	3	- 3	7	- 6	11	-12	17	-13	5	- 6	3	- 3	10	- 9	9	
O-T$_5$-6	1-26/32	6	- 4	2	- 2	3	- 3	4	- 4	8	- 7	5	- 7	7	- 5	3	- 8	4	- 3	7	- 9	7	- 7	6	- 6	4	- 6	10	- 9	9	
O-T$_5$-7	1-26/32	3	- 4	3	- 1	3	- 4	4	- 4	5	- 5	8	- 8	8	- 8	7	- 8	7	- 6	10	---	---	---	---	---	---	---	---	---	---	---
O-T$_5$-8	1-26/32	3	- 4	4	- 2	3	- 4	4	- 4	3	- 4	6	- 6	6	- 5	6	- 6	9	- 0	11	-11	8	- 9	8	- 8	6	- 6	7	-10	11	
O-T$_5$-9	1-26/32	6	- 7	5	- 3	4	- 4	6	- 6	4	- 4	4	- 4	5	- 5	5	-10	9	-10	15	-14	8	- 7	7	- 9	6	- 6	6	- 8	11	
Total		+28	-27	+23	-12	+21	-25	+24	-24	+35	-35	+37	-30	+34	-33	+24	-35	+36	-34	+54	-46	+34	-36	+26	-29	+19	-21	+33	-36	+40	
Ave.	2.816	+ 3.50	- 3.86	+ 3.29	- 1.77	+ 3.00	- 4.17	+ 4.00	- 4.00	+ 5.84	- 5.83	+ 6.17	- 6.00	+ 6.80	+ 6.30	+ 4.80	- 7.00	+ 7.20	- 6.80	+10.80	+ 1.50	+ 8.50	- 9.00	+ 6.50	- 7.25	+ 4.74	- 5.65	+ 8.25	- 8.00	+10.	
Cum.		+ 3.50	- 0.36	+ 2.93	+ 1.22	+ 4.22	+ .05	+ 4.05	+ .05	+ 5.89	+ .06	+ 6.23	+ .23	+ 7.03	+ .73	+ 5.53	- 1.47	+ 5.83	- .97	+11.77	+ .27	+ 8.77	- .23	+ 6.27	- .98	+ 3.77	- 1.48	+ 6.77	- 2.23	+ 2.77	

TABLE 5.8.—Length Change of U-Samples of Soil #2, in Open System.

Sample	Original Wt. (in.)	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
		Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.	Pr.	Th.
$0\text{-}U_5\text{-}1$	1-26/32	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$0\text{-}U_5\text{-}2$	1-26/32	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$0\text{-}U_5\text{-}3$	1-26/32	5	- 4	1	0	1	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$0\text{-}U_5\text{-}4$	1-26/32	5	- 5	1	0	0	- 1	8	- 7	4	- 6	8	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$0\text{-}U_5\text{-}5$	1-26/32	7	- 6	0	0	---	0	4	- 3	2	- 4	7	- 6	7	- 9	7	- 9	13	-17	20	-16	9	-10	5	- 7	4	- 4	10	-17	11	
$0\text{-}U_5\text{-}6$	1-26/32	4	- 5	2	0	1	- 1	1	0	0	- 2	7	- 6	7	- 9	8	- 9	12	-11	15	-15	9	-14	8	-10	5	- 5	10	-10	12	
$0\text{-}U_5\text{-}7$	1-26/32	9	- 6	3	- 2	2	- 2	4	- 5	0	- 4	7	- 6	7	- 9	10	- 9	11	-11	13	---	---	---	---	---	---	---	---	---	---	---
$0\text{-}U_5\text{-}8$	1-26/32	2	- 3	3	- 2	2	- 3	6	- 5	0	- 5	6	- 6	5	- 6	9	-10	11	-10	12	-12	11	-11	4	- 4	3	- 5	8	- 9	12	
$0\text{-}U_5\text{-}9$	1-26/32	7	- 5	1	- 1	1	- 5	9	- 8	7	- 8	7	- 7	9	- 9	13	-10	13	-13	18	-16	12	-11	7	- 9	5	- 6	6	- 5	9	
Total		+45	-34	+11	- 5	+ 7	-12	+32	-28	+13	-29	+42	-31	+35	-42	+47	-47	+60	-62	+75	-59	+41	-46	-24	-30	+17	-20	+34	-36	+44	
Ave.	2.816	+ 5.62	- 4.85	+ 1.57	- .71	+ 1.00	- 2.00	+ 5.34	- 4.67	+ 2.17	- 4.84	+ 7.00	- 6.20	+ 7.00	- 8.40	+ 9.40	- 9.40	+12.00	-12.40	+15.20	-14.75	+10.25	-11.50	+ 6.00	- 7.50	+ 4.25	- 5.00	+ 8.50	- 9.00	+11.00	
Cum.		+ 5.62	+ .77	+ 2.34	+ 1.63	+ 2.63	+ .63	+ 5.97	+ 1.30	+ 3.47	- 1.37	+ 5.63	- .57	+ 6.43	- 1.97	+ 7.43	- 1.97	+10.03	- 2.37	+12.83	- 1.92	+ 8.33	- 3.17	+ 2.83	- 4.67	+ .42	- 4.58	+ 3.92	- 5.08	+ 5.92	

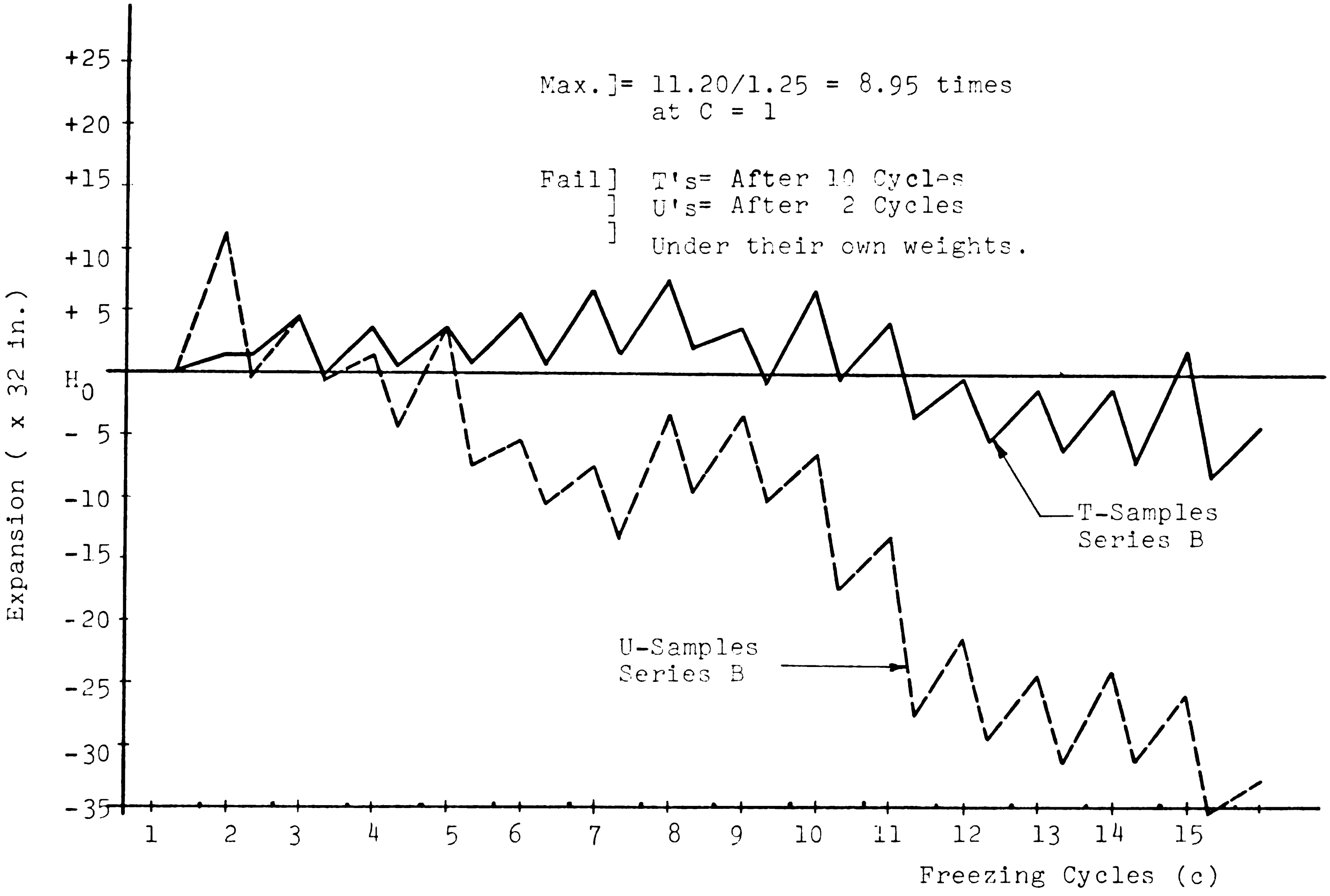


Figure 5.3.--Expansion and Settlement of Soil #1 in Open System.

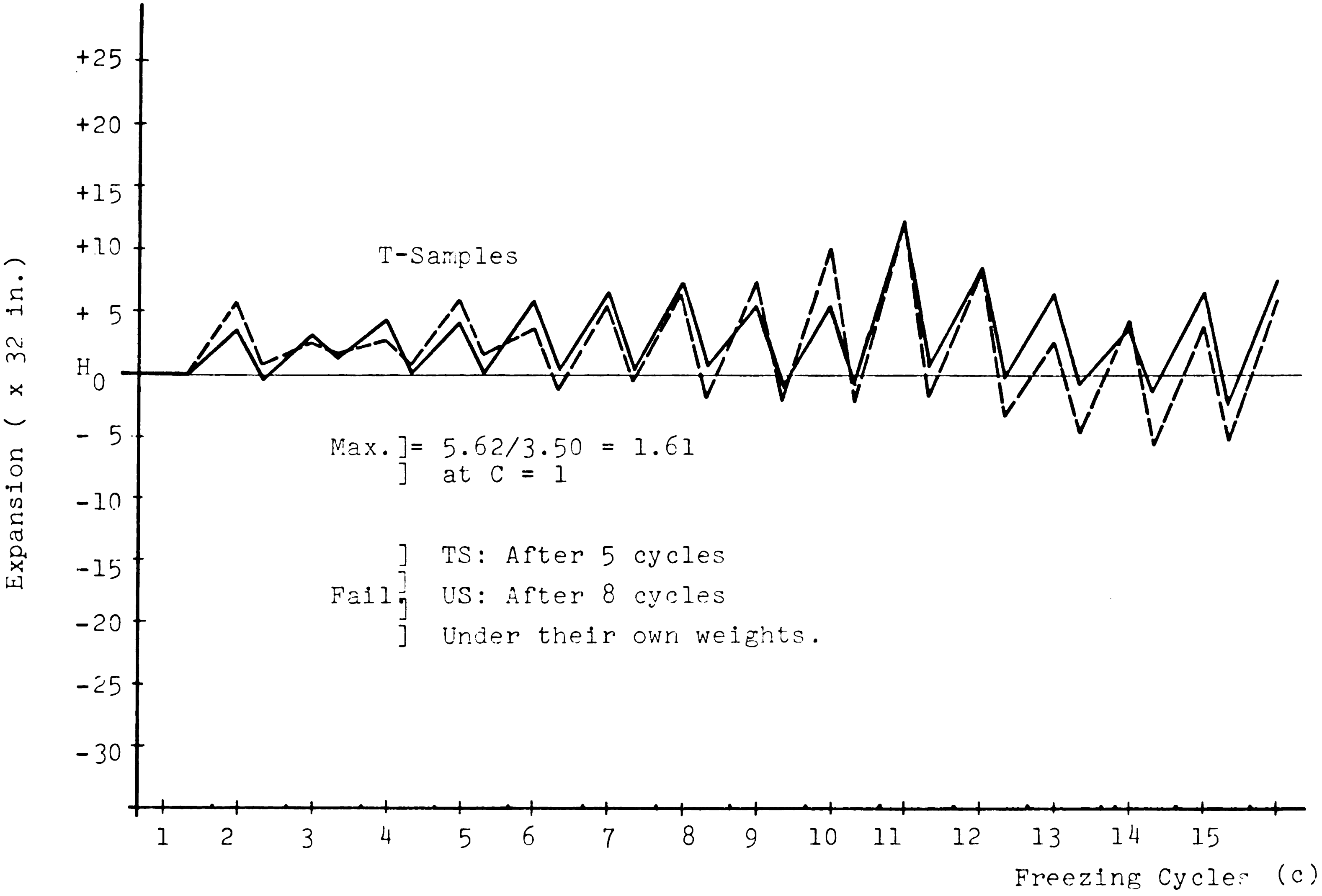
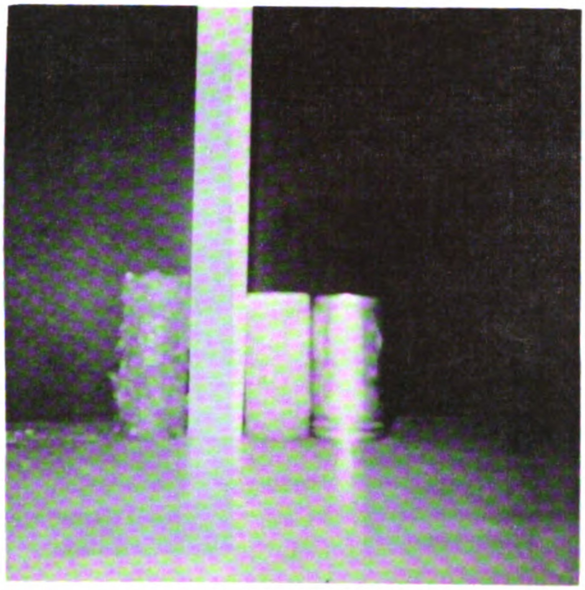
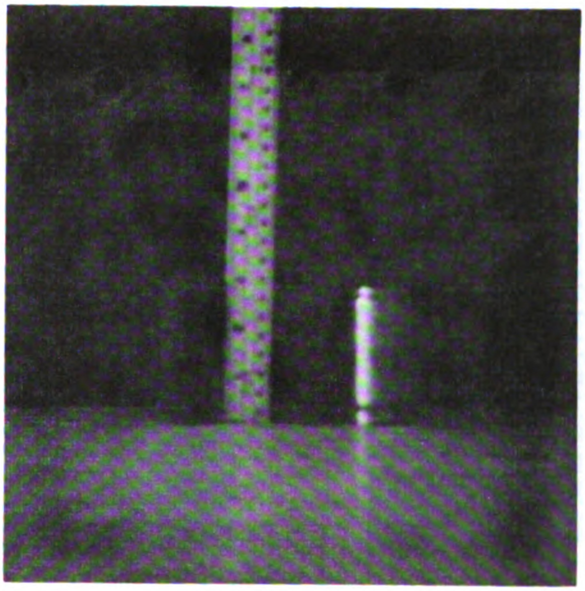


Figure 5.4.--Expansion and Settlement of Soil #2 in Open System.

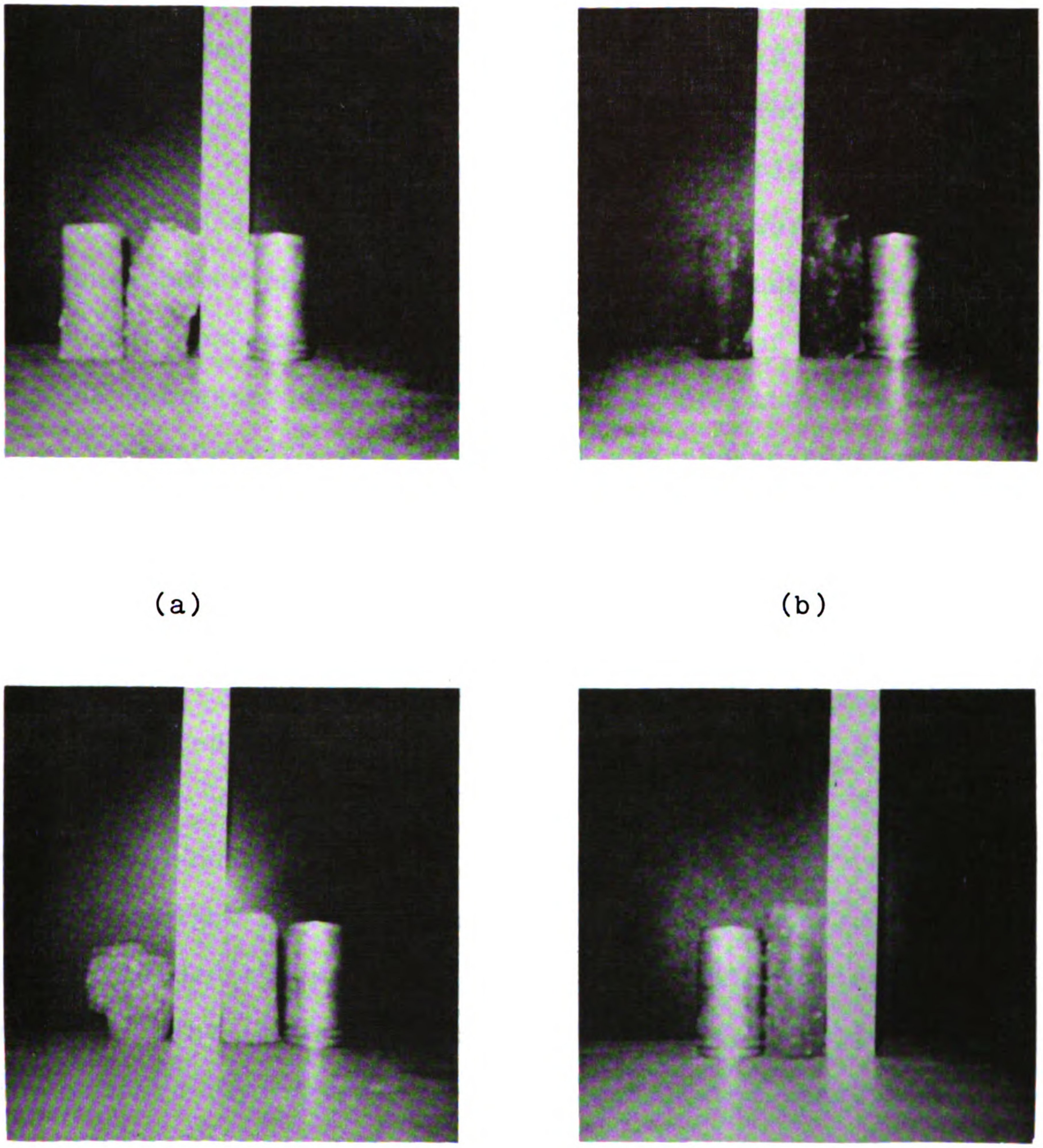


a) Soil #1



b) Soil #2

Figure 5-5. Treated and untreated samples after two complete cycles of freeze-thaw.



(a) (b)

(c) (d)

Figure 5-6. Treated and untreated samples after two complete cycles of freeze-thaw.
a) soil #3 b) soil #8 c) soil #7 d) soil #5

2. Water Content

Water absorption measurement of treated and untreated soils was a major concern of this study. As a preliminary study, waterproofing effect of the chemical TBC on Soil #1 was measured. The treated and untreated samples of Soil #1, having porous stones at the top and bottom, were contained in rubber membranes. Two rubber bands were used to secure the rubber membrane to the stones. A total of three treated and one untreated sample were submerged in water for 1151 hours (52 days +). This time limit was chosen because beyond it the water absorption of the treated samples was negligible. The untreated sample absorbed 97 percent of its total water capacity in less than 3 minutes. Therefore, the length of study was chosen based only on the behavior of the treated samples. At predetermined intervals, the samples were removed from the water and weighed. Total water head at mid-height of the soil samples was about 2.00 inches. Oven dry weight of samples at the end of the conclusion period yielded the water content of the soils for each interval. The results are given in Table 5.9. Figure 5.7 is a graphic representation of the calculated results.

Water contents of soil samples under cycles of freezing were measured for three groups of samples: the first group of samples consisted of one treated and two untreated samples for all nine different soils. This study was only carried out for two cycles of freezing. The second and

TABLE 5.9.--Water Absorption of Submerged Samples of Soil #1.

Sample	0		168		174		195		201		221		293		299		1151		Owen Dry Weight
	wt.	w %	wt.	w %	wt.	w %	wt.	w %	wt.	w %	wt.	w %	wt.	w %	wt.	w %	wt.	w %	
O-T_3-1	125.11	14.91	110.94	1.94	113.0	3.77	116.20	6.71	116.70	7.17	112.15	8.50	120.78	10.90	121.20	11.30	128.47	18.00	
O-T_3-2	124.93	15.15	110.56	1.94	112.05	3.23	115.10	6.08	115.56	6.51	117.25	7.24	119.30	9.95	119.60	10.22	130.00	19.80	
O-T_3-3	124.69	15.11	110.31	1.95	112.79	4.15	116.36	7.45	117.20	8.21	118.60	9.52	122.06	12.70	122.15	12.78	128.45	18.60	
O-N_3-1	124.96	15.10	110.59	1.86	143.72	32.52	144.15	32.74	144.50	33.08	149.60	33.22	145.03	33.62	145.12	33.65	145.22	33.76	

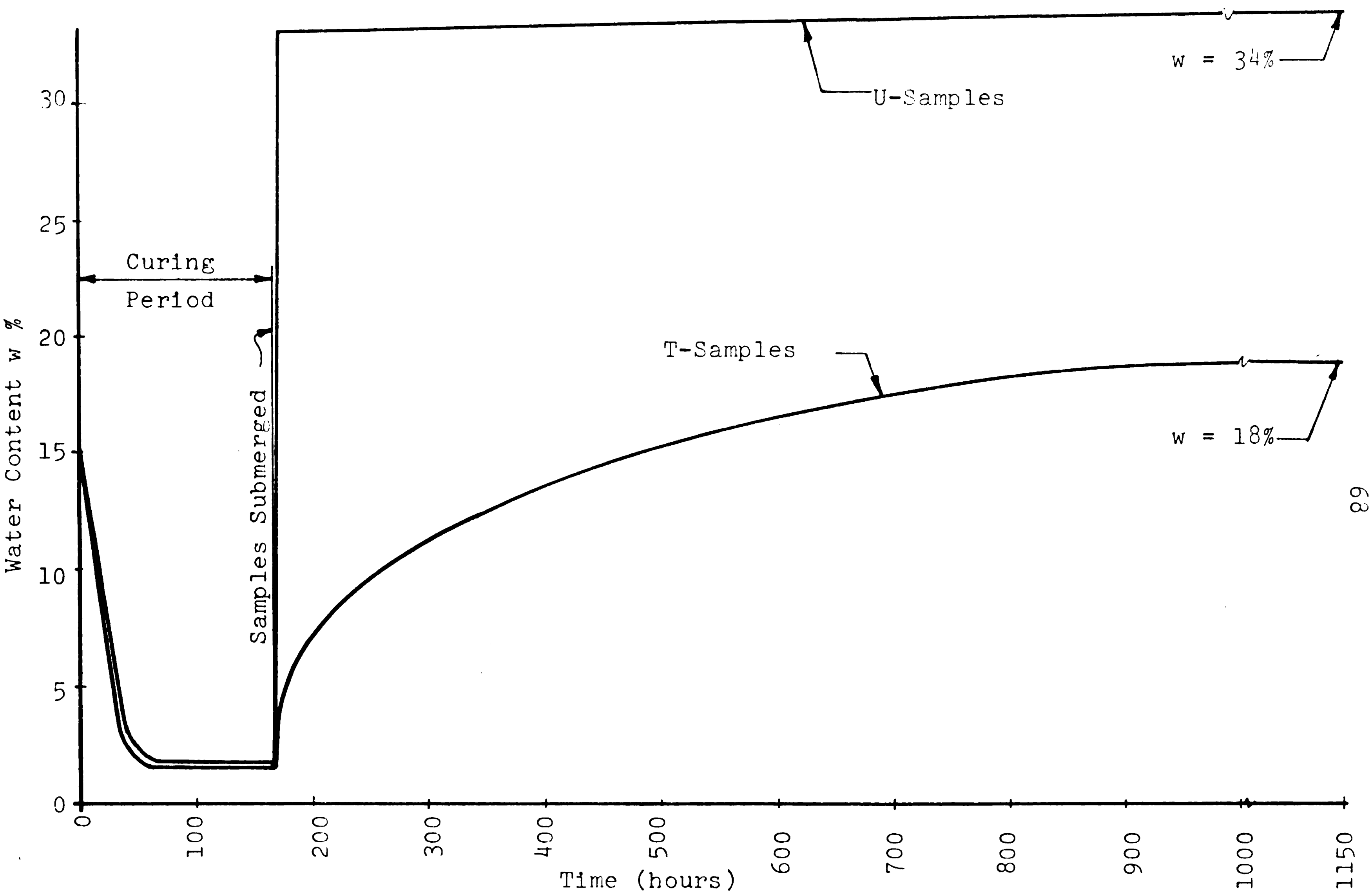


Figure 5.7.--Long Time Submerged Water Content of Soil #1.

third group were conducted on Series A and B of Soils #1 and #2 samples, as previously described in this chapter. Water retention, or negative water absorption, of all of the soils under moisture room and laboratory conditions was also studied. Water retention measurements for soils #1 through #9 are presented in Tables 5.10, 5.11, and Figures 5.8 and 5.9. The time of molding of the last sample was taken as the origin. Samples were transferred to the moisture room immediately and were left there until each reached an equilibrium water content. The samples were then taken to the laboratory and left for a new water content equilibrium condition. The samples, after being oven-dried for water content computations, were submerged in water for 24 hours and subsequently transferred to the open system freezing box. Untreated samples were introduced to capillary moisture from the bottom, instead of being submerged. Moisture contents of samples of Series A and Series B were measured at predetermined cycles for up to 20 cycles of freezing, on both open and closed system. Samples for moisture content determination and shear strength were taken at the end of 24 hours moisture absorption on the first, third, sixth, tenth, and fifteenth cycles of freezing for Series B samples and after each cycle of freezing for Series A samples. The moisture content values are shown in Tables 5.12 through 5.14, and Figures 5.10 through 5.15. Curves of moisture content in Figures 5.10 and 5.11 indicate

TABLE 5.10.--Water Retention of Treated Soil Samples.

Soil	Wt.	Elapsed Time (Hours)												
		In Moisture Room								In Lab.		Submerged for 24 Hours	Freezing (1 cycle)	O.D. wt.
		0	12 hrs	48	60	84	106	132	158	186 & 210	O.D. wt.			
#1	wt.	120.80	115.85	109.75	109.70	109.50	109.20	109.10	109.10	109.02	104.77	118.31	120.15	101.77
	wt.	121.00	115.30	110.50	110.00	110.00	109.50	109.60	109.50	109.40	105.00	118.00	120.10	102.00
	Ave. w %	15.28	10.19	5.00	4.73	4.64	4.31	4.26	4.21	4.13	0	16.15	17.60	0
#2	wt.	134.80	131.50	124.20	123.30	123.00	122.10	121.90	121.70	121.70	114.76	132.23	133.50	111.76
	wt.	134.60	129.70	123.40	122.60	122.10	121.40	121.20	121.04	121.00	113.18	132.12	134.75	111.18
	Ave. w %	18.20	14.60	8.64	7.89	7.54	6.81	6.66	6.50	6.48	0	18.60	19.80	0
#3	wt.	130.00	125.90	118.35	116.70	116.50	115.30	115.20	115.00	114.98	108.26	129.97	133.37	104.27
	wt.	129.35	123.60	117.90	116.50	115.90	114.60	114.10	114.30	114.19	108.46	128.55	129.34	104.49
	Ave. w %	19.40	15.12	9.37	7.64	7.08	6.07	5.84	5.83	5.73	0	23.85	25.94	0
# 4	wt.	142.90	139.50	131.90	130.50	130.30	130.00	129.90	129.60	129.66	127.40	139.40	137.88	121.32
	wt.	141.10	135.25	130.00	129.30	129.40	128.90	128.90	128.80	128.60	121.32	137.73	134.35	127.40
	Ave. w %	14.75	10.89	5.50	4.66	4.56	4.17	4.15	4.02	3.96	0	11.88	9.83	0
#5	wt.	133.15	128.80	119.65	119.15	119.10	118.80	118.80	118.80	118.74	113.42	126.33	126.42	113.42
	wt.	133.35	126.45	120.00	119.60	119.50	119.30	119.20	119.20	119.20	115.80	126.45	126.25	115.80
	Ave. w %	16.28	11.38	4.56	4.17	4.10	3.88	3.84	3.84	3.83	0	10.29	10.22	0
#6	wt.	144.85	140.70	134.10	133.40	132.70	132.70	132.60	132.40	132.40	127.34	141.30	136.70	127.34
	wt.	142.05	136.00	131.10	130.75	130.30	130.30	130.20	130.20	130.04	124.52	138.51	130.98	121.52
	Ave. w %	13.94	9.85	5.30	4.82	4.43	4.43	4.35	4.27	4.20	0	12.30	7.47	0
#7	wt.	120.25	116.00	108.40	107.90	107.90	107.80	107.70	107.70	107.60	104.46	119.32	134.06	104.51
	wt.	120.25	115.75	108.60	108.20	108.10	108.00	107.40	107.90	107.76	104.51	120.72	132.58	104.46
	Ave. w %	15.10	10.90	3.84	3.41	3.40	3.27	3.22	3.22	3.06	0	14.87	27.60	0
#8	wt.	128.65	124.80	115.90	114.80	114.50	114.00	114.00	114.00	114.00	109.99	128.78	121.95	104.92
	wt.	130.75	125.75	117.50	116.30	115.80	115.40	115.40	115.40	115.40	109.20	128.94	121.92	109.20
	Ave. w %	17.32	14.31	6.49	5.44	5.08	4.66	4.66	4.66	4.66	0	19.83	13.82	0
#9	wt.	126.71	123.35	116.20	114.90	114.00	113.30	113.20	113.20	113.20	110.72	117.57	121.92	110.72
	wt.	126.20	122.10	115.90	114.60	113.60	112.90	112.90	112.90	112.88	110.54	117.15	121.11	110.57
	Ave. w %	15.34	10.93	4.88	3.71	2.85	2.22	2.17	2.17	2.16	0	6.57	9.83	0

TABLE 5.11.--Water Retention of Untreated Samples of Soil #1.

		Elapsed Time (Hours)									
		In Moist Room						In Lab.			
Soil		0	21	43	69	95	140	168 & 175	O.L.	Soaked for 24 hrs	Freezing (1 cycle)	O. L. Weight
#1	wt.	122.80	111.80	109.60	109.60	109.60	109.60	109.39	106.47	134.25	141.64	106.47
	w %	15.13	5.01	2.94	2.94	2.94	2.94	2.74	0	26.10	33.30	0
#2	w5.	138.90	125.10	120.90	120.50	120.20	120.00	120.00	117.14	135.68	142.60	117.14
	w %	18.56	6.80	3.21	2.87	2.61	2.44	2.44	0	15.41	21.70	0
#3	wt.	130.90	120.60	116.00	115.50	115.20	115.30	115.13	111.42	137.75	146.73	111.42
	w %	19.30	8.23	4.11	3.66	3.39	3.39	3.33	0	23.60	31.67	0
#4	wt.	140.30	124.60	125.40	125.30	125.10	125.10	125.10	124.09	139.05	142.99	124.09
	w %	13.10	4.45	1.06	0.98	0.87	.82	.82	0	12.07	15.25	0
#5	wt.	132.50	121.00	118.00	118.10	118.10	118.10	118.01	116.42	139.75	149.75	116.42
	w %	13.80	3.93	1.36	1.44	1.44	1.44	1.37	0	20.00	28.60	0
#6	wt.	145.10	135.60	132.40	132.40	132.10	132.10	131.92	131.11	145.15	146.56	131.11
	w %	10.67	3.43	0.98	0.98	0.76	0.76	0.62	0	10.71	11.78	0
#7	wt.	122.40	111.90	108.10	108.00	108.00	108.00	107.93	106.02	134.20	144.73	106.02
	w %	15.45	5.54	1.96	1.87	1.87	1.87	1.80	0	26.58	36.50	0
#8	wt.	135.70	127.60	119.20	118.70	118.50	118.50	118.50	116.97	136.12	139.85	116.97
	w %	16.00	9.10	1.91	1.48	1.31	1.31	1.31	0	16.37	19.58	0
#9	wt.	127.90	118.80	114.10	112.90	112.50	112.40	112.40	110.54	133.05	139.24	107.54
	w %	15.71	7.47	3.22	2.13	1.77	1.68	1.68	0	20.18	25.95	0

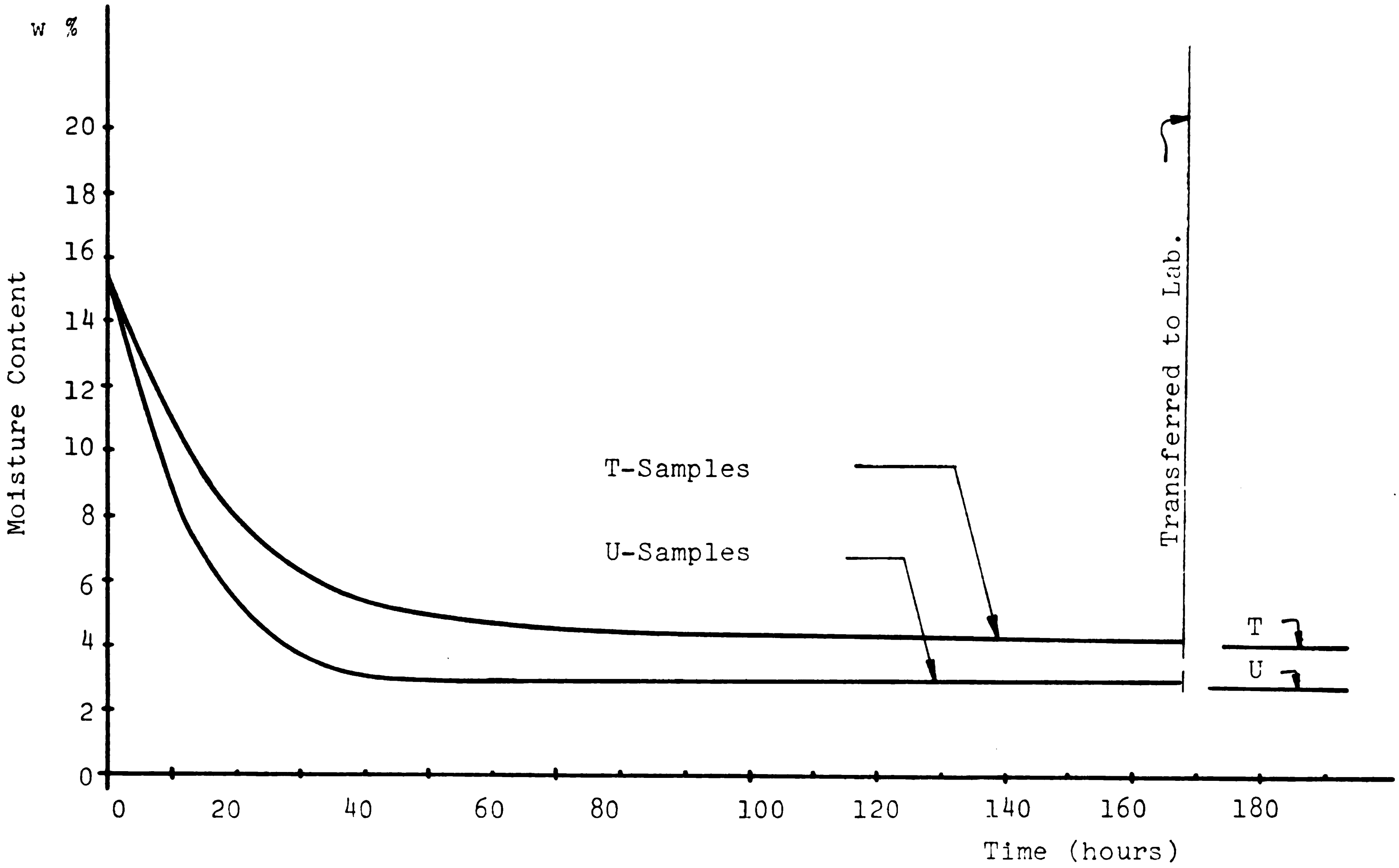


Figure 5.8.--Water Retention Curve for T and U Samples of Soil #1.

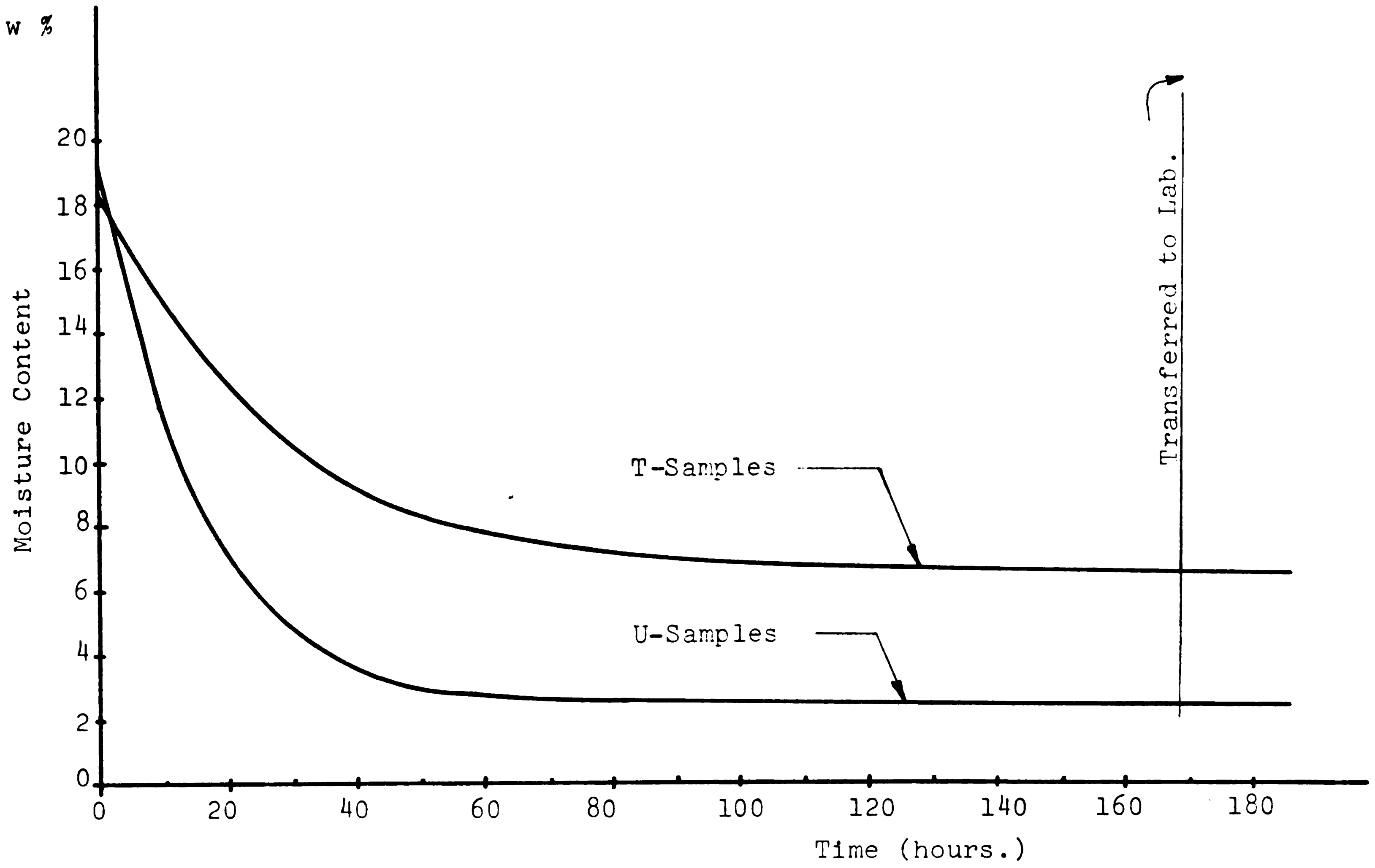


Figure 5.9.--Moisture Retention Curve of Treated and Untreated Samples of Soil #2.

TABLE 5.12.--Water Content of Series B Samples, in Open System.

Freezing Cycles	Soil #1		Soil #2	
	Treated	Untreated	Treated	Untreated
0	5.19%	23.70%	8.00%	16.10%
1	6.10	26.70	9.56	25.16
2	---	---	---	---
3	8.43	31.41	12.17	21.95
4	---	---	---	---
5	---	---	---	---
6	17.24	38.00	16.45	29.12
7	---	---	---	---
8	---	---	---	---
9	---	---	---	---
10	26.40	42.20	25.12	33.70
11	---	---	---	---
12	---	---	---	---
13	---	---	---	---
14	---	---	---	---
15	31.50	43.00	30.60	34.71

TABLE 5.13.--Water Content of Series B Samples in Closed System.

Freezing Cycles	Soil #1		Soil #2	
	Treated	Untreated	Treated	Untrested
0	2.68	2.41	4.13	3.66
1	3.36	2.63	4.91	4.21
2	---	---	---	---
3	2.85	2.22	4.92	4.26
4	---	---	---	---
5	---	---	---	---
6	3.15	2.28	5.01	4.25
7	---	---	---	---
8	---	---	---	---
9	---	---	---	---
10	2.85	2.53	4.91	4.08
11	---	---	---	---
12	---	---	---	---
13	---	---	---	---
14	---	---	---	---
15	2.73	2.26	2.38	3.93

TABLE 5.14.--Water Content of Series A Samples, Soil #1.

Freezing Cycles	Closed System		Open System	
	Treated	Untreated	Treated	Untreated
From lab.	3.62	2.33	3.62	2.33
Submerged	6.66	13.72	3.50	24.10
1	---	---	7.70	39.50
2	16.46	22.14	14.91	26.83
3	7.36	7.14	26.15	33.64
4	---	---	21.76	28.00
5	8.28	10.67		
6	---	---		
7	6.80	11.61		
8	5.04	6.88		
9	6.51	8.42		
10	5.34	7.10		
11	---	---		
12	3.74	3.56		
13	2.94	4.10		
14	---	---		
15	2.47	2.55		
16	---	---		
17	2.43	2.58		
18	---	---		
19	---	---		
20	2.40	2.45		

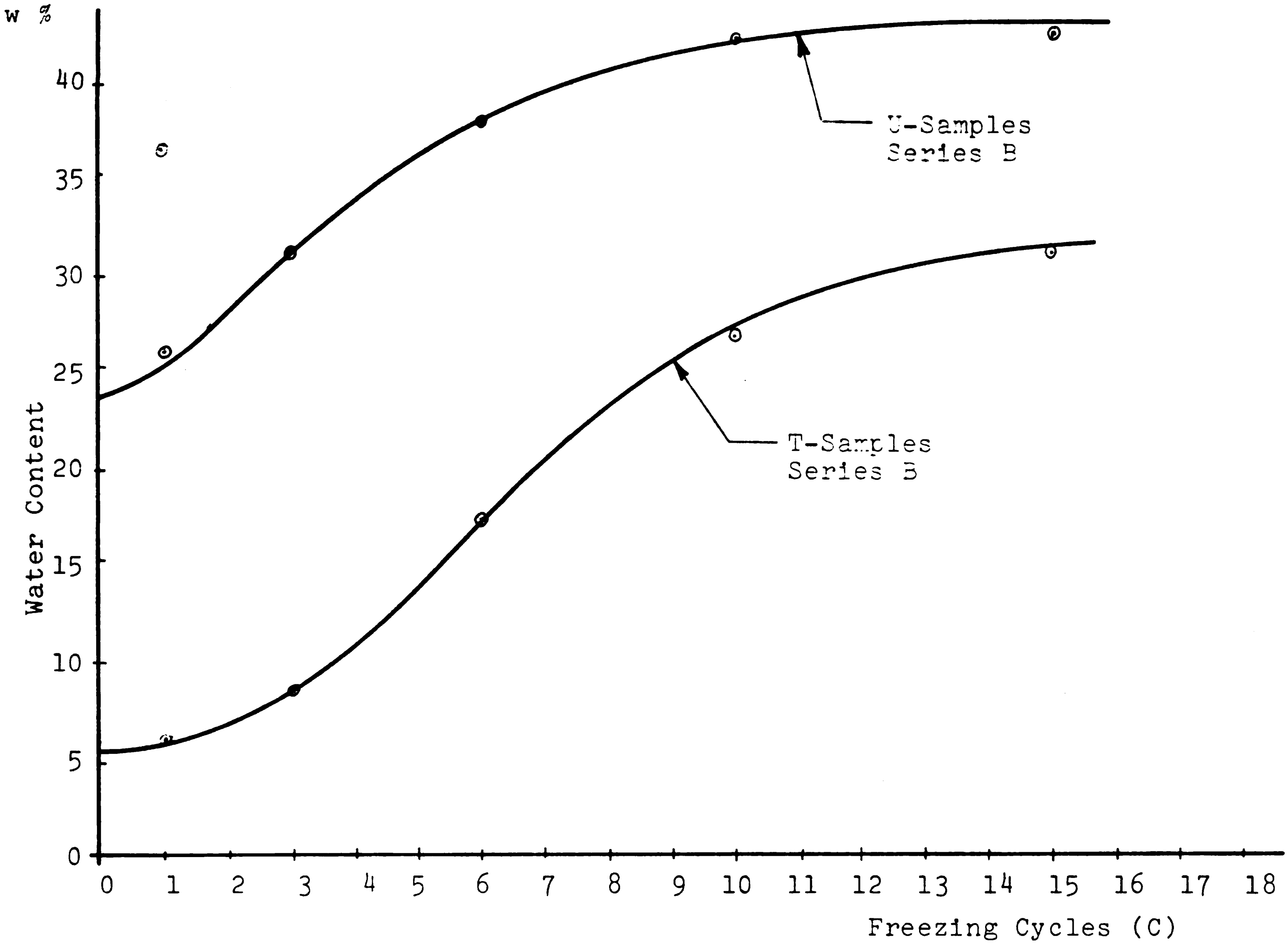


Figure 5.10.--Water Content of Soil #1 in Open System.

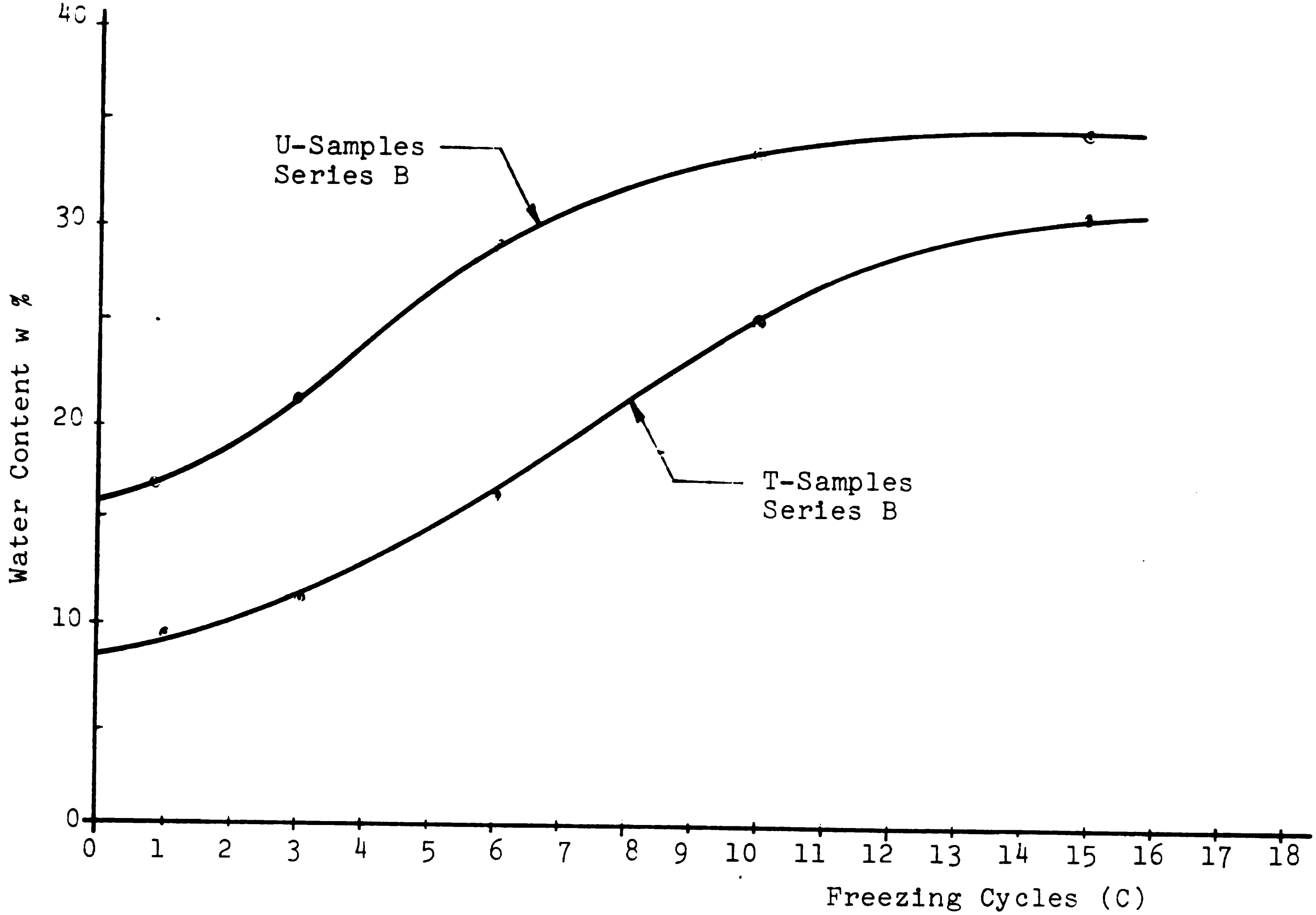


Figure 5.11.--Water Content of Soil #2 in Open System.

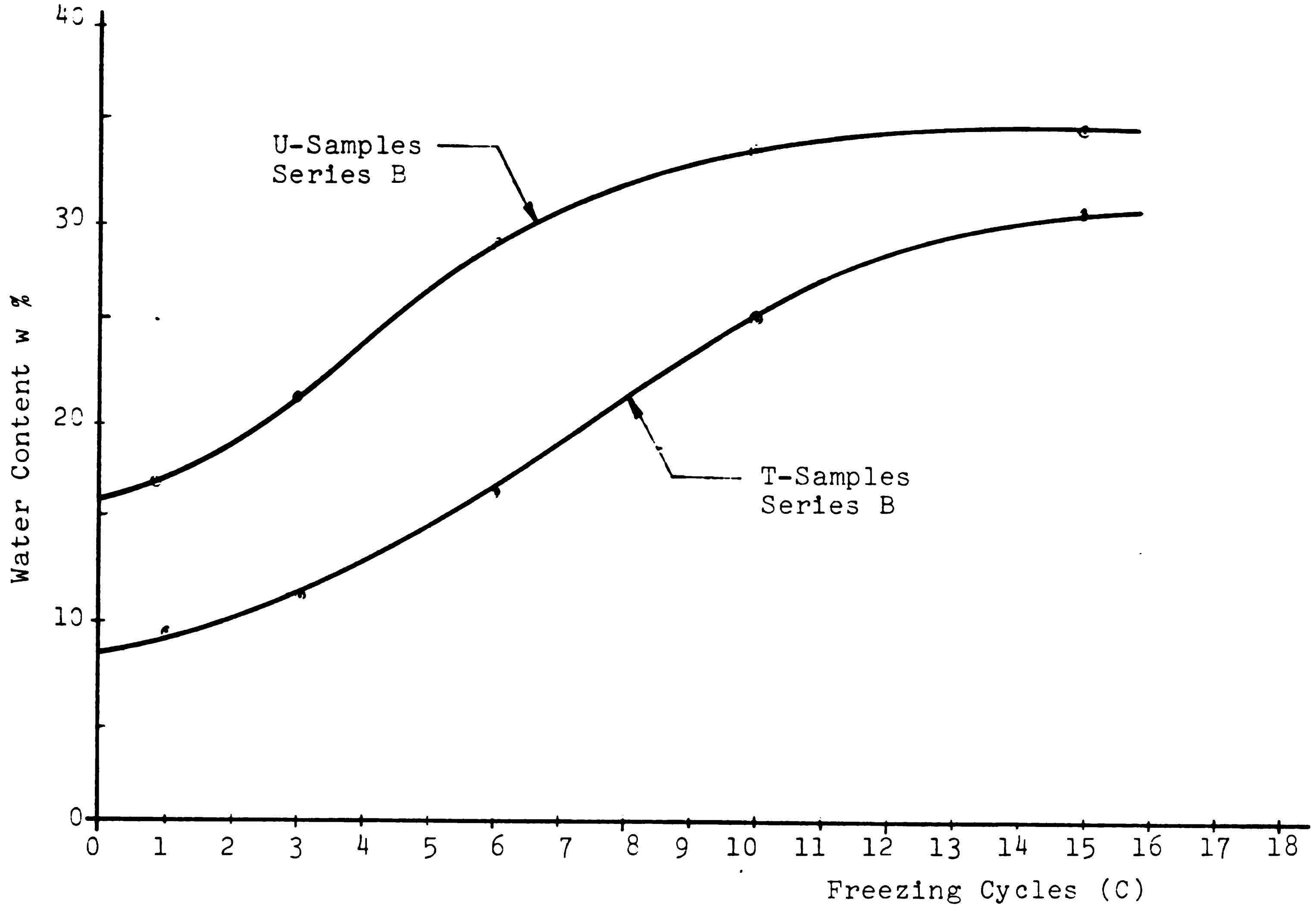


Figure 5.11.--Water Content of Soil #2 in Open System.

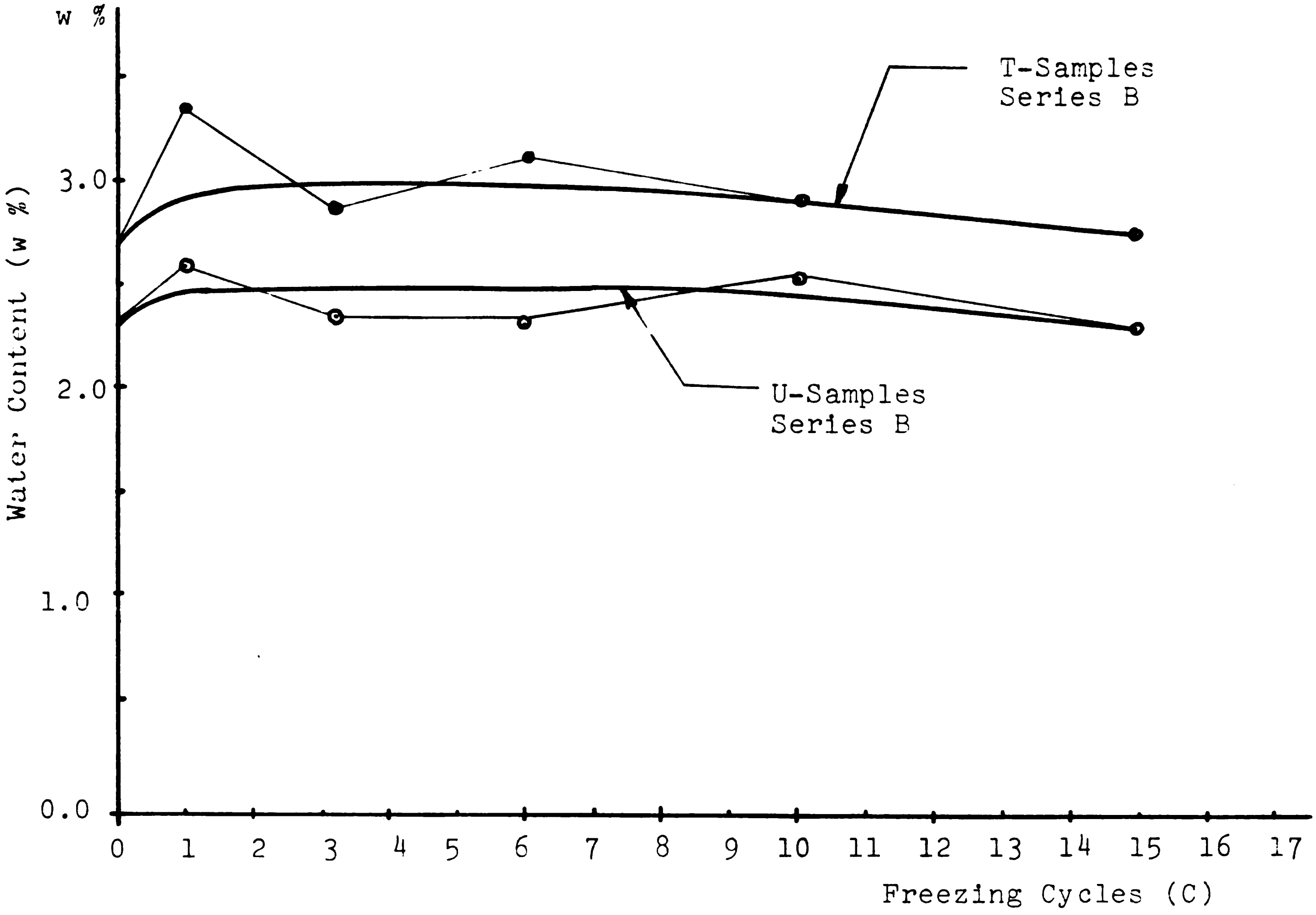


Figure 5.12.--Water Content of Soil #1 in Closed System.

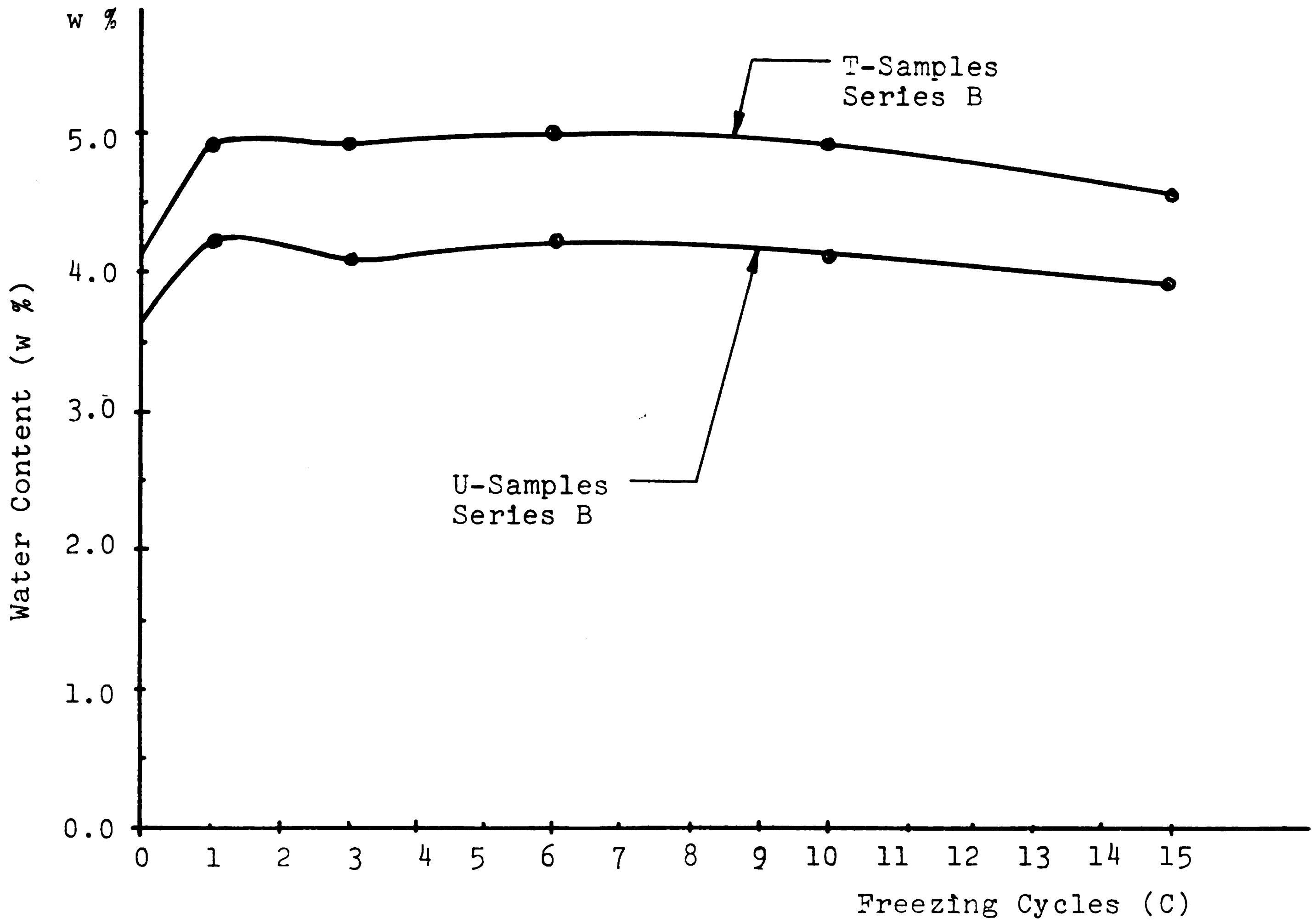


Figure 5.13.--Water Content of Soil #2 in Closed System.

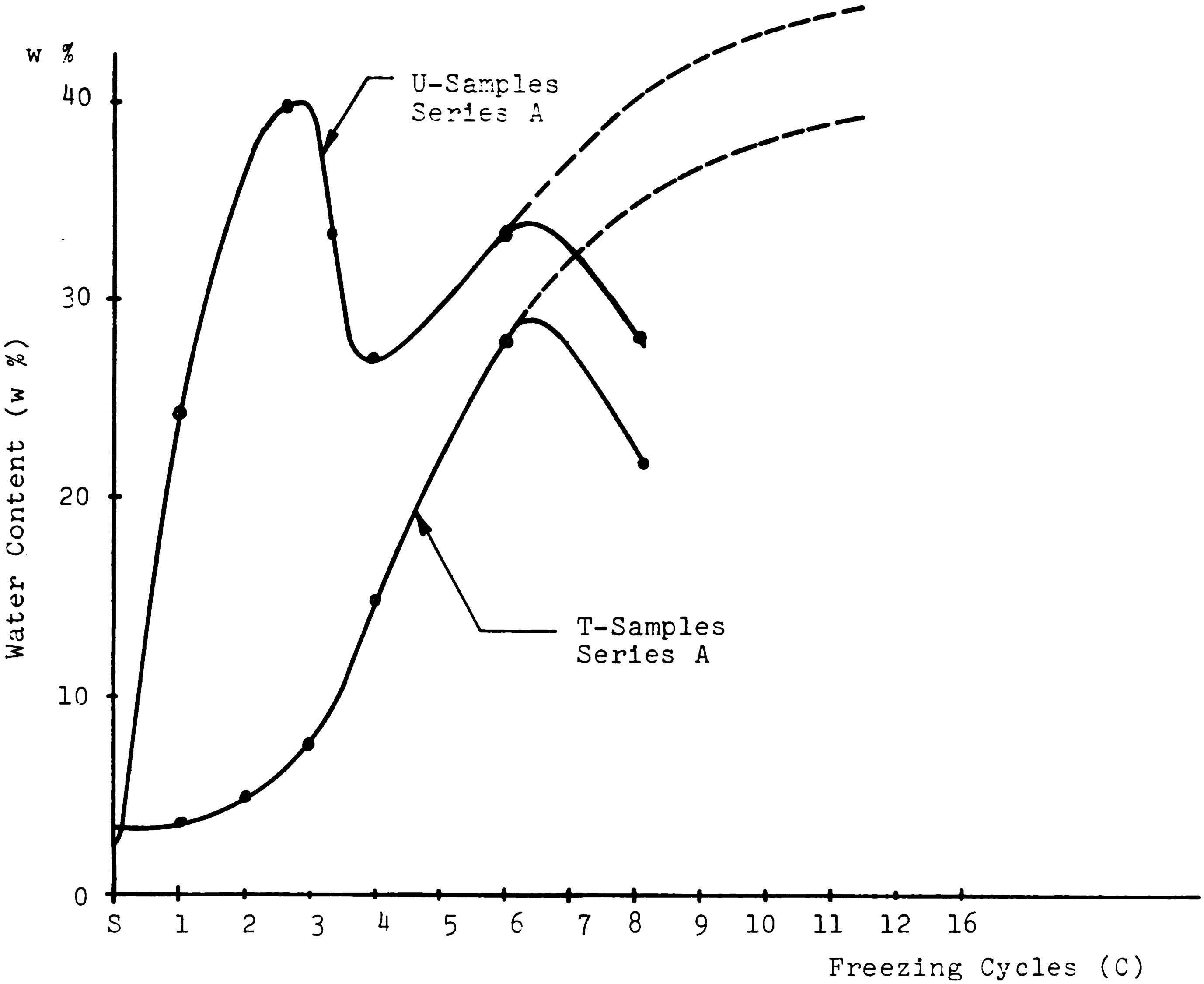


Figure 5.14.--Water Content of Series A Samples, in Open System.

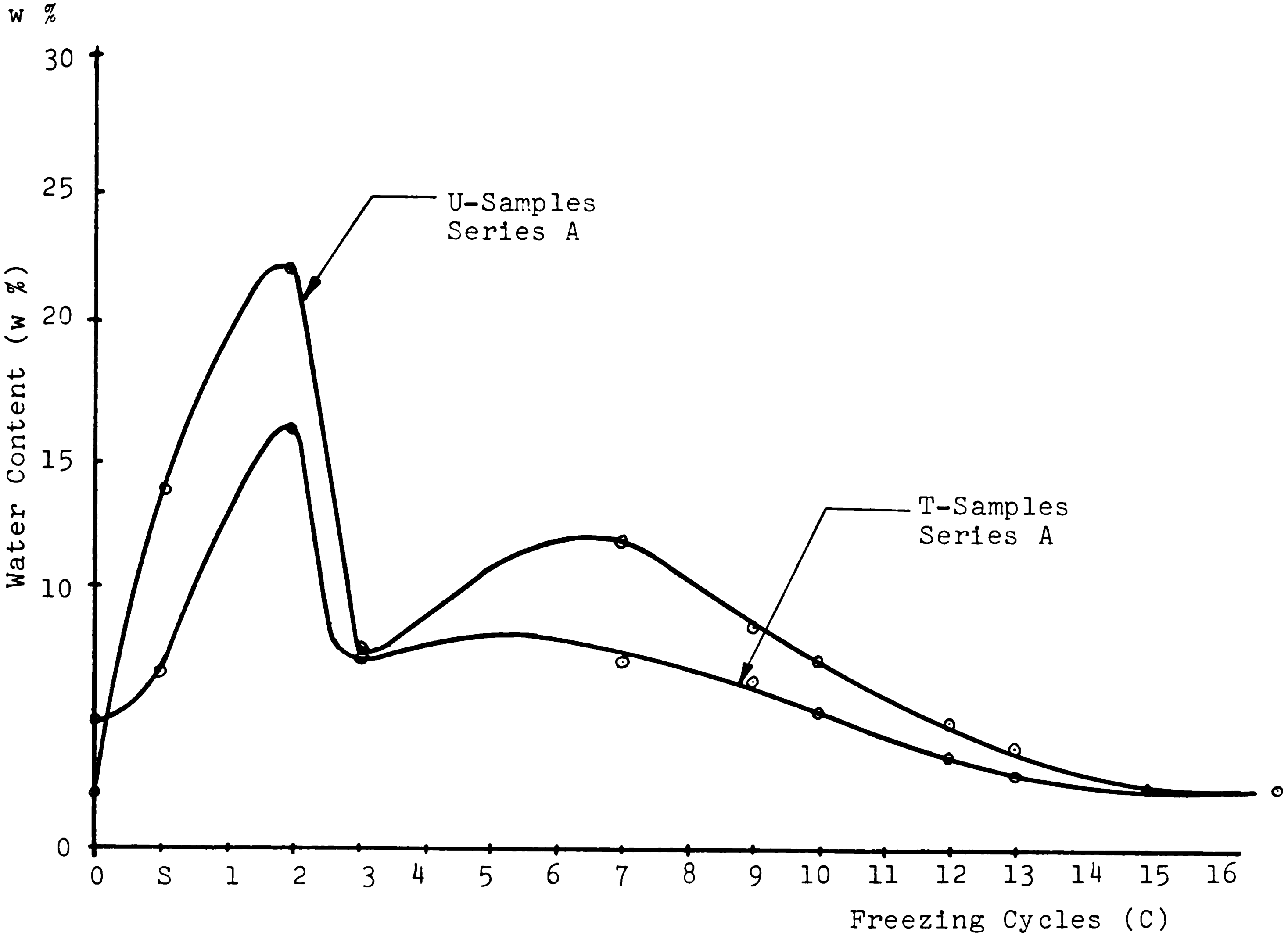


Figure 5.15.--Water Content of Series A Samples, in Closed System.

that water absorption for both soils, treated or untreated, when subjected to open system freezing, follows the path of a S-shaped or so-called logistic curve. This basic idea for the derivation of a general formula was presented in Chapter VI.

3. Shear Strength

Shear strength of soil samples was determined for freezing cycles as employed in water content determination. The same samples taken for water content were first tested for strength, and the broken samples were transferred to moisture cans for moisture determination. Maximum load at failure, in an unconfined compression test, was measured and converted to shear strength of the soils. This study was conducted on all the samples used for water content, as described in part 2 of this section. Unconfined compression test, due to lack of lateral pressure, change of internal soil conditions, and friction of the sample ends, does not provide very reliable values of soil shear strength. With the above consideration a comparative study between treated and untreated samples, and not the exact values of soil strength as a criterion, unconfined strength was considered acceptable. The results of the tests are corrected for sample size and area change upon load application and are presented in Tables 5.15, 5.16 and Figures 5.16 through 5.18. The shear strength study included

TABLE 5.15.--Maximum Shear Stress of Series B Samples, (Kg/sq. in.)

	Open System				Closed System			
	Soil #1		Soil #2		Soil #1		Soil #2	
Cycles	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated
0	7.20	1.80	19.57	2.77	61.10	55.60	45.30	67.85
1	6.25	0	11.30	0.40	39.40	53.70	67.00	62.70
3	1.77	0	4.42	0.80	46.10	53.20	52.45	61.5
6	6.23	0	0.78	0.39	45.00	40.18	59.90	51.62
10	9.10	0	0.39	0	31.50	41.80	47.70	63.85
15	0.77	0	0.39	0	48.10	48.85	28.75	61.45

TABLE 5.16.--Maximum Shear Stress of Series A Samples (Kg/sq.in).

	Closed System		Open System	
Cycles	Treated	Untreated	Treated	Untreated
0	50.60	54.30	51.15	52.17
	2.68	3.78	12.60	0.62
1	---	---	---	---
2	1.50	2.94	3.61	0
3	3.45	6.75	1.30	0
5	2.20	3.81	0.70	0
7	3.30	3.85	0.30	0
8	6.79	7.74		
9	3.45	4.04		
10	3.52	5.25		
12	9.65	16.32		
13	31.70	15.23		
15	18.35	39.10		
17	23.50	31.90		
20	27.90	50.07		

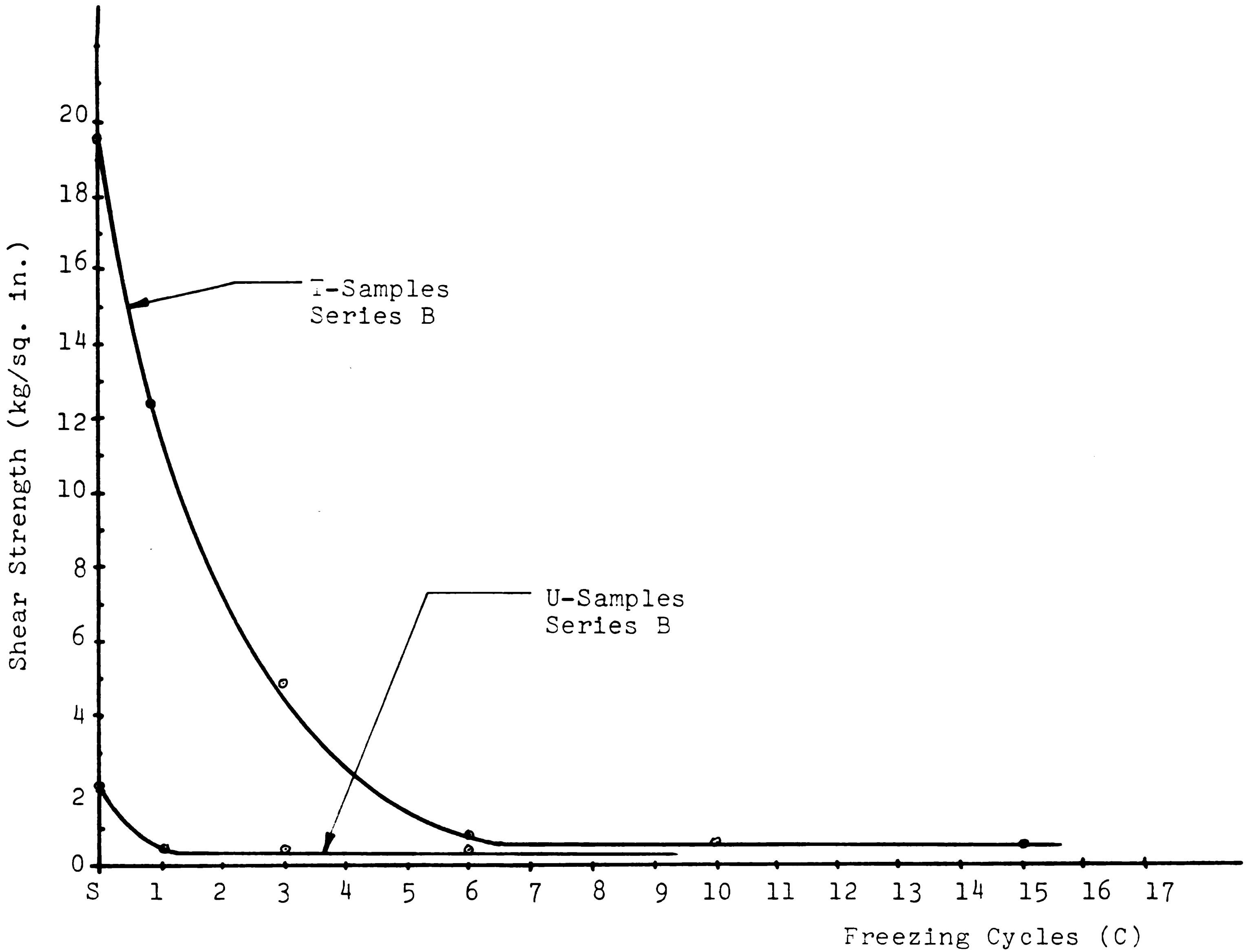


Figure 5.16.--Shear Strength of Soil #2 as Determined by Unconfined Compression Test, from Open System.

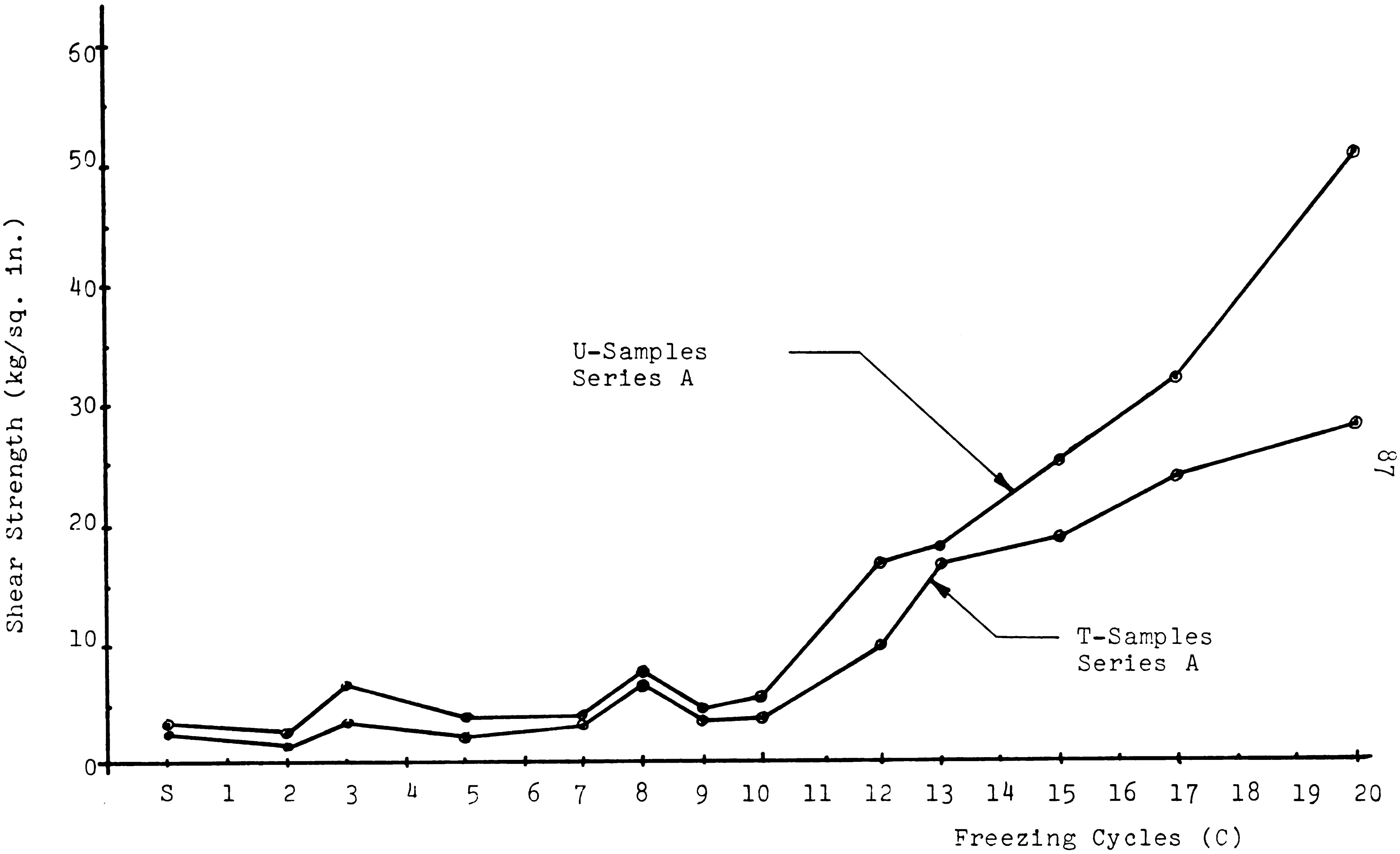


Figure 5.17.--Shear Strength of Soil #1 as Determined by Unconfined Compression Test, from Closed System.

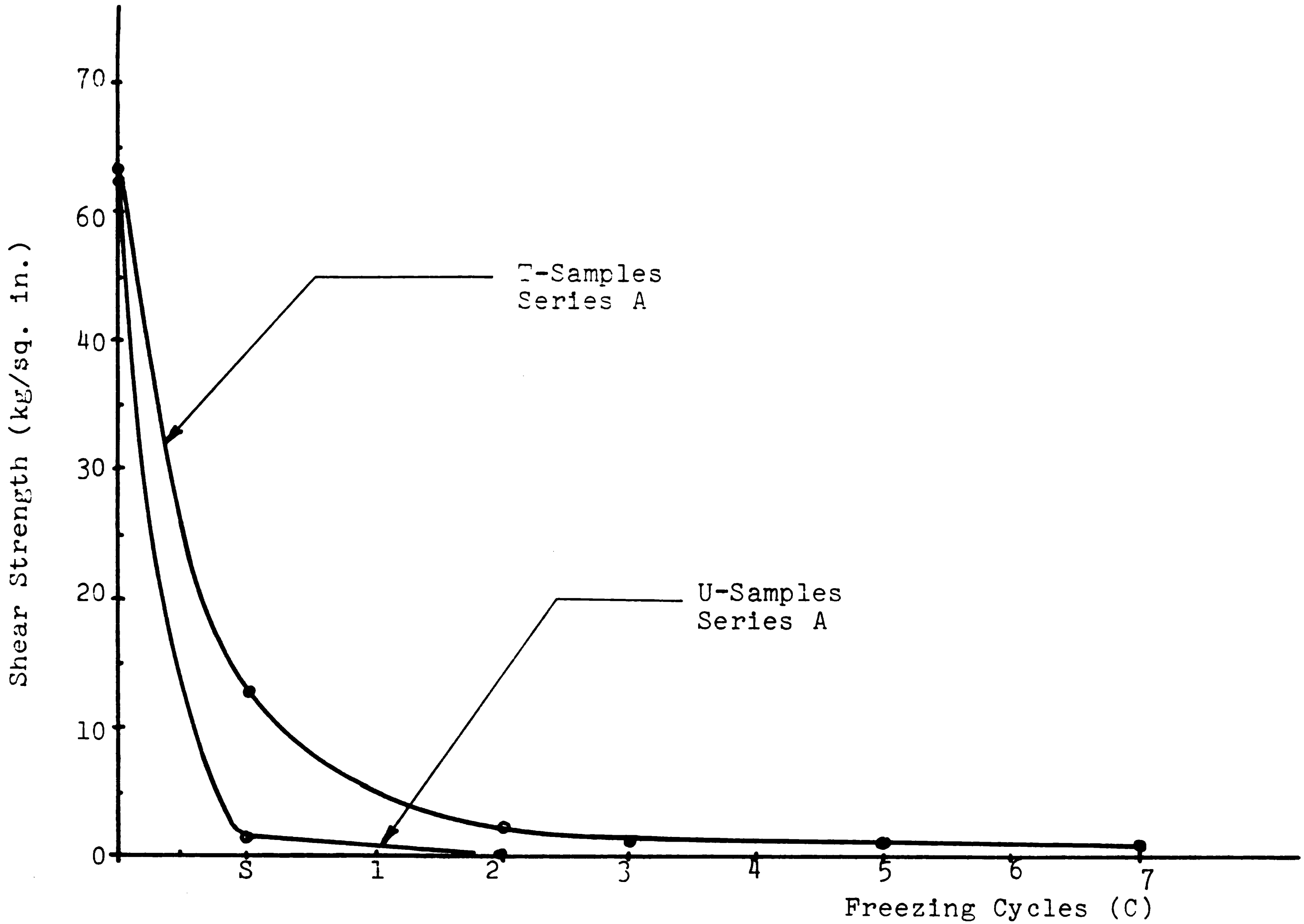


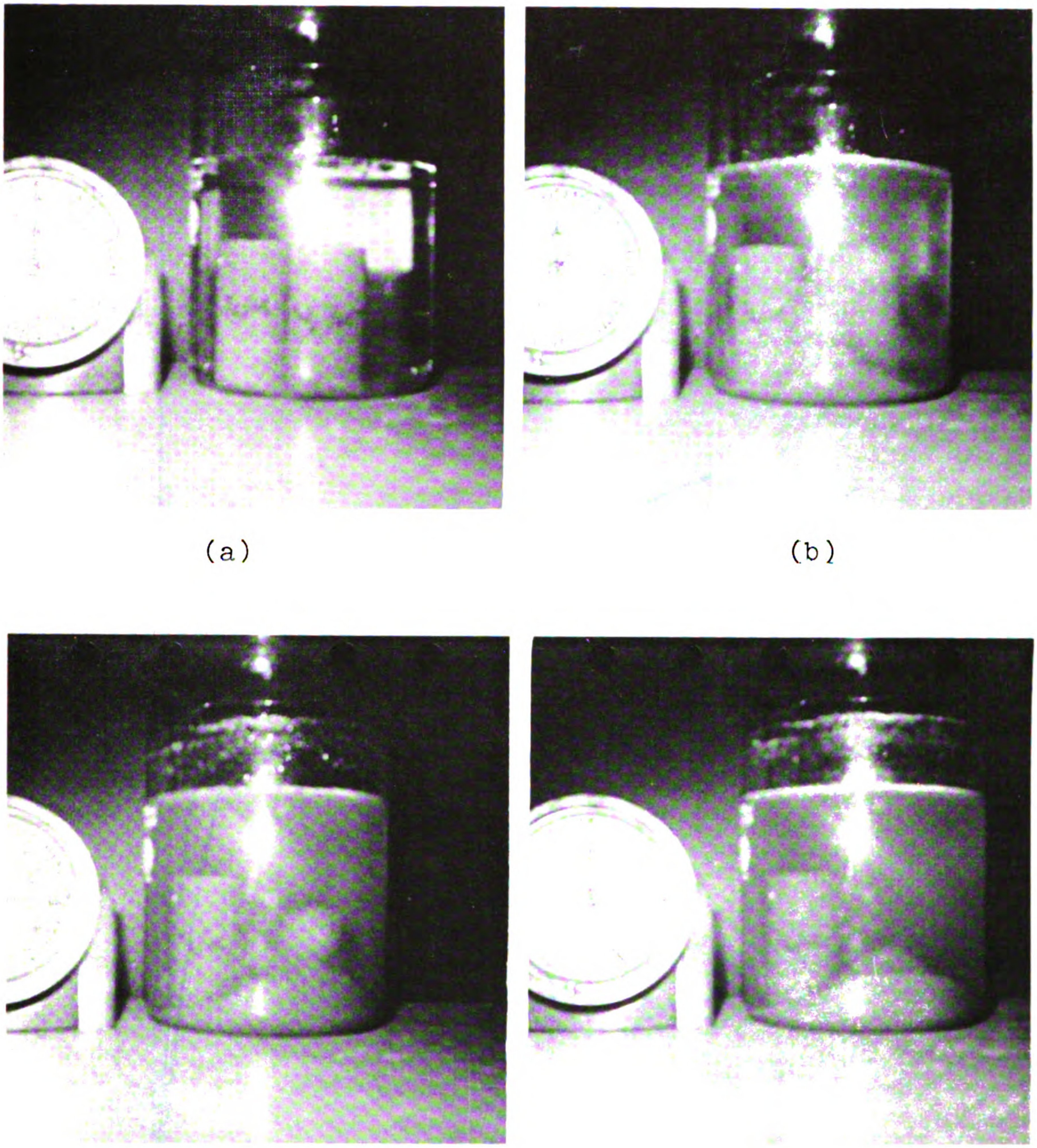
Figure 5.18.--Shear Strength of Soil #1 as Determined by Unconfined Compression Test, from Open System.

Series A and Series B samples of Soils #1 and #2. The results, although scattered for the reasons already discussed, present good indications of chemical additive effect on stabilizing the samples in connection with water and effect on treated samples not exposed to water. In connection with this study, the submerged strength of samples after varied numbers of freezing cycles was measured. Figure 5.19 shows a demonstration of treated and untreated samples of Soil #1 when submerged in water.

4. Water Absorption

The rate and extent of ice lens growth in soil may be studied by observation of water movement to freezing fronts in an open system (2). Water migration to freezing fronts was chosen and employed for detailed study of freezing rate in Soil #1. Water absorption was continuously measured to compare ice lens growth rates for the treated and untreated samples. Water absorption curves, as prepared by a computing system, are presented in Figures 5.20 and 5.21. The water absorption test was run at soil laboratories of the Dow Chemical Company and Figures 5.20 and 5.21 are provided by Dr. G. H. Brandt (4).

Temperature gradient is a very important factor in the performance of soil and water immigration. High temperature gradients may move considerable amounts of water into soil, while at low temperature gradients water flow is lower, depending on the type and state of soil (2). The



(a) (b)

(c) (d)

Figure 5-19. Demonstration of submerged strength of soil #1. a) after zero second. b) after five second. c) after 16 second and d) after 25 second. Sample at left is treated.

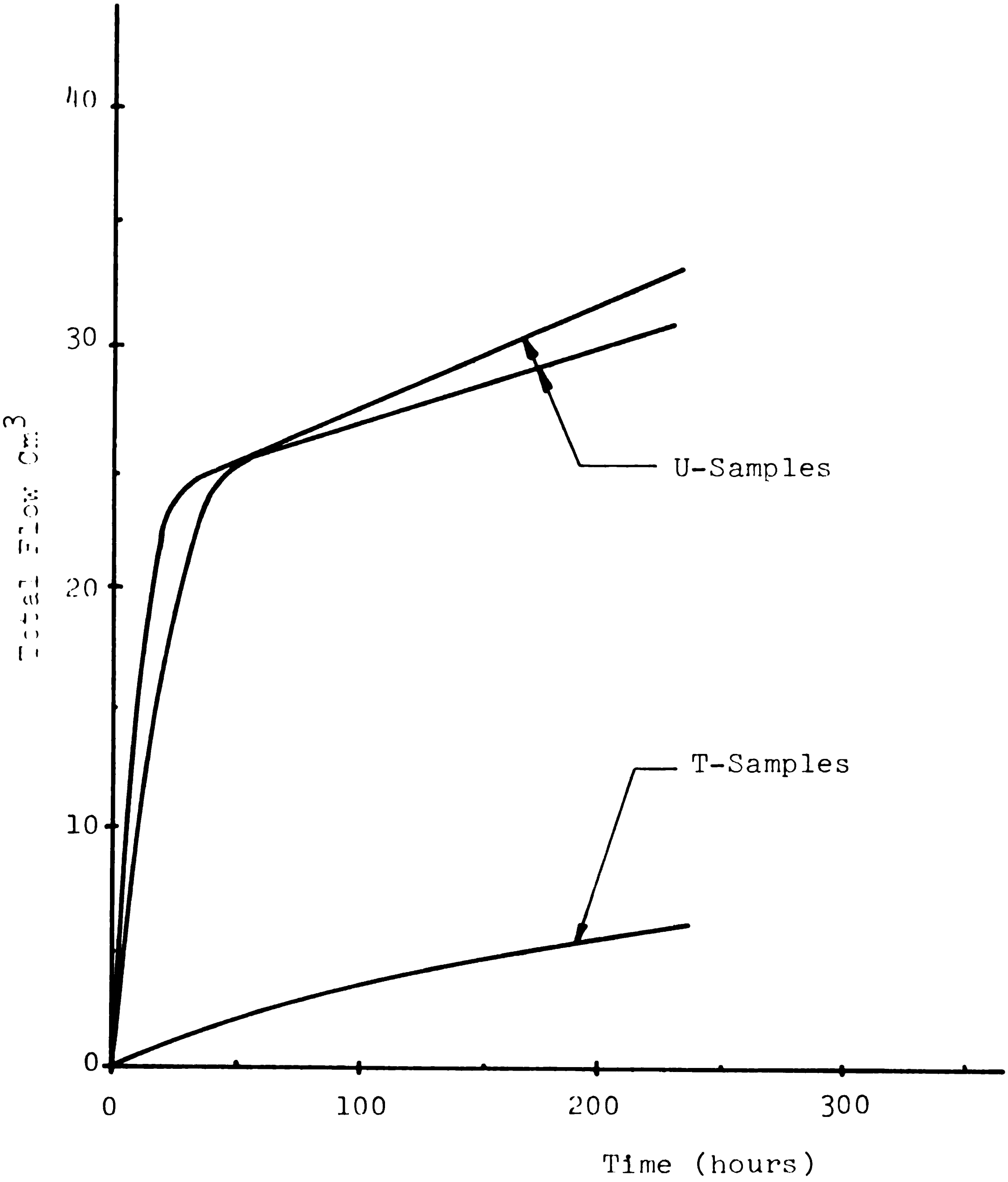


Figure 5.20.--Water Absorbtion of Soil #1.

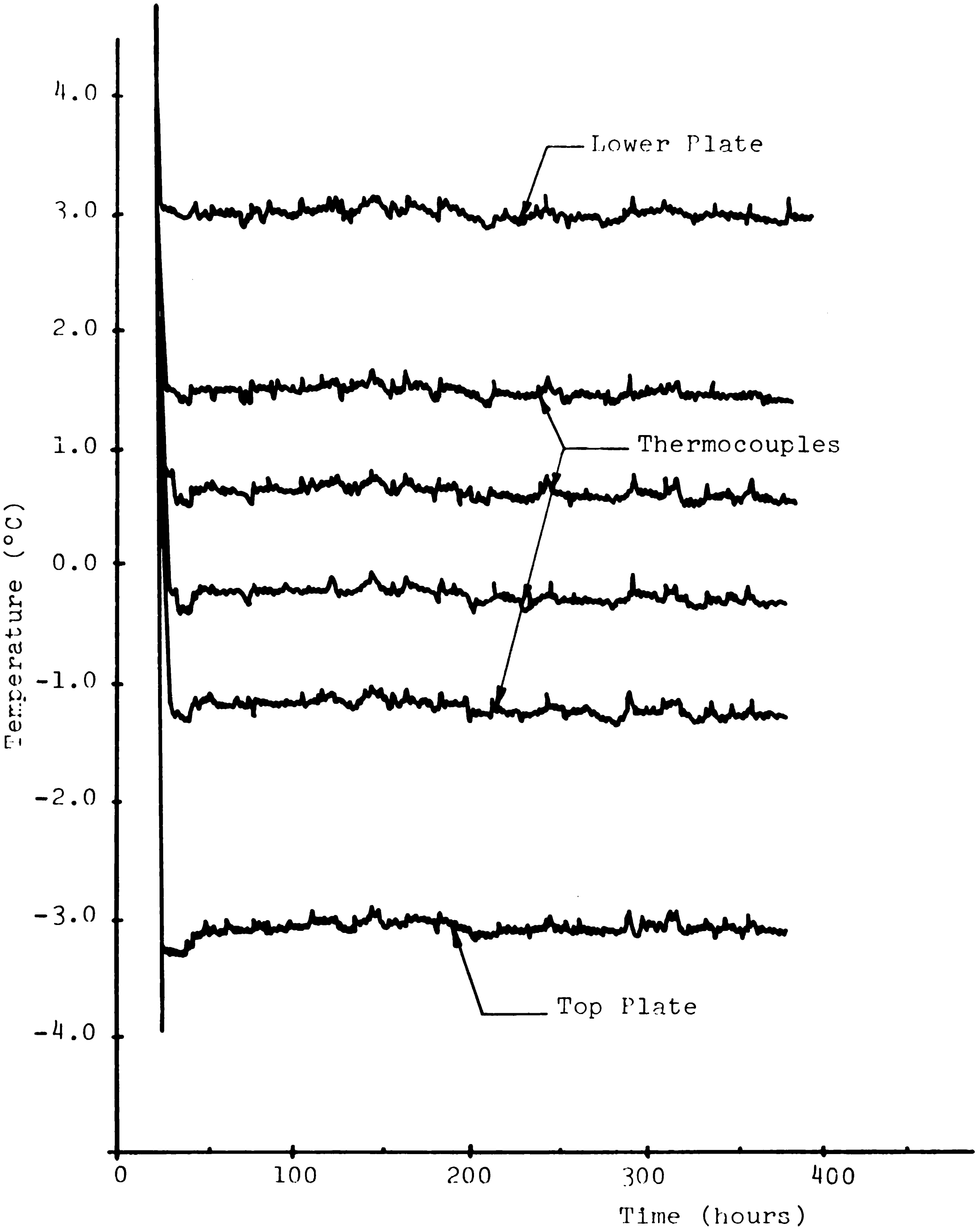


Figure 5.21.--Temperature Profile Across 2" x 4" Samples.

rate of water movement is also much different if ice is nucleated and is growing, than if the system is supercooled and ice formation has not been nucleated. Consideration of the above factors makes it necessary to present the temperature gradient influencing this study.

Temperature profile across the top surface of the soil samples was given in Figure 4.3, Chapter IV. The temperature of the reservoir water before and after freezing was measured to be +22.5°C and +3.5°C, respectively. Using the two known boundary values and assuming similar time lag between the two boundary points, a temperature profile for water in the reservoir may be constructed. This profile is shown in Figure 5.22 in dashed line. The temperature differential varies between 15°C and 7.5°C. With the distance between the two points being 7-1/2 inches, as shown in Figure 4.1, Chapter IV, the temperature gradient may be computed. It varies from 0.76°C/cm to 0.38°C/cm, with the mean value of about 0.60°C/cm, which is below the critical limit and gives realistic and reliable results.

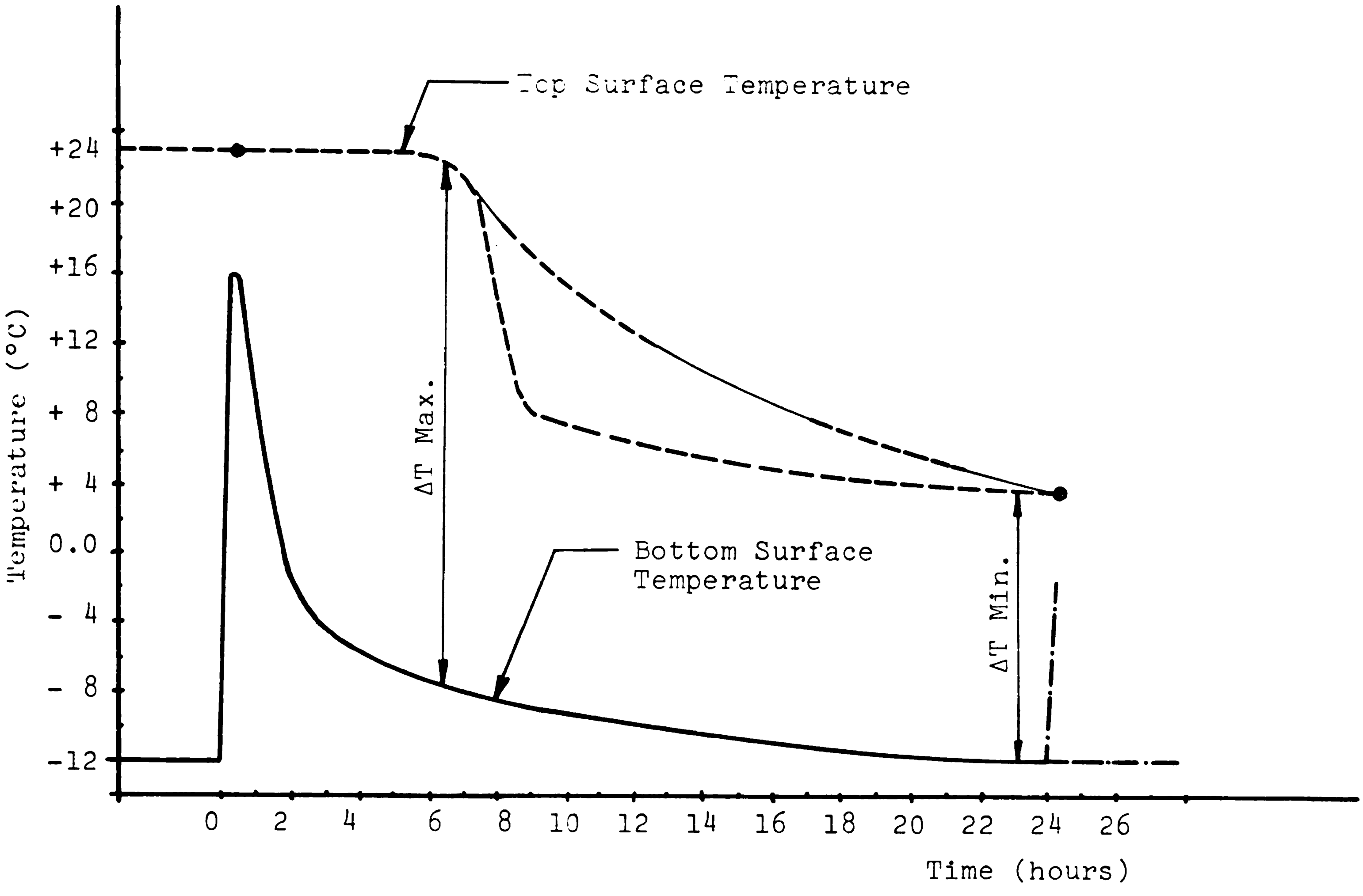


Figure 5.22.--Temperature Profile Across Harvard Size Samples.

CHAPTER VI

DISCUSSION AND PRESENTATION OF THEORY

The results plotted by IBM 1130 computing system, as shown in Figures 5.21 and 5.22, indicate the effectiveness of the chemical employed for waterproofing the soil. Duplicate untreated (natural soil) samples absorbed many times more water than the treated (made waterproof) samples while exposed to the same temperature gradients of 0.60°C/cm for 200+ hours. The variation of water absorption is also true for the 24 hours capillary absorbtion before freezing of the soil samples. Untreated samples of Soil #1 absorbed 24.7 cc of water by capillarity and 7.8 cc of water during the freezing period, while the treated samples absorbed only 1.2 cc of water by capillarity and 3.7 cc of water under freezing exposure. The untreated samples of Soil #1 absorbed 22.3 times as much water by capillary action and their total absorption was about seven times greater than that of the treated samples of the same soil. Most of the moisture absorption in the untreated soils occurred during the first hours of exposure to water, while the treated samples showed a great resistance to water absorption and absorbed practically no water by capillary action. After the period of severe water absorption, the untreated soil samples continue to have a larger rate of absorption than the treated samples. The water absorption of Soil #2 in the freezing boxes indicates similar results as obtained for Soil #1 but with a lesser degree of waterproofing.

It appears that waterproofing chemicals similar to the one used in this study are able to limit water absorption of soils by reducing the soil-water surface tension which is accompanied by a decrease in the soil capillary conductivity. Waterproofed soil samples absorbed negligible capillary moisture and their water content remained at about the optimum moisture content even when they were submerged in water for extended periods of time, while untreated samples of the same soils absorbed water freely. When the samples, after being exposed to capillary action for a period of time, are under freezing temperature the untreated soils start their freezing cycle with a higher water content than their treated counterparts. Since the thermal conductivity of water is higher than that of soil, the freezing temperature may penetrate deeper and faster into the untreated soils which have higher water content. The coefficient of thermal conductivity incrases from about 3 to 14 for silt and clay soils for water content rising from 5 percent to 35 percent (18). When ice is nucleated, and starts to grow, water migrates approximately twice as fast to the freezing fronts in the untreated soils as in the chemically waterproofed soil samples. Formation of ice lens is less extensive in the treated soils because less water is available for freezing and consequently less expansion is expected, as was observed in this study.

For the first cycle of freezing all the soils behaved very similarly. Untreated samples absorbed large amounts of water, while the treated samples retained water contents of a few percent. The capillary absorption of treated samples for a 24 hour period before freezing was approximately zero. The clay Soil #2 indicated somewhat different behavior for the first few cycles of freezing, then approached the expected normal behavior similar to silt soils. The different behavior of clay Soil #2 was probably resultant of expansion of the soil and blocking the water flow paths; after the samples reached an adjusted state of compaction, moisture flow again was normal. This adjustment did not occur in the silty soils and they had a uniform behavior throughout the test cycle. The expansion rate, which is an indication of ice lens growth, was limited in the treated samples. Figure 5.1 shows an expansion approximately 11 times greater for untreated samples of Soil #1, as compared to treated samples. The expansion of untreated samples was a uniform amount above the treated soil samples, until the condition of failure. Figure 5.2 shows that although Soil #2 had a greater heave after the first freezing cycle, it did not expand more than the treated soil samples, up to eight cycles of freezing. This variation of soil expansions was probably due to the swell characteristics of clay Soil #2 under uniform moisture absorption and stepwise water absorption and would need further study. In Figures 5.3 and 5.4 the elevations of top surfaces of the soil samples were plotted after 24 hours of freezing and 12 hours of thaw. It may be seen that the treated Soil #1 had a very small expansion with the first freezing cycle, while untreated samples of the same soil expanded more than 10 times that of the treated samples. It is further shown that the untreated Soil #1 started to fail under its own weight after the second cycle of freezing, while the treated samples retained their shape for more than 10 consecutive cycles of freezing and the elevation of their top surfaces did not change much beyond 10 cycles of freezing. For Soil #2 the expansion with freezing was much the same as Soil #1 but with a smaller rate.

Submerged water absorption of treated and untreated samples of Soil #1 are plotted in Figure 5.7. Figure 5.7 is probably the most significant demonstration of the waterproofing effect of the chemical used. Samples here were tightly jacketed in rubber membrane and could only absorb water from top and bottom through porous stones. This model may be thought of as equivalent to the most adverse field condition for the soil. It was shown that the frost-susceptible Soil #1, when untreated, lost its strength in a very short time, while the treated samples resisted failure and after 52 days of submergence their water content only reached a maximum stable limit of less than 18 percent. The failure of untreated samples, when not jacketed in rubber tubes, is demonstrated in Figure 5.19. It took less than 30 seconds for the untreated sample to reach a fluid state, while treated samples in the same jar and under the same conditions maintained their molded shape, and retained this shape for a much longer time. After approximately two weeks a series of cracks appeared on the end surfaces of treated, submerged samples, extending from one end of the samples to the other end. These cracks were wider at the edges of the samples and gradually faded toward the centers of the end surfaces. The first part of the curves in Figure 5.5 is an approximate condition of water content of samples in the moisture room between the times of molding and submerging, or approximately 168 hours. This period of seven days was recommended by the manufacturer of the chemical for obtaining optimum strength (5). The exact sahpe of the first part of the curve in Figure 5.7 is shown in Figure 5.8. Figure 5.9 shows a similar curve for Soil #2. These two curves were plotted to demonstrate the moisture retention property of the chemical on the soils. Tables 5.10 and 5.11 show the results of moisture retention studies on all of the nine soils. As can be seen, the chemical had a similar effect on all the soils tested.

Moisture content of treated soils after 168 hours in the moisture room and then in the laboratory was a small percent higher than the untreated samples. It was also observed that vapor water absorption had almost no effect on the clay soils but it had some effect on silty nature soils. This can be noted in Tables 5.10 and 5.11 and also in Figures 5.8 and 5.9 when the samples were transferred from the moisture room to the laboratory, at the end of seven days of curing. The moisture retention curves are hyperbolas, and they may be presented with the general formula of hyperbolas as:

$$w = \frac{a}{b+dt} \tag{6-1}$$

in which w is moisture content, t is time, and a, b, and d are constant coefficients.

The same samples used for water retention were used for freezing studies in open system. Columns 14 and 15 of Table 5.10 and colums 11 and 12 of Table 5.11 show the water content of the soils after freezing. To show the effect of waterproofing, pictures of treated and untreated samples of some of the soils after the second thaw are shown in Figures 5.5 and 5.6. In these pictures the size and shape of the samples after the freezing period may be compared with the Harvard mold. Figure 5.6_c shows the failure of an untreated sample of Soil #7, while the treated sample still has almost its original shape. This soil is yellowish in color and has about 75 percent silt, 19 percent clay, and 6 percent sand.

As far as water content is concerned, as stated previously in Chapters IV and V, Series B samples were most suitable. Tables 5.12 and 5.13 give the water content of the samples of this series with the cycles of freezing. The results are further plotted in Figures 5.10 through 5.13. Of these, the results of the open system are very interesting. It may be noted that the curves of Figures 5.10 and 5.11 follow the path of an S-shaped curve or so-called logistic curve. The general formula for the logistic curve may be written as:

$$Y = L \,/\, (1+m.\exp.n.c) \qquad (6\text{-}2)$$

where for our case Y is water content at any freezing cycle c, L is upper limit for Y, or saturation water content, and m and n are coefficients that may be determined with sufficient known boundary conditions. Taking the three necessary boundary conditions as water contents of soil at three equally distanced freezing cycles, the formulas developed by R. Pears (11) may be employed. Using Pears' method, the constants of formula 6-2 may be determined by selecting three points uniformly spaced along the c axis, $(0, Y_o)$, (C_1, Y_1), and $(2C_1, Y_2)$ and substituting in the following formulas (11):

$$L = [2Y_oY_1Y_2 - Y_1^2 (Y_o + Y_2)] / (Y_oY_2-Y_1^2) \quad (6\text{-}3)$$

$$m = (L - Y_o) / Y_o \quad (6\text{-}4)$$

$$n = (1/C_1) L_n [Y_o(L-Y_1) / Y_1 (L - Y_o)] \quad (6\text{-}5)$$

and the percent saturation P, at any cycle, may be calculated using:

$$P = 100Y / L = 100 / (1+m \cdot \exp.\ n \cdot c) \quad (6\text{-}6)$$

Formula 6-6 is a rewrite of formula 6-2, assuming the saturation point having a value of 100. The L_n in the above formulas indicates logarithms on natural basis, or naperian logarithms. Solution for water content by this method requires running a few cycles of freeze-thaw on the soil under study. It is then possible to calculate and plot the entire curve or compute the maximum possible freezing water content, or its water content after any given number of freezing cycles. As an example, the curve for treated samples from Figure 5.10 is worked out theoretically, using formulas 6-2 through 6-5.

With the data, taking the origin at the third cycles

$C_o = 0$, $Y_o = 8.50$

$C_1 = 3$, $Y_1 = 17.00$

$C_2 = 2 \cdot 3 = 6$, $Y_2 = 25.00$

a. Maximum saturation:

$$L=\frac{(2\cdot 8.50\cdot 17.0\cdot 25.0) - (17.0)^2 (8.5+25.0)}{(8.5\cdot 25.0) - (17.0)^2}=\frac{-2450}{-76.5}=32.04$$

b. Coefficients:

$$m = (32.04-8.50) / 8.50 = 2.77$$

$$n = (1/3)\ L_n \frac{8.5\ (32.04-17.0)}{17.0\ (32.04-8.5)}=(1/3)\ L_n(0.32)=-0.380$$

c. General formula

$$Y = 32.04 / (1+2.77\ e^{-0.380C}) \qquad , e = 2.718$$

where C is the number of cycles for a particular water content w.

These formulas are equivalently good for untreated soils as well as treated soils, but only for the case when water is available to satisfy the soil tension with dropping temperatures, or it is valid for the open system of freezing only. The water content of soils in closed system is not of much importance and as found in this study, no considerable problem may arise when water is not available during soil freezing. Figures 5.12 and 5.13 do not indicate any significant result other than the samples adjusting themselves to the temperature and moisture conditions in the freezing boxes, and treated soil samples having a higher water content throughout the period. This property was previously discussed as water retention properties of the soil-waterproofing chemicals in this chapter.

Behavior of Series A samples appears not to be different from that of Series B. Thus comparison is shown in Figure 5.14. Untreated samples of this series at the end of 24 hours of exposure to zero tension water level, increased their water content to approximately 24 percent, while treated samples remained at less than 5 percent water content. The high water content of the untreated samples at the first cycle of freezing causes a very high water migration to freezing fronts. Part of this water content was drained away after first thaw and the soil behavior after that was normal until about the fifth freezing cycles, at which no more water was available in the reservoir and the water content decreased due to evaporation. Although these curves appear different from the S-shaped curves of Figure 5.10, an approximate graphical curve fitting verifies that they are not much different, especially for treated samples. The approximate graphical fittings are showr by dashed lines in Figure 5.14.

Shear strengths of Soils #1 and #2 are given in Tables 5.16, 5.17 and Figures 5.16 through 5.18. The strength reduction with increasing water content is obvious. An interesting observation from Figure 5.17 indicates that the treated samples exhibit lower strengths for each cycle of freezing. The waterproofing chemical had no effect on the shear strength of the treated soils not exposed to water. The treatment of soils with the chemical waterproofers actually may decrease soil strength by diminishing the bonding moisture.

CHAPTER VII

CONCLUSIONS

With regard to the experimental results for the chemically treated soil samples and the comparison to their untreated counterparts, the following conclusions may be made:

1. Waterproofing chemicals similar to the one used in this study are not able to stop, but limit water absorption, of soils by reducing the tendency of soil particles to absorb water and also by decreasing their capillary conductivity, therefore perserving soil strength.
2. Waterproofing chemicals may work in two ways: they repel water if the treated soil is in contact with water, but they retain a slight percent more moisture from the natural soil if treated but not in contact with water.
3. Moisture retention may be represented as a hyperbolic function of time and the constants of general formula for each soil may be obtained with known moisture contents at given boundary points.
4. There is a maximum limit for water content of soils made waterproof. For silty soils this limit is a few percent

above the optimum moisture content, when untreated soil absorbs water freely.

5. Water absorption by soils exposed to freezing cycles in open system of freezing may be presented by an S-shaped curve. General formulas with coefficients and method of predicting of maximum water content are presented.

6. TBC waterproofing chemical is an additive of promise and may be used with some problem soils to overcome, or at least limit, soil-water problems.

7. Considering the shear strength of the treated soils, it may be suggested that the waterproofing chemical not be used for unpaved, load-bearing soils, under severe weather conditions and high water table.

8. Waterproofing chemicals, similar to the one used in this study, have no effect on soils treated when not in contact with water. They may actually decrease soil strength.

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BIBLIOGRAPHY

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APPENDIX

DATA

Measurements for Height of Samples (in.)
Soil #1
Series B.

Sample	Submerged (24 hrs.)	Freezing Cycles 1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16	
		Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.
$O-T_1$	$1\frac{30}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-T_2$	$1\frac{26}{32}$	$1\frac{20}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-T_3$	$1\frac{30}{32}$	$1\frac{29}{32}$	$1\frac{29}{32}$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{26}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-T_4$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{28}{32}$	2.00	$1\frac{28}{32}$	$1\frac{30}{32}$	$1\frac{28}{32}$	$1\frac{30}{32}$	$1\frac{25}{32}$	$1\frac{31}{32}$	$1\frac{23}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-T_5$	$1\frac{30}{32}$	$1\frac{31}{32}$	2.00	$1\frac{28}{32}$	$1\frac{31}{32}$	$1\frac{29}{32}$	2.00	$1\frac{29}{32}$	2.00	$1\frac{27}{32}$	$1\frac{31}{32}$	$1\frac{25}{32}$	$1\frac{29}{32}$	$1\frac{18}{32}$	$1\frac{31}{32}$	$1\frac{29}{32}$	$2\frac{5}{32}$	$1\frac{26}{32}$	$2\frac{5}{32}$	$2\frac{1}{32}$	$2\frac{10}{32}$	$2\frac{9}{32}$	$2\frac{15}{32}$	$2\frac{11}{32}$	$2\frac{15}{32}$	$2\frac{11}{32}$	$2\frac{16}{32}$	$2\frac{6}{32}$	$2\frac{18}{32}$	$2\frac{29}{32}$	---	---	---
$O-T_6$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{28}{32}$	$1\frac{31}{32}$	$1\frac{28}{32}$	$1\frac{30}{32}$	$1\frac{29}{32}$	$1\frac{30}{32}$	$1\frac{27}{32}$	$1\frac{31}{32}$	$1\frac{25}{32}$	2.00	$1\frac{26}{32}$	$2\frac{1}{32}$	2.00	$2\frac{4}{32}$	$1\frac{25}{32}$	$2\frac{4}{32}$	$1\frac{26}{32}$	$2\frac{4}{32}$	2.00	$2\frac{16}{32}$	$2\frac{2}{32}$	$2\frac{9}{32}$	$2\frac{2}{32}$	$2\frac{9}{32}$	$1\frac{30}{32}$	$2\frac{9}{32}$	$2\frac{6}{32}$	---	$2\frac{11}{32}$	---
$O-T_7$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{31}{32}$	$1\frac{30}{32}$	$1\frac{31}{32}$	$1\frac{29}{32}$	$1\frac{31}{32}$	$1\frac{28}{32}$	$1\frac{31}{32}$	$1\frac{26}{32}$	2.00	$1\frac{27}{32}$	$2\frac{1}{32}$	$2\frac{1}{32}$	$2\frac{12}{32}$	$2\frac{1}{32}$	$2\frac{12}{32}$	$2\frac{5}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-T_8$	2.00	$1\frac{31}{32}$	$1\frac{31}{32}$	$1\frac{29}{32}$	$2\frac{1}{32}$	$1\frac{28}{32}$	$2\frac{1}{32}$	$1\frac{30}{32}$	$1\frac{31}{32}$	$1\frac{28}{32}$	$1\frac{31}{32}$	$1\frac{26}{32}$	$1\frac{31}{32}$	$1\frac{17}{32}$	2.00	$1\frac{30}{32}$	$2\frac{1}{32}$	$1\frac{27}{32}$	$2\frac{1}{32}$	$1\frac{29}{32}$	$2\frac{2}{32}$	$1\frac{30}{32}$	$2\frac{3}{32}$	$1\frac{30}{32}$	$2\frac{3}{32}$	$1\frac{30}{32}$	$2\frac{5}{32}$	$1\frac{30}{32}$	$2\frac{8}{32}$	$2\frac{4}{32}$	---	$2\frac{5}{32}$	---
$O-T_9$	2.00	$1\frac{28}{32}$	$1\frac{28}{32}$	$1\frac{28}{32}$	$2\frac{1}{32}$	$1\frac{25}{32}$	$2\frac{1}{32}$	$1\frac{24}{32}$	$1\frac{31}{32}$	$1\frac{27}{32}$	$1\frac{31}{32}$	$1\frac{28}{32}$	$1\frac{31}{32}$	$1\frac{27}{32}$	$1\frac{31}{32}$	$1\frac{27}{32}$	2.00	$1\frac{25}{32}$	2.00	$1\frac{25}{32}$	$1\frac{31}{32}$	$1\frac{28}{32}$	$1\frac{30}{32}$	$1\frac{28}{32}$	$1\frac{31}{32}$	$1\frac{27}{32}$	$1\frac{31}{32}$	$1\frac{23}{32}$	2.00	$1\frac{23}{32}$	---	$1\frac{22}{32}$	

Sample	Capillary Moisture (24 hrs.)	Freezing Cycles 1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16	
		Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.
$O-U_1$	$1\frac{28}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_2$	$1\frac{26}{32}$	$1\frac{8}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_3$	$1\frac{28}{32}$	$1\frac{10}{32}$	$1\frac{24}{32}$	$1\frac{20}{32}$	$1\frac{25}{32}$	$1\frac{24}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_4$	$1\frac{22}{32}$	$1\frac{12}{32}$	$1\frac{24}{32}$	$1\frac{21}{32}$	$1\frac{26}{32}$	$1\frac{24}{32}$	$1\frac{27}{32}$	$1\frac{16}{32}$	$1\frac{28}{32}$	$1\frac{26}{32}$	$2\frac{1}{32}$	$2\frac{5}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_5$	$1\frac{18}{32}$	$1\frac{18}{32}$	$1\frac{24}{32}$	$1\frac{14}{32}$	$1\frac{24}{32}$	$1\frac{20}{32}$	$1\frac{28}{32}$	$1\frac{16}{32}$	$1\frac{30}{32}$	$1\frac{25}{32}$	$2\frac{1}{32}$	$1\frac{31}{32}$	$2\frac{15}{32}$	$2\frac{10}{32}$	$2\frac{20}{32}$	$2\frac{14}{32}$	$2\frac{22}{32}$	$2\frac{10}{32}$	$2\frac{23}{32}$	$2\frac{12}{32}$	$2\frac{24}{32}$	$2\frac{18}{32}$	$2\frac{26}{32}$	$2\frac{20}{32}$	$2\frac{26}{32}$	$2\frac{19}{32}$	$2\frac{27}{32}$	$2\frac{22}{32}$	$2\frac{31}{32}$	$2\frac{27}{32}$	---	---	---
$O-U_6$	$1\frac{18}{32}$	$1\frac{8}{32}$	$1\frac{24}{32}$	$1\frac{14}{32}$	$1\frac{24}{32}$	$1\frac{21}{32}$	$1\frac{18}{32}$	$1\frac{19}{32}$	$1\frac{30}{32}$	$1\frac{30}{32}$	$2\frac{3}{32}$	$2\frac{4}{32}$	$2\frac{21}{32}$	$2\frac{2}{32}$	$2\frac{15}{32}$	$2\frac{8}{32}$	$2\frac{18}{32}$	$2\frac{6}{32}$	$2\frac{18}{32}$	$2\frac{11}{32}$	$2\frac{28}{32}$	$2\frac{18}{32}$	$2\frac{26}{32}$	$2\frac{16}{32}$	$2\frac{26}{32}$	$2\frac{19}{32}$	$2\frac{25}{32}$	$2\frac{20}{32}$	$2\frac{31}{32}$	3.00	---	$3\frac{5}{32}$	---
$O-U_7$	$1\frac{26}{32}$	$1\frac{26}{32}$	$1\frac{29}{32}$	$1\frac{23}{32}$	$1\frac{26}{32}$	$1\frac{23}{32}$	$1\frac{28}{32}$	$1\frac{22}{32}$	$1\frac{28}{32}$	$1\frac{31}{32}$	$2\frac{3}{32}$	$2\frac{4}{32}$	$2\frac{18}{32}$	$2\frac{11}{32}$	$2\frac{19}{32}$	$2\frac{13}{32}$	$2\frac{22}{32}$	$2\frac{10}{32}$	$2\frac{20}{32}$	$2\frac{11}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---
$O-U_8$	$1\frac{26}{32}$	$1\frac{8}{32}$	$1\frac{24}{32}$	$1\frac{23}{32}$	$1\frac{26}{32}$	$1\frac{25}{32}$	$1\frac{30}{32}$	$1\frac{25}{32}$	$2\frac{2}{32}$	$2\frac{1}{32}$	$2\frac{6}{32}$	$2\frac{7}{32}$	$2\frac{18}{32}$	$2\frac{9}{32}$	$2\frac{20}{32}$	$2\frac{10}{32}$	$2\frac{18}{32}$	$2\frac{6}{32}$	$2\frac{16}{32}$	$2\frac{6}{32}$	$2\frac{18}{32}$	$2\frac{19}{32}$	$2\frac{26}{32}$	$2\frac{22}{32}$	$2\frac{28}{32}$	$2\frac{21}{32}$	$2\frac{28}{32}$	$2\frac{22}{32}$	$3\frac{1}{32}$	3.00	---	3.00	---
$O-U_9$	$1\frac{26}{32}$	$1\frac{12}{32}$	$1\frac{24}{32}$	$1\frac{24}{32}$	$1\frac{27}{32}$	$1\frac{26}{32}$	2.00	$1\frac{25}{32}$	$2\frac{6}{32}$	$2\frac{6}{32}$	$2\frac{8}{32}$	$2\frac{12}{32}$	$2\frac{23}{32}$	$2\frac{13}{32}$	$2\frac{17}{32}$	$2\frac{12}{32}$	$2\frac{20}{32}$	$2\frac{9}{32}$	$2\frac{18}{32}$	$2\frac{8}{32}$	$2\frac{19}{32}$	$2\frac{11}{32}$	$2\frac{21}{32}$	$2\frac{20}{32}$	$2\frac{24}{32}$	$2\frac{15}{32}$	$2\frac{23}{32}$	$2\frac{17}{32}$	$2\frac{26}{32}$	$2\frac{21}{32}$	---	$2\frac{19}{32}$	---

Height of Sample = 5.00" - measured distance.

Measurement of Height of Samples (in.)
Soil #2
Series B

Sample	Submerged (24 hrs.)	Freezing Cycles																															
		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16	
		Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.
O-T_1	$2\frac{3}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_2	$2\frac{2}{32}$	$1\frac{30}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_3	2.00	$1\frac{30}{32}$	$2\frac{1}{32}$	$1\frac{29}{32}$	$1\frac{30}{32}$	$1\frac{28}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_4	$2\frac{3}{32}$	$2\frac{1}{32}$	$2\frac{3}{32}$	2.0	$2\frac{2}{32}$	$1\frac{31}{32}$	$2\frac{2}{32}$	$1\frac{31}{32}$	$2\frac{2}{32}$	$1\frac{28}{32}$	$2\frac{1}{32}$	$1\frac{26}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_5	$2\frac{4}{32}$	$2\frac{2}{32}$	$2\frac{5}{32}$	$2\frac{3}{32}$	$2\frac{4}{32}$	$2\frac{1}{32}$	$2\frac{4}{32}$	$2\frac{1}{32}$	$2\frac{4}{32}$	$1\frac{27}{32}$	$2\frac{3}{32}$	$1\frac{28}{32}$	$2\frac{1}{32}$	$1\frac{25}{32}$	$2\frac{3}{32}$	2.00	$2\frac{5}{32}$	$1\frac{30}{32}$	$2\frac{4}{32}$	$1\frac{25}{32}$	$2\frac{5}{32}$	$1\frac{26}{32}$	$2\frac{7}{32}$	$2\frac{2}{32}$	$2\frac{8}{32}$	$2\frac{5}{32}$	$2\frac{8}{32}$	$1\frac{30}{32}$	$2\frac{7}{32}$	$1\frac{30}{32}$	—	$1\frac{14}{32}$	—
O-T_6	$2\frac{4}{32}$	$1\frac{30}{32}$	$2\frac{2}{32}$	2.00	$2\frac{2}{32}$	$1\frac{31}{32}$	$2\frac{2}{32}$	$1\frac{30}{32}$	$2\frac{2}{32}$	$1\frac{26}{32}$	$2\frac{1}{32}$	$1\frac{28}{32}$	$2\frac{3}{32}$	$1\frac{28}{32}$	$2\frac{3}{32}$	2.00	$2\frac{3}{32}$	$1\frac{31}{32}$	$2\frac{2}{32}$	$1\frac{27}{32}$	$2\frac{4}{32}$	$1\frac{29}{32}$	$2\frac{4}{32}$	$1\frac{30}{32}$	$2\frac{4}{32}$	2.00	$2\frac{6}{32}$	$1\frac{28}{32}$	$2\frac{5}{32}$	$1\frac{28}{32}$	—	—	—
O-T_7	$2\frac{3}{32}$	2.00	$2\frac{4}{32}$	$2\frac{1}{32}$	$2\frac{2}{32}$	$1\frac{31}{32}$	$2\frac{3}{32}$	$1\frac{31}{32}$	$2\frac{3}{32}$	$1\frac{30}{32}$	$2\frac{3}{32}$	$1\frac{27}{32}$	$2\frac{3}{32}$	$1\frac{27}{32}$	$2\frac{3}{32}$	$1\frac{28}{32}$	$2\frac{3}{32}$	$1\frac{28}{32}$	$2\frac{2}{32}$	$1\frac{24}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---
O-T_8	$2\frac{3}{32}$	2.00	$2\frac{4}{32}$	2.0	$2\frac{2}{32}$	$1\frac{31}{32}$	$2\frac{3}{32}$	$1\frac{31}{32}$	$2\frac{3}{32}$	2.00	$2\frac{4}{32}$	$1\frac{30}{32}$	$2\frac{4}{32}$	$1\frac{30}{32}$	$2\frac{3}{32}$	$1\frac{29}{32}$	$2\frac{3}{32}$	$1\frac{26}{32}$	$2\frac{3}{32}$	$1\frac{24}{32}$	$2\frac{3}{32}$	$1\frac{27}{32}$	$2\frac{4}{32}$	$1\frac{28}{32}$	$2\frac{4}{32}$	$1\frac{30}{32}$	$2\frac{4}{32}$	$1\frac{29}{32}$	$2\frac{7}{32}$	$1\frac{26}{32}$	—	$1\frac{17}{32}$	—
O-T_9	$2\frac{3}{32}$	$1\frac{29}{32}$	$2\frac{4}{32}$	$1\frac{31}{32}$	$2\frac{2}{32}$	$1\frac{30}{32}$	$2\frac{2}{32}$	$1\frac{28}{32}$	$2\frac{2}{32}$	$1\frac{30}{32}$	$2\frac{2}{32}$	$1\frac{30}{32}$	$2\frac{2}{32}$	$1\frac{29}{32}$	$2\frac{2}{32}$	$1\frac{29}{32}$	$2\frac{2}{32}$	$1\frac{25}{32}$	$2\frac{3}{32}$	$1\frac{30}{32}$	$2\frac{2}{32}$	$1\frac{26}{32}$	$2\frac{1}{32}$	$1\frac{26}{32}$	$2\frac{3}{32}$	$1\frac{29}{32}$	$2\frac{3}{32}$	$1\frac{29}{32}$	$2\frac{5}{32}$	$1\frac{26}{32}$	—	$1\frac{18}{32}$	—

Samples	Capillary Moisture (24 hrs.)	Freezing Cycles																															
		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15		16	
		Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.	Fr.	Th.
O-U_1	2.00	---		---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U_2	2.00	$1\frac{26}{32}$		---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U_3	$1\frac{21}{32}$	$1\frac{27}{32}$		$1\frac{30}{32}$	$1\frac{30}{32}$	$1\frac{29}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U_4	$2\frac{2}{32}$	$1\frac{29}{32}$		$2\frac{1}{32}$	2.00	2.00	$2\frac{1}{32}$	$1\frac{25}{32}$	2.00	$1\frac{28}{32}$	$2\frac{2}{32}$	$1\frac{26}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U_5	$2\frac{2}{32}$	$1\frac{27}{32}$		$2\frac{1}{32}$	2.00	$2\frac{1}{32}$	$2\frac{1}{32}$	$1\frac{29}{32}$	2.00	$1\frac{30}{32}$	$2\frac{2}{32}$	$1\frac{27}{32}$	$2\frac{1}{32}$	$1\frac{26}{32}$	$2\frac{3}{32}$	$1\frac{29}{32}$	$2\frac{5}{32}$	$1\frac{24}{32}$	$2\frac{9}{32}$	$1\frac{21}{32}$	$2\frac{5}{32}$	$1\frac{28}{32}$	$2\frac{6}{32}$	$2\frac{1}{32}$	$2\frac{8}{32}$	$2\frac{4}{32}$	$2\frac{8}{32}$	$1\frac{30}{32}$	$1\frac{10}{32}$	$1\frac{31}{32}$	---	---	---
O-U_6	$2\frac{2}{32}$	$1\frac{30}{32}$		$2\frac{1}{32}$	$2\frac{1}{32}$	2.00	$2\frac{1}{32}$	2.00	2.00	2.00	$2\frac{2}{32}$	$1\frac{27}{32}$	$2\frac{1}{32}$	$1\frac{26}{32}$	$2\frac{3}{32}$	$1\frac{27}{32}$	$2\frac{4}{32}$	$1\frac{24}{32}$	$2\frac{3}{32}$	$1\frac{20}{32}$	$2\frac{3}{32}$	$1\frac{24}{32}$	$2\frac{6}{32}$	$1\frac{30}{32}$	$2\frac{8}{32}$	$2\frac{3}{32}$	$2\frac{8}{32}$	$1\frac{30}{32}$	$2\frac{8}{32}$	$1\frac{28}{32}$	---	---	$1\frac{21}{32}$
O-U_7	$2\frac{6}{32}$	$1\frac{29}{32}$		2.00	$2\frac{2}{32}$	2.00	$2\frac{2}{32}$	$1\frac{30}{32}$	$2\frac{3}{32}$	2.00	$2\frac{4}{32}$	$1\frac{29}{32}$	$2\frac{3}{32}$	$1\frac{28}{32}$	$2\frac{5}{32}$	$1\frac{27}{32}$	$2\frac{4}{32}$	$1\frac{25}{32}$	$2\frac{4}{32}$	$1\frac{23}{32}$	---	---	---	---	---	---	---	---	---	---	---	---	---
O-U_8	$2\frac{5}{32}$	$2\frac{3}{32}$		$2\frac{3}{32}$	$2\frac{5}{32}$	$2\frac{3}{32}$	$2\frac{6}{32}$	2.00	$2\frac{5}{32}$	2.00	$2\frac{5}{32}$	$1\frac{31}{32}$	$2\frac{5}{32}$	2.00	$2\frac{6}{32}$	$1\frac{29}{32}$	$2\frac{7}{32}$	$1\frac{28}{32}$	$2\frac{6}{32}$	$1\frac{26}{32}$	$2\frac{6}{32}$	$1\frac{27}{32}$	$2\frac{6}{32}$	$2\frac{2}{32}$	$2\frac{6}{32}$	$2\frac{3}{32}$	$2\frac{8}{32}$	2.00	$2\frac{9}{32}$	$1\frac{29}{32}$	---	---	$1\frac{21}{32}$
O-U_9	$2\frac{3}{32}$	$1\frac{28}{32}$		$2\frac{1}{32}$	$2\frac{2}{32}$	$2\frac{1}{32}$	$2\frac{6}{32}$	$1\frac{29}{32}$	$2\frac{4}{32}$	$1\frac{29}{32}$	$2\frac{5}{32}$	$1\frac{30}{32}$	$2\frac{5}{32}$	$1\frac{28}{32}$	$2\frac{5}{32}$	$1\frac{24}{32}$	$2\frac{4}{32}$	$1\frac{23}{32}$	$2\frac{4}{32}$	$1\frac{20}{32}$	$2\frac{4}{32}$	$1\frac{24}{32}$	$2\frac{3}{32}$	$1\frac{28}{32}$	$2\frac{5}{32}$	2.00	$2\frac{6}{32}$	2.00	$2\frac{5}{32}$	$1\frac{28}{32}$	---	---	$1\frac{18}{32}$

Height of Samples = 5.00' - measured distance.

Series B Samples
Soils #1 and #2

Sample O-T_1-#1
After 24 hours capillarity moisture

Load Dial. ($x10^{-4}$ in.)	Strain Dial. ($x10^{-3}$ in.)
0	0
47	12
70	19
85	22
100	26
120	31
130	35
137	43
70	73
50	95

cont'r wt. & sample wt. = 149.80 grs.
cont'r wt. & oven dry wt. = 144.22
cont'r wt. = 36.88

w = 5.58/107.34 = 5.19%

Sample O-U_1-#1
After 24 hours of capillarity moisture

2	5
5	12
8	20
11	29
12	38
13	50
13	75
11	91
11	120

cont'r wt. & sample wt. = 171.16 grs.
cont'r wt. & oven dry wt. = 145.53
cont'r wt. = 37.40

2 = 25.63/108.13 = 23.70%

Sample O-T_1-#2

After 24 hours of capillarity moisture

Load Dial.	Strain Dial.
9	1
34	5
65	10
136	20
210	30
311	40
353	70
357	80
350	90

cont'r wt. & sample wt. = 154.57 grs.
cont'r wt. & oven dry wt. = 145.88
cont'r wt. = 37.26

w = 8.69/108.62 = 8%

Sample O-U_1-#2

After 24 hours of capillarity moisture

0	0
5	8
10	25
15	44
30	130
40	212
43	240
50	295
56	350
60	379

cont'r wt. & sample wt. = 163.87
cont'r wt. & oven dry wt. = 146.47
cont'r wt. = 37.70

w = 17.40/108.77 = 16.1%

Sample C-T_1-#1

After 24 hours of capillarity moisture

Load Dial.	Strain Dial.
0	0
22	1
42	2
81	4
132	6
231	9
332	11
433	14
600	18
660	23
680	27
681	31

cont'r wt. & sample wt. = 140.20
cont'r wt. & oven dry wt. = 137.33
cont'r wt. = 37.62

w = 2.67/99.71 = 2.68%

Sample C-U_1-#1

After 24 hours of capillarity moisture

0	0
54	1
110	2
165	3
269	4
345	5
421	7
480	10
535	13
585	16
635	20
640	27

cont'r wt. & sample wt. = 149.10
cont'r wt. & oven dry wt. = 146.50
cont'r wt. = 38.61

2 = 2.60/107.89 = 2.41%

Sample C-T_1-#2

After 24 hours of capillarity moisture

Load Dial.	Strain Dial.
0	0
54	3
100	5
193	5
254	12
343	16
397	20
450	25
497	30
532	35
558	40
565	44
543	50

cont'r wt. & sample wt. = 143.55
cont'r wt. & oven dry wt. = 139.35
cont'r wt. = 37.51

$w = 4.20/101.84 = 4.13\%$

Sample C-U_1-#2

After 24 hours of capillarity moisture

0	0
20	0
60	0
75	0.5
131	1.5
180	2
272	3
341	4
392	5
427	7
467	10
523	14

cont'r wt. & sample wt. = 154.36
cont'r wt. & oven dry wt. = 150.22
cont'r wt. = 37.26

$w = 4.14/112.96 = 3.66\%$

Sample C-T_1-#2 (cont'd)

Load Dial.	Strain Dial.
591	20
637	25
669	30
679	32
687	34
700	36^5
719	39
730	42
732	45
725	50

Sample O-T_2-#1

W-#1
After one freezing cycle

0	0
12	1
26	4
45	8
69	14
91	20
103	25
109	39
90	50

cont'r wt. & sample wt. = 148.92
cont'r wt. & oven dry wt. = 142.50
cont'r wt. = 36.86

w = 6.42/105.64 = 6.09%

Sample O-U_2-#1
After one freezing cycle

Load Dial.	Strain Dial.
0	0
0	

cont'r wt. & sample wt. = 184.35
cont'r wt. & oven dry wt. = 154.56
cont'r wt. = 37.40

w = 29.79/117.16 = 25.30%

Sample O-T_2-#2
After one freezing cycle

Load Dial. $0x10^{-4}$ in.	Strain Dial. $0x10^{-3}$ in.
8	1
29	5
41	10
94	50
105	70
152	130
171	150
205	200
195	220

cont'r wt. & sample wt. = 155.86
cont'r wt. & oven dry wt. = 145.50
cont'r wt. = 37.26

w = 10.36/108.24 = 9.56%

Sample O-U_2-#2
After one freezing cycle

Load Dial.	Strain Dial.
0	0
112	20
1	38
2	80
6	315
7	400

cont'r wt. & sample wt. = 171.50
cont'r wt. & oven dry wt. = 147.00
cont'r wt. = 37.70

w = 27.50/109.30 = 25.16%

Sample C-T_2-#1
After one freezing cycle

39	1
86	3
315	10
417	15
461	20
517	30

cont'r wt. & sample wt. = 123.30
cont'r wt. & oven dry wt. = 120.52
cont'r wt. = 37.62

w = 2.78/82.90 = 3.36%

Sample C-U_2-#1
After one freezing cycle

0	0
49	1
112	3
337	10
563	20
619	26
625	30

cont'r wt. & sample wt. = 148.00
cont'r wt. & oven dry wt. = 145.20
cont'r wt. = 38.61

w = 2.80/106.59 = 2.63%

Sample C-T_2-#2

After one freezing cycle

Load Dial.	Strain Dial.
0	0
97	5
268	10
592	30
691^5	47
716	50
729	53

cont'r wt. & sample wt. = 159.10
cont'r wt. & oven dry wt. = 153.40
cont'r wt. = 37.51

w = 5.70/115.89 = 4.91%

Sample C-U_2-#2

After one freezing cycle

0	0
42	1
434	10
560	20
689	40
692	42
692^5	45
690	47

cont'r wt. & sample wt. = 151.88
cont'r wt. & oven dry wt. = 147.25
cont'r wt. = 37.26

w = 4.63/109.99 = 4.21%

Sample O-T_3-#1
After three freezing cycles

Load Dial.	Strain Dial.
0	0
9	5
13	10
18	20
25	40
32	80
26	100

cont'r wt. & sample wt. = 153.93
cont'r wt. & oven dry wt. = 144.84
cont'r wt. = 36.88

w = 9.09/107.76 = 8.43%

Sample O-U_3-#1
After three freezing cycles

0	0
0	-

cont'r wt. & sample wt. = 179.70
cont'r wt. & oven dry wt. = 145.67
cont'r wt. = 37.40

w = 34.03/108.27 = 31.41%

Sample O-T_3-#2
After three freezing cycles

0	0
7	5
10^5	10
25	37
30	47
75	159
80	187
80^5	200
81	210
80	240

cont'r wt. & sample wt. = 163.03
cont'r wt. & oven dry wt. = 149.38
cont'r wt. = 37.26

w = 13.65/112.12 = 12.17%

Sample O-U_3-#2
After three freezing cycles

Load Dial.	Strain Dial.
0	0
1	6
2	21
4	61
12	300
15	443
18	600

cont'r wt. & sample wt. = 172.48
cont'r wt. & oven dry wt. = 148.23
cont'r wt. = 37.70

w = 24.25/110.53 = 21.95%

Sample C-T_3-#1
After three freezing cycles

0	0
14	1
218	10
480	21
557	30
569	35
360	37

cont'r wt. & sample wt. = 147.52 grs.
cont'r wt. & oven dry wt. = 144.50
cont'r wt. = 37.62

w = 3.02/106.88 = 2.85%

Sample C-U_3-#1

After three freezing cycles

Load Dial.	Strain Dial.
0	0
26	1
295	7
475	15
548	20
605	25
622	28

cont'r wt. & sample wt. = 149.70 grs.
cont'r wt. & dry oven wt. = 147.38
cont'r wt. = 38.61

w = 2.41/108.77 = 2.10%

Sample C-T_3-#2

After three freezing cycles

0	0
15	1
195	10
435	20
550	30
606	40
615	45
610	50

cont'r wt. & sample wt. = 156.59
cont'r wt. & dry oven wt. = 151.00
cont'r wt. = 37.51

w = 5.59/113.49 = 4.92%

Sample C-U_3-#2

After three freezing cycles

0	0
28	1
359	10
489	20
545	25
662	40
678	44

cont'r wt. & sample wt. = 152.57
cont'r wt. & dry oven wt. = 148.07
cont'r wt. = 37.26

w = 4.50/110.81 = 4.06%

Sample C-U_3-#1 (cont'd)

Load Dial.	Strain Dial.
685	50
670	55

Sample O-T_4-#2

After six freezing cycles

0	0
3	10
4	20
8	158
12	334
15	540

cont'r wt. & sample wt. = 165.32

cont'r wt. & dry oven wt. = 147.22

cont'r wt. = 37.26

w = 18.10/109.96 = 16.45%

Sample O-T_4-#1

After six feeezing cycles

0	0
18	5
28	10
50	20
68	30
86	40
102	50
110	60
110	70

cont'r wt. & sample wt. = 156.88 grs.

cont'r wt. & oven dry wt. = 139.20

cont'r wt. = 36.88

w = 17.68/102.32 = 17.24%

Sample O-U_4-#1

Load Dial.	Strain Dial.
0	0
0	0

cont'r wt. & sample wt. = 183.40 grs.
cont'r wt. & oven dry wt. = 143.22
cont'r wt. = 37.40

w = 40.18/105.82 = 38.00%

Sample O-U_4-#2
After six freezing cycles

0	0
1	30
3	120
5	270
7	460
75	560

cont'r wt. & sample wt. = 172.81
cont'r wt. & oven dry wt. = 146.21
cont'r wt. = 37.76

w = 26.60/108.45 = 23.74%

Sample C-T_4-#1
After six freezing cycles

0	0
28	1
233	10
450	20
533	30
560	40

cont'r wt. & sample wt. = 143.56
cont'r wt. & oven dry wt. = 140.33
cont'r wt. = 37.62

w = 3.23/102.71 = 3.15%

Sample $C\text{-}U_4$-#1

After six freezing cycles

Load Dial.	Strain Dial.
0	0
28	1
58	3
123	6
266	10
338	15
433	20
497	25
537	30

cont'r wt. & sample wt. = 143.05
cont'r wt. & dry oven wt. = 140.50
cont'r wt. = 38.61

w = 2.55/111.89 = 2.28%

Sample $C\text{-}T_4$-#2

After six freezing cycles

0	0
252	17
356	20
518	30
607	40
658	50
669	55
671^5	58
670	62

cont'r wt. & sample wt. = 154.41
cont'r wt. & dry oven wt. = 148.83
cont'r wt. = 37.51

w = 5.58/111.32 = 5.01%

Sample C-U_4-#2

After six freezing cycles

Load Dial.	Strain Dial.
0	0
85	3
381	15
429	20
520	30
590	40
610	45
600	48

cont'r wt. & sample wt. = 153.00

cont'r wt. & dry oven wt. = 148.28

cont'r wt. = 37.26

w = 4.72/111.02 = 4.25%

Sample O-T_4-#1

After ten freezing cycles (test on upper half only)

0	0
40	5
68	10
102	20
121	25
136	25
161	5

cont'r wt. & sample wt. = 164.34 grs.

cont'r wt. & dry oven wt. = 142.86

cont'r wt. = 37.40

w = 21.48/105.46 = 20.40% &
40% L. H.

Sample O-U_4-#1

After ten freezing cycles

0	0
0	-

cont'r wt. & sample wt. = 191.27 grs.

cont'r wt. & dry oven wt. = 145.47

cont'r wt. = 36.88

w = 45.80/108.59 = 42.20%

Sample O-T_4-#2

After ten freezing cycles

Load Dial.	Strain Dial.
0	0
0+	-

cont'r wt. & sample wt. = 176.15 grs.

cont'r wt. & dry oven wt. = 148.17

cont'r wt. = 37.26

w = 27.98/110.91 = 25.12%

Sample O-U_4-#1

After ten freezing cycles

Load Dial.	Strain Dial.
0	0
0	-

cont'r wt. & sample wt. = 183.00

cont'r wt. & dry oven wt. = 146.37

cont'r wt. = 37.70

w = 36.63/108.67 = 33.70%

Sample C-T_4-#1

After ten freezing cycles

Load Dial.	Strain Dial.
0	0
82	5
125	10
238	20
362	30
445	40
460±	46±

cont'r wt. & sample wt. = 129.48

cont'r wt. & dry oven wt. = 126.94

cont'r wt. = 37.62

w = 2.54/89.32 = 2.85%

Sample C-U_4-#1

After ten freezing cycles

Load Dial.	Strail Dial.
0	0
100	5
242	10
424	15
495	20
578	30

cont'r wt. & sample wt. = 145.48 grs.
cont'r wt. & dry oven wt. = 142.74
cont'r wt. = 38.61

w = 2.64/104.13 = 2.53%

Sample C-T_4-#2

After ten freezing cycles

0	0
65	5
188	10
422	20
504	30
567	40
580	45
540	45

cont'r wt. & sample wt. = 151.20 grs.
cont'r wt. & dry oven wt. = 145.88
cont'r wt. = 37.51

w = 5.32/108.37 = 491%

Sample C-U_4-#2

After ten freezing cycles

0	0
50	0
125	2
470	10
554	15

cont'r wt. & sample wt. = 152.94 grs.
cont'r wt. & dry oven wt. = 148.10
cont'r wt. = 37.26

w = 4.84/110.84 = 4.08%

Sample C-U_4-#1 (cont'd)

Load Dial.	Strain Dial.
676	28
685	30
694	33
700	30$\pm$

Sample O-T_5-#1
after fifteen freezing cycles

0	0
0	-

cont'r wt. & sample wt. = 176.60
cont'r wt. & dry oven wt. = 143.12
cont'r wt. = 36.88

w = 33.48/106.24 = 31.50%

Sample O-U_5-#1
After fifteen freezing cycles

0	0
0	-

cont'r wt. & sample wt. = 192.94 grs.
cont'r wt. & dry oven wt. = 146.27
cont'r wt. = 37.40

w = 46.67/108.87 = 43.00%

Sample O-T_5-#2
After fifteen freezing cycles

0	0
0	-

cont'r wt. & sample wt. = 182.74
cont'r wt. & dry oven wt. = 147.71
cont'r wt. = 37.26

w = 35.04/110.45 = 30.60%

Sample O-U_5-#2
After fifteen freezing cycles

Load Dial.	Strain Dial.
0	0
0	0

cont'r wt. & sample wt. = 184.12
cont'r wt. & dry oven wt. = 146.40
cont'r wt. = 37.70

w = 37.72/108.70 = 34.70%

Sample C-T_5-#1
After fifteen freezing cycles

0	0
46	3
268	10
500	20
578	30
584	--

cont'r wt. & sample wt. = 140.12
cont'r wt. & dry oven wt. = 137.40
cont'r wt. = 37.62

w = 2.72/99.78 = 2.73%

Sample C-U_5-#1
After fifteen freezing cycles

0	0
80	1
457	10
575	20
589	25
570	27

cont'r wt. & sample wt. = 150.18 grs.
cont'r wt. & dry oven wt. = 147.70
cont'r wt. = 38.61

w = 2.48/109.09 = 2.26%

Sample C-T_5-#2

After fifteen freezing cycles

Load Dial.	Strain Dial.
0	0
30	1
350	10
436	20
429	25
430±	27

cont'r wt. & sample wt. = 150.85 grs.
cont'r wt. & oven dry wt. = 146.10
cont'r wt. = 37.51

w = 4.75/108.59 = 4.37%

Sample C-U_5-#2

After fifteen freezing cycles

0	0
23	1
397	10
531	20
619	30
673	40
683	45
680	50

cont'r wt. & sample wt. = 153.04
cont'r wt. & oven dry wt. = 148.67
cont'r wt. = 37.26

w = 04.37/111.41 = 3.91%

Series A Samples

Sample O-T_{88}-#1

After seven days of curing period

Load Dial.	Strain Dial.
0	0
81	5
198	10
306	14
400	20
412	25
415±	30

cont'r wt. & sample wt. = 147.40

cont'r wt. & oven dry wt. = 143.60

cont'r wt. = 39.70

w = 3.80/102.90 = 3.62%

Sample O-U_{88}-#1

After seven days curing period

0	0
102	5
304	10
459	14
560	20
616	26
627	30
629	33

cont'r wt. & sample wt. = 118.00

cont'r wt. & oven dry wt. = 116.30

cont'r wt. = 40.0

w = 1.80/76.20 = 2.33%

Sample C-T_2-#1
Submerged for 24 hours

Load Dial.	Strain Dial.
0	0
15	14
20	19
28	26
51	60
46	80
22	100

cont'r & sample wt. = 150.2
cont'r & oven dry wt. = 143.2
cont'r wt. = 38.0

w = 7.00/105.2 = 6.67%

Sample C-U_2-#1
After 24 hours of capillarity moisture

0	0
14	7
22	10
31	15
41	20
62	30
72	40
50	50

cont'r & sample wt. = 160.3
cont'r & oven dry wt. = 145.6
cont'r wt. = 38.3

w = 14.7/107.3 = 13.7%

Sample O-T_2-#1
After one freezing cycle

Load Dial.	Strain Dial.
0	0
98	6
50	9
190	12
224	22
208	43

cont'r wt. & sample wt. = 146.3 grs.
cont'r wt. & oven dry wt. = 142.6
cont'r wt. = 37.10

w = 3.7/105.5 = 3.50%

Sample O-U_2-#1
After one freezing cycle

0	0
10	50
12	130
13	180
14	460
12	600

cont'r wt. & sample wt. = 172.4 grs.
cont'r wt. & oven dry wt. = 146.4
cont'r wt. = 38.4

w = 26.0/108.0 = 24.1%

Sample O-T_2-#1
After one freezing cycle

Load Dial.	Strain Dial.
0	0
98	6
50	9
190	12
224	22
208	43

cont'r wt. & sample wt. = 146.3 grs.
cont'r wt. & oven dry wt. = 142.6
cont'r wt. = 37.10

w = 3.7/105.5 = 3.50%

Sample O-U_2-#1
After one freezing cycle

0	0
10	50
12	130
13	180
14	460
12	600

cont'r wt. & sample wt. = 172.4 grs.
cont'r wt. & oven dry wt. = 146.4
cont'r wt. = 38.4

w = 26.0/108.0 = 24.1%

Sample O-T_{13}-#1
After one freezing cycle

Load Dial.	Strain Dial.
0	0
23	38
58	43
102	70
108	75
110	80

cont'r wt. & sample wt. = 154.5
cont'r & oven dry wt. = 145.0
cont'r wt. = 37.4

w = 9.5/107.6 = 8.85%

Sample O-U_{13}-#1
After one freezing cycle

Load Dial.	Strain Dial.
0	0
0	30
0	40
0	50
1	63
3	80
8	130
12	213
20	500

cont'r wt. & sample wt. = 172.8
cont'r wt. & oven dry wt. = 146.8
cont'r wt. = 37.9

w = 26/108.9 = 24.9%

Sample O-T_{10}-#1
After two freezing cycles

Load Dial.	Strain Dial.
0	0
87	5
130	8
243	10
324	14
400	20

cont'r wt. & sample wt. = 152.10 grs.
cont'r wt. & oven dry wt. = 143.90
cont'r wt. = 37.40

w = 8.2/106.5 = 7.70%

Sample O-U_{10}-#1
After two freezing cycles

Load Dial.	Strain Dial.
0	0
0	-

cont'r wt. & sample wt. = 186.05
cont'r wt. & oven dry wt. = 144.15
cont'r wt. = 38.20

w = 41.9/105.95 = 39.5%

Sample C-T_{34}-#1
After two freezing cycles

0	0
22	34
26	40
27.5	50
25	60
18	70

cont'r wt. & sample wt. = 155.50 grs.
cont'r wt. & oven dry wt. = 138.80
cont'r wt. = 37.35

w = 16.70/101.45 = 16.46%

Sample C-U_{34}-#1
After two freezing cycles

0	0
20	10
31	20
48	50
55	60
38	70

cont'r wt. & sample wt. = 158.00
cont'r wt. & oven dry wt. = 134.30
cont'r wt. = 27.10

w = 23.7/107.2 = 22.14%

Sample O-T_{23}-#1
After three freezing cycles

Load Dial.	Strain Dial.
0	0
10	10
13	30
18	45
22	65
22	80
18	100

cont'r wt. & sample wt. = 160.50
cont'r wt. & oven dry wt. = 144.30
cont'r wt. = 37.20

w = 16.0/107.3 = 14.9%

Sample O-U_{23}-#1
After three freezing cycles

0	0
1	36
2	70
4	160
8	450
10	570
12	655

cont'r wt. & sample wt. = 213.80
cont'r wt. & oven dry wt. = 184.80
cont'r wt. = 76.70

w = 29.0/108.10 = 26.80%

Sample C-T_{44}-#1
After three freezing cycles

0	0
24	10
45	20
68	30
65	35
35	65

cont'r wt. & sample wt. = 149.20
cont'r wt. & oven dry wt. = 141.60
cont'r wt. = 38.10

w = 7.6/103.50 = 7.36%

Sample O-U_{44}-#1
After three freezing cycles

Load Dial.	Strain Dial.
0	0
51	15
67	20
101	30
120	40
128	50
118	60

cont'r wt. & sample wt. = 154.50
cont'r wt. & oven dry wt. = 146.70
cont'r wt. = 37.50

w = 7.8/109.2 = 7.14%

Sample O-T_{51}-#1
After five freezing cycles

Load Dial.	Strain Dial.
0	0
0+	-

cont'r wt. & sample wt. = 148.10
cont'r wt. & oven dry wt. = 125.10
cont'r wt. = 37.10

w = 23.0/88.0 = 26.15%

Sample O-U_{61}-#1
After five freezing cycles

Load Dial.	Strain Dial.
0	0
0	-

cont'r wt. & sample wt. = 188.00
cont'r wt. & oven dry wt. = 148.80
cont'r wt. = 37.90

w = 37.20/110.9 = 33.6%

Sample C-T_{63}-#1
After five freezing cycles

Load Dial.	Strain Dial.
0	0
20	12
33	20
38	25
42	30
41	35

cont'r wt. & sample wt. = 186.30 grs.
cont'r wt. & oven dry wt. = 177.80
cont'r wt. = 75.10

w = 8.5/102.7 = 8.28%

Sample C-U_{63}-#1
After five freezing cycles

Load Dial.	Strain Dial.
0	0
34	5
43	10
59	20
70	30
67	40

cont'r wt. & sample wt. = 158.00
cont'r wt. & oven dry wt. = 146.30
cont'r wt. = 37.40

w = 11.7/108.9 = 10.76%

Sample O-T_{21}-#1
After seven freezing cycles

Load Dial.	Strain Dial.
0	0
1	20
3	51
5	104
6	149
8	600

cont'r wt. & sample wt. = 162.00 grs.
cont'r wt. & oven dry wt. = 139.83
cont'r wt. = 38.61

w = 22.17/101.73 = 21.76%

Sample O-U_{21}-#1
After seven freezing cycles

Load Dial.	Strain Dial.
0	0
6	500

cont'r wt. & sample wt. = 178.42
cont'r wt. & oven dry wt. = 147.75
cont'r wt. = 38.23

w = 30.67/109.52 = 28.0%

Sample C-T^{97}-#1
After seven freezing cycles

0	0
29	10
52	25
63	40
30	60

cont'r wt. & sample wt. = 182.27
cont'r wt. & oven dry wt. = 175.35
cont'r wt. = 74.17

w = 6.89/101.21 = 6.8%

Sample C-U_{97}-#1
After seven freezing cycles

0	0
35	10
52	20
70	30
74	40
46	60

cont'r wt. & sample wt. = 146.90 grs.
cont'r wt. & oven dry wt. = 134.53
cont'r wt. = 27.05

w = 12.47/107.48 = 11.6%

Sample C-T-#1
After ten freezing cycles

Load Dial.	Strain Dial.
0	0
20	5
35	10
60	20
66.5	30
50	45

cont'r wt. & sample wt. = 186.96
cont'r wt. & oven dry wt. = 181.30
cont'r wt. = 75.29

w = 5.66/106.01 = 5.34%

Sample C-U-#1
After ten freezing cycles

0	0
27	5
45	10
78	20
98	30
100	33
70	60

cont'r wt. & sample wt. = 191.10 grs.
cont'r wt. & oven dry wt. = 183.42
cont'r wt. = 75.34

w = 7.68/108.08 = 7.10%

Sample C-T_{53}-#1
After fifteen freezing cycles

0	0
50	3
130	8
210	11
390	15
350	26

cont'r wt. & sample wt. = 178.35 grs.
cont'r wt. & oven dry wt. = 175.88
cont'r wt. = 75.29

Sample C-U_{53}-#1
After fifteen freezing cycles

Load Dial.	Strain Dial.
0	0
120	6
270	10
435	14
511	20
541	22

cont'r wt. & sample wt. = 129.38
cont'r wt. & oven dry wt. = 127.09
cont'r wt. = 37.18

w = 2.29/89.91 = 2.55%

Sample C-T_{40}-#1
After twenty freezing cycles

0	0

cont'r wt. & sample wt. = 138.28
cont'r wt. & oven dry wt. = 136.50
cont'r wt. = 37.29

w = 1.78/99.21 = 1.80%

Hydrometer Analysis

Soil #1
"O" Correction = 3.00
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/E	K	diam. (D) mm.
0	27.5								
1	27.5	41	40	80	42	9.4	9.4	0.0125	0.0365
2	27.5	31	30	60	32	11.1	5.55	0.0125	0.0295
3	27.5	29	28	56	30	11.4	3.80	0.0125	0.0244
4	27.5	24^5	23^5	47	25^5	12.1	3.03	0.0125	0.0217
5	27.5	22	21	42	23	12.5	2.50	0.0125	0.0197
10	27.5	17	16	32	18	13.3	1.33	0.0125	0.0144
15	27.5	15	14	28	16	13.7	0.91	0.0125	0.0119
20	27.5	14	13	26	15	13.8	0.69	0.0125	0.0104
30	27.5	13	12	24	14	14.0	0.46	0.0125	0.0085
60	27.5	12	11	22	13	14.2	0.24	0.0125	0.0061
73	27.5	11	10	20	12	14.3	0.20	0.0125	0.0056
126	27.5	11	10	20	12	14.3	0.11	0.0125	0.0041
14x60							0.02	0.0125	0.0018

G_s = 2.65

Percent finer = $\frac{Rc\cdot}{50\ gc}$ = 50 Rc

D = K $\sqrt{L/_t}$

Hydrometer Analysis

Soil #2
"D" Correction = 3.00
C_r = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/E	K	diam. (D) mm.
0	27.5								
1	27.5	31	30	60	32	11.1	11.10	0.0125	0.0416
2	27.5	29	28	56	30	11.4	5.70	0.0125	0.0299
3	27.5	28^5	27^5	55	29^5	11.45	3.82	0.0125	0.0244
4	27.5	28	27	54	29	11.5	2.87	0.0125	0.0212
5	27.5	27^5	26^5	53	28^5	11.6	2.32	0.0125	0.0191
10	27.5	25^5	24^5	49	26^5	11.95	1.20	0.0125	0.0137
15	27.5	25	24	48	26	12.0	0.80	0.0125	0.0112
20	27.5	24	23	46	25	12.2	0.61	0.0125	0.0098
30	27.5	23	22	44	24	12.4	0.41	0.0125	0.0080
60	27.5	21	20	40	22	12.7	0.21	0.0125	0.0057
72	27.5	20	19	38	21	12.9	0.16	0.0125	0.0050
125	27.5	19	18	36	20	13.0	0.10	0.0125	0.0039
14x60							0.02		0.0018

% finer = $R_c/W_s = (R_c \frac{100}{50}) = 2R_c$

Hydrometer Analysis

Soil #3
"O" Correction = 5.00
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/E	K	diam. (D) mm.
0	27.5								
1	27.5	39	36	72	40	9.7	9.70	0.0125	0.0389
2	27.5	37	34	68	38	10.1	5.05	0.0125	0.0281
3	27.5	36	33	66	37	10.2	3.40	0.0125	0.0231
4	27.5	35^5	32^5	65	36.5	10.3	2.57	0.0125	0.0200
5	27.5	35	32	64	36	10.4	2.08	0.0125	0.0180
10	27.5	33	30	60	34	10.7	1.07	0.0125	0.0129
15	27.5	32	29	58	33	10.9	0.73	0.0125	0.0107
20	27.5	31	28	56	32	11.1	0.56	0.0125	0.0094
30	27.5	30	27	54	31	11.2	0.37	0.0125	0.0076
60	27.5	28	25	50	29	11.5	0.19	0.0125	0.0055
71	27.5	27	24	48	28	11.7	0.16	0.0125	0.0050
124	27.5	25^5	22.5	45	26.5	11.95	0.10	0.0125	0.0039
14x60									0.0002

Hydrometer Analysis

Soil #4
"O" Corrections = 3.00
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/E	K	diam. (D) mm.
0	27.5								
1	27.5	26	25	50	27	11.9	11.90	0.0125	0.0431
2	27.5	24	23	46	25	12.2	6.10	0.0125	0.0345
3	27.5	23	22	44	24	12.4	4.13	0.0125	0.0254
4	27.5	22	21	42	23	12.5	3.13	0.0125	0.0221
5	27.5	21^5	20.5	41	22.5	12.6	2.52	0.0125	0.0198
10	27.5	19^5	18.5	37	20.5	12.95	1.30	0.0125	0.0143
15	27.5	18^5	17.5	35	19.5	13.1	0.87	0.0125	0.0117
20	27.5	17.5	16.5	33	18.5	13.25	0.66	0.0125	0.0102
30	27.5	17	16	32	18	13.3	0.44	0.0125	0.0083
60	27.5	15	14	28	16	13.7	0.23	0.0125	0.0060
68	27.5	13.5	13.5	27	15.5	13.8	0.21	0.0125	0.0057
121	27.5	13	12	24	14	14.0	0.12	0.0125	0.0043
14x60							0.02		0.0002

Hydrometer Analysis

Soil #5
"O" Correction = 3
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/t	K	diam. (D) mm.
0	27.5								
1	27.5	42	41	82	43	9.2	9.20	0.0125	0.0379
2	27.5	39	38	76	40	9.7	4.85	0.0125	0.0256
3	27.5	34^5	33.5	67	35.5	10.45	3.48	0.0125	0.0233
4	27.5	32	31	62	33	10.9	2.73	0.0125	0.0206
5	27.5	29	28	56	30	11.4	2.28	0.0125	0.0189
10	27.5	23^5	22.5	45	24.5	12.3	1.23	0.0125	0.0139
15	27.5	20	19	38	21	12.9	0.86	0.0125	0.0116
20	27.5	18	17	34	19	13.2	0.66	0.0125	0.0102
30	27.5	16^5	15.5	31	17.5	13.4	0.45	0.0125	0.0084
60	27.5	14	13	26	15	13.8	0.23	0.0125	0.0060
14x60	27.5	9^5	8.5	17	10.5	14.6	0.02	0.0125	0.0002

Hydrometer Analysis

Soil #6
"O" Correction = 3
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/t	K	diam. (D) mm.
0	27.5								
1	27.5	27.5	26.5	53	28.5	11.6	11.60	0.0125	0.0426
2	27.5	25	24	48	26	12.0	6.00	0.0125	0.0306
3	27.5	24.5	23.5	47	25.5	12.1	4.03	0.0125	0.0252
4	27.5	23.5	22.5	45	24.5	12.3	3.07	0.0125	0.0219
5	27.5	23	22	44	24	12.4	2.48	0.0125	0.0196
10	27.5	21	20	40	22	12.7	1.27	0.0125	0.0140
15	27.5	20	19	38	21	12.9	0.86	0.0125	0.0116
20	27.5	19	18	36	20	13.0	0.65	0.0125	0.0101
30	27.5	18	17	34	19	13.2	0.44	0.0125	0.0083
60	27.5	16	15	30	17	13.5	0.23	0.0125	0.0060
14x60	27.5	9.5	8.5	17	10.5	14.6	0.02	0.0125	0.00022

Hydrometer Analysis

Soil #7
"C" Correction = 3
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/t	K	diam. (D) mm.
0	27.5								
1	27.5	47	46	92	48	8.4	8.40	0.0125	0.0362
2	27.5	42	41	82	43	9.2	4.60	0.0125	0.0268
3	27.5	37	36	72	38	10.1	3.37	0.0125	0.0230
4	27.5	33	32	64	34	10.7	2.68	0.0125	0.0204
5	27.5	32	31	62	33	10.9	2.18	0.0125	0.0185
10	27.5	25	24	48	26	12.0	1.20	0.0125	0.0137
15	27.5	22	21	42	23	12.5	0.83	0.0125	0.0114
20	27.5	19^5	18.5	37	20.5	12.95	0.65	0.0125	0.0101
30	27.5	16^5	15.5	31	17.5	13.4	0.45	0.0125	0.0084
60	27.5	14.0	13	26	15	13.8	0.23	0.0125	0.0060
14x60	27.5	8.5	7.5	15	9.5	14.75	0.02	0.0125	0.0002

Hydrometer Analysis

Soil #8
"O" Correction = 5.00
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/t	K	diam. (D) mm.
0	27.5								
1	27.5	49	46	92	50	8.1	8.10	0.0125	0.0356
2	27.5	46.5	43.5	87	47.5	8.5	4.25	0.0125	0.0257
3	27.5	45	42	84	46	8.8	2.93	0.0125	0.0214
4	27.5	44	41	82	45	8.9	2.23	0.0125	0.0187
5	27.5	43.5	40.5	81	44.5	9.0	1.80	0.0125	0.0163
10	27.5	41	38	76	42	9.4	0.94	0.0125	0.0121
15	27.5	39	36	72	40	9.7	0.65	0.0125	0.0101
20	27.5	37.5	34.5	69	38.5	10.0	0.50	0.0125	0.0088
30	27.5	35	32	64	36	10.4	0.35	0.0125	0.0074
60	27.5	30	27	54	31	11.2	0.19	0.0125	0.0055
14x60	27.5	13	10	20	14	14.0	0.02	0.0125	0.0002

Hydrometer Analysis

Soil #9
"O" Correction = 2-1/2
C_T = 2.25

Elapsed time (t) min.	Temp. (T) °C	Actual Hyd. Reading Ra	Corr'd Hyd. Reading Rc	% finer	Hyd. Corr'd only for miniscus R	L	L/t	K	diam. (D) mm.
0	27.5								
1	27.5	18	18	36	19	13.2	13.20	0.0125	0.0454
2	27.5	16	16	32	17	13.5	6.75	0.0125	0.0325
3	27.5	15	15	30	16	13.7	4.56	0.0125	0.0267
4	27.5	14^5	14.5	29	15.5	13.75	3.44	0.0125	0.0232
5	27.5	14	14	28	15	13.8	2.78	0.0125	0.0204
10	27.5	13	13	26	14	14.0	1.40	0.0125	0.0147
15	27.5	12	12	24	13	14.2	0.95	0.0125	0.0122
20	27.5	11	11	22	12	14.3	0.71	0.0125	0.0105
30	27.5	10^5	10.5	21	11.5	14.4	0.48	0.0125	0.0086
60	27.5	9	9	18	10	14.7	0.25	0.0125	0.0063
14x60	27.5	7	7	14	8	15.0	0.02	0.0125	0.0002