FACTORS EFFECTING FROST ACTION

THESIS

BY
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ACKNOWLEDGEMENT

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ABSTRACT

Soil characteristics play an important role in civil engineering structures. One of the characteristic phenomena associated with the behaviour of soils is frost heaving. Frost heaving causes considerable damage to highways, foundations, airfields and other types of earth structures. A significant problem to be considered seriously.

Basic features of frost action and factors in fluencing frost action has been shortly reviewed.

Taking void ratio as a parameter, experiments were performed to measure the saturation capillary heads of different soil fractions and their various conbinations. For this purpose a transparent capillary tube, made of far glas, was constructed in the laboratory. Permeabilities of the same soils were measured, at the same void ratio as in the cases of capillarity tests. Freezing of the soils were performed in a specially constructed freezing chamber, thus being able to measure their moisture content increases, which causes the main destructure heaving in the bases and foundation of civil engineering structures.

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HISTORICAL INTRODUCTION

Ground freezing and heaving has, from the earliest times, been a subject of observation and discussion among the people. The early literature indicated familiarity with breaking of plant roots by heaving of the ground surface and contained descriptions of frost boils and ground hear frost (needle ice). Heaving associated with freezing of ground was mentioned by Runeberg in 1765, who found clear ice in soil, and 1854 by Volger. (1)

During development of stage coach traffic in 1700's, it was observed that frost heaving caused damage to curverts. People at that time did not fully understand the phenomenon of softening.

The coming of automobile brought with it the necessity for preventing the softening and in some cases the complete break down of the road surfaces during the spring thawing period. Then the technical problems associated with frost action attained real significance from a practical as well as economical point of view. The problem became an acute one prior to 1920 and in the early 1920's causing investigations to be undertaken in different countries.

The present concept that frost heaving is due to the growth of ice crystals into ice lenses owes its origins to Taber's study(1) of the work of Lavelle, and Becker and Day on crystal growth. In 1907, Taber showed experimentally that ice forming in clay soils lifted surface weights. He then concluded that heaving is caused by the growth of ice crystals into lenses or layers of ice. That, however, was only the beginning of Taber's extensive study of frost action in soils.

Taber's early statement brought forth considerable discussion in the published literature. New designs appeared, supported by either facts or experience. Taber's concept on frost heaving was not conceived by many engineers for a long time and they still stick to the old concept expressed by Runeberg in 1765 that the frost heaving was due to volume change of the contained water changing to ice (approximately 9% volume increase).

Taber, later on, with his comprehensive report in 1929, disproved this concept with the use benzine and nitrobenzine which solidify with a decrease in volume. As early as 1897 Holmquist observed that in clay solis the soil between the lowest ice layers was often unfrozen indicating a lower freezing point after some water had been drawn out in the process of forming the overlying layers of ice. That observation was followed by extensive studies of the freezing point in soil during the period 1914 to 1923 by Bouyoucos who found marked differences in the freezing points in different soils and for a given soil at different moisture contents. It was the findings of Holmquist and Bouyoucos and other later investigaters which made possible a plausible explanation of Taber's concept of water continuing to flow to and nourishing growing ice crystals until they develope into ice layers.

Runeberg in 1765, by measuring the moisture content of a piece of frozen clay, found that it contained four times as much moisture as it had contained before it was frozen.

From that time on much attention was directed to the movement of water in soil. Briggs (1897), Bouyoucos (1921), Lebideff (1927) and Zunker (1933) are among those who held that forces responsible for water movements were analogous to those which move water in a capillary tube. Buchingham had a different view. He made his comparison with the flow of electricity through a conductor and assumed that water flowed in an analogous manner, the driving force water being the result of the difference in moisture content in the soil. He called that driving force the "capillarity potential" (1).

Those who have studied the freezing and heaving of soils saw in the existing concepts no completely satisfactory explanation of the forces responsible for drawing the water into the freezing zone. Taber aggreed that during the growth of ice layer in clay, water is supplied to the crystals through small capillary passages but held that (1) "... the upward movement of water should not be attributed to capillarity as there is no free surface or meniscus. The uplift is due to cohesive forces in the water". Beskow's concept of freezing and heaving did not differ materially from those of Taber. He saw the practibility of recognising water movement by what he called capillary suction, the rate of flow being dependent on the pressure difference and the size of pore channels. He developed a capillarimeter to give a relative measure of the height of capillar rise in soils. His practical treatment of water movement as it is related to frost heaving is perhaps the most comprehensive available.

Some of the earliest field studies in the United States were measurements of soil moisture content, and soil heaving of subgrades by the Illinois Department of Highways in the Bates experimental road in the early 1920's. Also they conducted load bearing tests with repeated application of load. Their tests indicated a marked reduction in load carrying capacity of subgrades during the frost melting period.

Studies in Michigan, starting in 1920's brought out the relation between soil type, soil profile characteristics, soil water conditious and heaving.

In 1925, the Swedish Institute of Roads sponsored a conference on frost action. With the help of papers issued by this conference, and with that background of information and cooperation, Beskow and his friends attacked the problem. They have taken into account the various phases of the phenomena including snow plowing, drainage, significance of geological factors supporting value during the frost melting period, the capillary properties of soil, and how to measure it, measures to insolate and to isolate frost, the use of choloride salts and sulfide liguors, corrugation and counter measures. The results of their studies were published in a single bulletin in 1935.

Scientists also were interested in this soil freezing and frost boil phenomena. Forbes, in 1837 observed soil temperature to depths of over 25 ft., with a specially constructed thermometer 26 ft. long capable of measuring temperatures to one-hundredth degree F.

Early studies of fundamental in nature was followed by field studies of various designs to prevent or reduce the occurrence of major frost heaving. The problem of severe differential heaving seemed to be well understood after the symposium held at Purdue University in 1938. Engineers could recognize, from soil survey data, areas where severe heaving might accur and would also prepare designs with reasonable assurance that they would be successful.

Engineers were also aware of the marked reduction in beaming capacity which followed frost melting in areas of severe heaving and which expressed themselves in the form of frost boils and a subsequent breakup of road surfaces of the lighter types.

However, as the wheel loads of commercial traffic became heavier and the number of commercial vehicles increased rapidly in the early 1940's it became evident that engineers had insufficient knowledge of frost phenomena to predict the effect which the heavier and more concentrated traffic would have on the great milage of roads subject to a some what lighter form of frost action. Those more recent developments resulted in the extensive investigation of frost action by the Corps of Engineers. That work was begins in 1945 and constitutes the most comprehensive field and laboratory studies of frost action conducted in U.S.A.

CHAPTER I

DEFINITION OF FROST ACTION

Among the many terms which have been used to describe the process of soil freezing and heaving and thawing and their effect on pavements and structures, some of them are: frost action, freeze damage, frost heave, frost boil, mud boil and spring break up. The term, frost, is the process of congealing of liquids with special reference to water. Because the act of freezing is the fundamental phase of the whole phenomena, the term frost action is widely used to describe the above mentioned series of actions and damages.

Thus the word frost action covers over all phenomena, including freezing and thawing and heaving, as well as changes in water content in porosity or structure of the soil or changes in their capacity to support loads.

FUNDAMENTAL CONCEPTS AND DEFINITIONS

For purposes of clarity in the subsequent sections, some terms have been taken from a list prepared and approved by the HRB Committe on Frost Heave and Frost action in soils(2).

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

Percent Heave:- The ratio, expressed as a percentage, of the amount of heave to the depth of frozen soil before freezing.

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

Non-Frost Susceptible materials:- Cohensionless materials, such as crushed rock, gravel; sand, slag and cinders in which significant detrimental ice segregation does not occur under normal freezing conditions.

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

Ice lenses:- Ice formations in soil occuring essentially parallel to each other, generally normal to th

PHYSICAL PROCESS OF SOIL FREEZING

The Structure of frozen soil:-

It has been observed by many investigators that the structure of frozen soil shows different variations. Kokkonen classifies it into two forms: Massive or homogenous and stratified frozen soils (1), (3).

Homogenous Frozen Soil

This type of frozen soil is associated with coarse grained soi usually medium sands and coarser. (approximately 0.4mm. particle diameter or larger) (11). The water in the natural voids is frozen without formation ice lenses. This kind of formations can also take place in fine grained soils being well below full saturation, and under rapid freezing conditions.

Stratified Frozen Soil

This kind of formation occurs in a layery appearance. Its formation is initiated in the original voids of the soil. The volum of the ice stratification, later on, exceeds the volume of the origi nal voids, due to suction of water from other cavities and ground water with the act of capillarity.

The layers are usually parallel to the ground surface and perpendicular to the direction of heat loss. Between the layers, soft unfrozen clay accumulation is usually encountered. (2)

The thickness of the layers depends upon the fineness of the soils. The finer the soil, the thicker will be the ice lenses, and the wider they are seperated.

Figure (1) below illustrates ice crystallization in open fissures. (1)

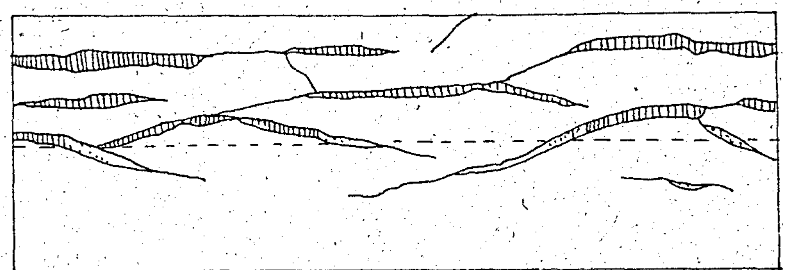


Fig. 1 Schematic diagram illustrating ice crystallization in open fissures and progressive development of fissures below the frost line (dashed line is frost line). (After Beskow 1947-12)

Figure (2) shows the formation ice layers in zone of freezing (11).

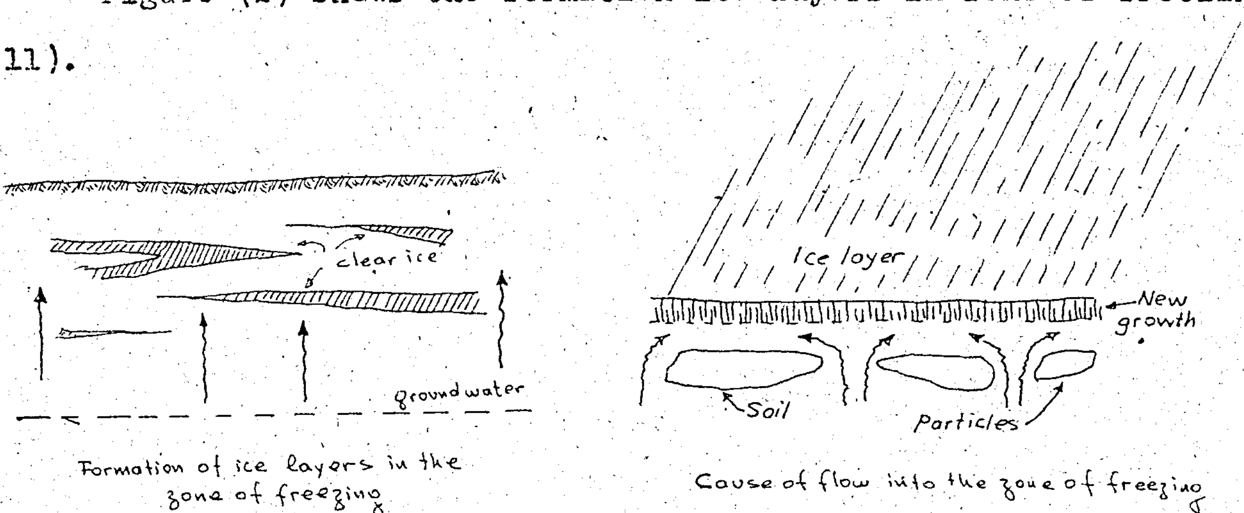


Fig. 2

Figure (3) shows basic types of structures of frozen soil(13).

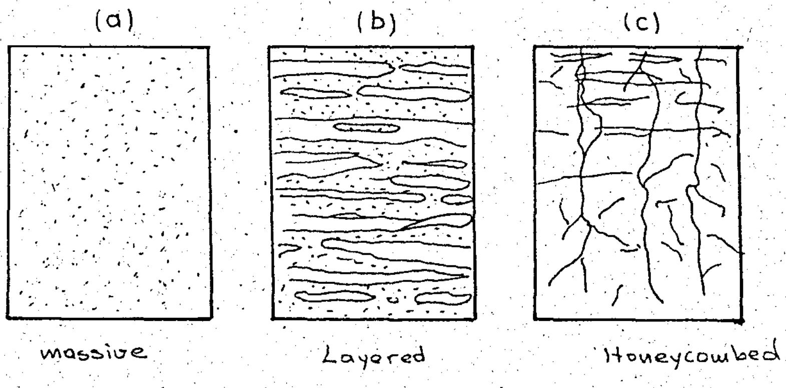


Fig. 3

Freezing Point in Soil and amount of freezable water in soil

Researchers (1, 4, 13, 2) working on the field of soil freezi have often found unfrozen soft clay between deepest ice layers. Th means that a lower temperature is required to freeze the water in remaining clay deposits after the "more-free" water has frozen. Th lowering of the freezing temperature may amount to a few degree C.

Accordingly, not all the water is frozen when the soil mass i subjected to subfreezing temperature. This phenomena is experimentally shown to be true for soils containing a high percentage of fine-grained particles. The cause of this particularity is explain by the nature of the surface forces developed between the water films surrounding the fine particles and particles itself. Therefore, the temperature decrease required for freezing of the water held to the soil particles will vary with the intensity of the inte actions.

Freezing point and the quantity of unfrozen water as a proportion of the total water content, or percent unfrozen water varies with.

a) original water content

b) percent water-saturation

c) freezing temperature

d) clay content

e) charge density of soil particles

f) electrolyte concentration

g) soil structure

h) freezing history of soil

The results of the experiments performed by Bouyoucos is shown graphically below (1)

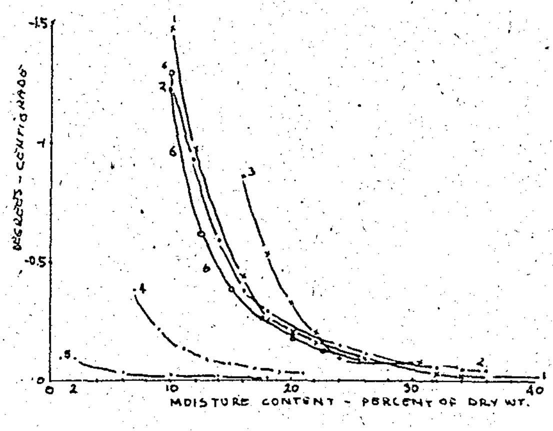


Fig.4 Freezing temperatures of different soils. No.1 humus loam, No.2 and 6 clay loam. No.3 silt loam, No.4 sandy loam and No.5 a quartz sand.

The Volume Change of Water on Freezing

The density of ice at 0°C is 0.91674 and that of water at the same temperature is 0,99987. The increase in volume of one gram of water when it solidifies is 0,0907 cc. or slightly greater than 9%. (1, 20)

Theories on the formation of ice lenses and heaving

Earliest records of observations indicate that frost heaving is attributable to the volume increase of soil water on freezing. That opinion apparently was held widely until after 1900 when Johanson discovered that water flows to the freezing zone and two years later Taber explained the cause of heaving.

Taber's theory explaining the mechanics of heaving is based on the premise that (1) all soil water does not freeze at the same temperature which makes it possible for water to move to the growing crystal, (2) the growing crystal displaces material overlying it and thus develope ice lenses. He placed metal weights on wet clays and exposed them to freezing. When ice formed, the metal weights were raised and this was due to growing ice crystals, (3) the frost line is relatively stationary during the growth of crystals forming the ice lens or

He held (ref.1) that "During the growth of an ice layer in clay water is supplied to the crystals through small capillary passages but the upward flow of water should not be attributed to capillarity as there is no free surface or meniscus. The uplift is due to the cohersive forces in the water"..... "Conditions existing during the growth of an ice layer in clay are particularly favorable for the uplift of water by molecular cohesion.

"A growing ice crystal is in contact with a thin film of water similar to the adsorbed layer that forms on other solids. As molecules are removed from the films and attached to the crystal, they are replaced by others from the surrounding water. When an ice crystal grows in a direction in which growth is opposed by a solid body such as a clay particle, the pressure is exerted through this film which seperates them.... After the available water has been exhausted, the film may be frozen, but it does not freeze easily. Cohesive is greater between the molecules in the films and between these molecules and the ice than it is between water molecules that are not close to ice crystals.

"Orientation and attachment of a water molecule to an ice crystal is accompanied by a slight repulsion, proportional to the change in volume, and this results in a slight displacement of the whole structure relative to the neighbouring solid" "As the new molecule is attached to the ice crystal, another molecule is drawn" "into the film by cohesion, and this is the direct cause of most of the displacement."

"The growth of ice layers in soils and the accompanying pressur effects are therefore attributed to molecular cohesion. The energy for the process is of course supplied by the removal of heat. Water is not only pulled into the film under anice crystal with force sufficient to lift the overlying load but considerable force must be exerted in pulling it through dense clay to the growing crystal: hence in these experiments, water had been placed under tension sufficient to lift a colomn of water over 150 meters (492 ft.) in height".

"The growth of ice layers is stopped by lack of water supply which may be due to rupturing of the upward moving filaments and films of water under tension or to the inability of molecules to enter films under pressure. Pressure tends to reduce the thickness of the nourishing film by expelling some of the molecules and since the expulsive forces are increased the attractive forces must likewise be increased by lowering the temperature, else molecules cannot enter the film. Pressure decreases molecular mobility in the film, retards crystal growth, and lowers the freezing point. The growth of ice crystals under pressure in open systems is possible because water occupying very small voids can be under cooled.

Taber'sexplanation as to why ice layers do not form in coarse grained soils is "The freezing isotherm (line of freezing temperature cannot advance as rapidly in water as in the minerals found in soils, for it is a poorer conductor of heat, has a greater specific heat, and also much heat has to be removed in converting water into ice. Hence, if ice crystals in growing downward come into contact with the top of a large soil particle, and begin to surround it so that the temperature at the top of the particle drops below freezing, then the temperature of the bottom of the particle will reach the freezing point before the water with which it is in contact. Therefore freezing takes place in part outward from the surface of large mineral particles that are incontact with water, and not merely through the downward growth of ice crystals as in pure water."

"When a growing ice crystal closely approaches a soil particle the water seperating them is gradually reduced to very thin film and further growth of the crystal in this direction can take place only as molecules of water enter this film. If the soil particles is relatively small so that the moleculer do not have far to travel through the film, and if growth is relatively slow, so that they have time to enter between ice and particle, then the growing ice crystal will exclude the particle; and if the particle is relatively large and if freezing is relatively rapid, the particle is gradually surrounded by the ice. To build up a layer of ice, which consists of many prismatic crystals, the capillaries supplying the water must be closely spaced."

Later on Benkelman and Olmstead stated a theory as to the nature of frost heaving. They have conducted laboratory experiments on various soils. They froze their specimens under fluctuating temperature conditions. From the results obtained they concluded tentetatively that excessive heaving may occur in soil of almost any grading or texture provided an adequate supply of water is present or available. They held the theory ".... offered an explanation of the formation of ice plates of any size and number. All that is required is a saturated with water and a fluctuating frost line ....."(1).

They were advocating theory which explains the frost heave as an expansion of the initial water of the soil.

Winn summarized the findings of most of the principal investigators on conditions necessary for frost action to accur as shown in the following outline.

"1. Destructive freezing associated with formation of segregated ice.
2. Total frost heave equal to the sum of the total thickness of ice lenses.
3. Total frost heave in direct proportions to increase in total water content of frozen soil.
4. Soil must equal state of capillary saturation for ice segregation to take place.
5. A supply of water must be available either in soil or from some external source i.e. water table.
6. For normal conditions of temperature, the percentage of 0.02 mm. diameter of grains is critical.
7. One slow freeze will cause heaving. Thawing and refreezing increases severity but does not change basic action.
8. Cumulative curve of degree hours of freezing plotted against time is qualitative measure of increase of heave with time.

9. The following factors are all necessary for ice segregation and frost heave.

   a) Capillary saturation of the soil at beginning and during freezing process.

   b) A free supply of water from within or without

   c) A minimum percentage of grains smaller than 0.02 mm. (3 to 10%)

   d) Gradual decrease in temperature of air above soil to below freezing temperature."

Later investigators have held several theories on the ice segregation mechanism. E. Penner, R.T. Martin, L.W. Gold, and Tscowich are some of these. (2, 4, 5, 13)

Factors influencing the magnitude, rate, and nature of frost action

Frost action, as a typical soil behavior, is a very complicated one. There are many factors which influences it. And its occurrence is possible only when the combination of conditions prevailing for it is favorable. However, it is again desirable to seperate these factors for a convenient analysis. These main factors can be listed as follows,

1. Climatical factors
2. Influence of pressure on heaving
3. Influence of physical characteristics and properties of soil
4. Physico-chemical properties

1. Climatic Factors

(a) Rate of freezing

Beskow and Taber (1), conducting many laboratory experiments, stated the importance of effect of rate of freezing. Although rate of freezing did not influence the total heave, it did influence the thickness of ice lenses, and thus the distribution of water excess and the consequent reduction in heaving capacity.

Figure 5, (1) shows an example of results of freezing tests illustrating the independence of frost heaving on rate of freezing. The soil used was a very fine filt (38 % coarser than 0.02, 75 % coarser than 0.006, 10 % finer than 0.002. (After Beskow)

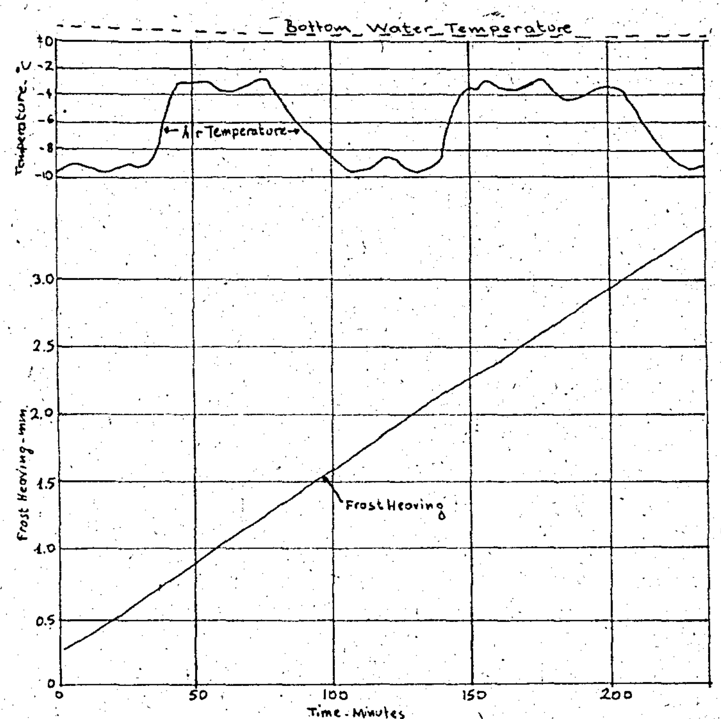


Fig. 5 An example of the results of freezing tests illustrating the independence of frost-heaving on the rate of freezing. The soil used was a very fine silt. Pressure 410 gr. per sq. cm. (0.014 psi.). (After Beskow)

(b) Effect of Thawing and Refreezing

Frost action is more severe after a thaw than after a single freeze and that there is a greater increase in soil moisture content and reduction in load carrying capacity following several cycles of freezing and thawing.

2. <u>Influence of Pressure on Heaving</u>

(a) Load Pressure

Results of Taber's experiments (1) on various soil samples showed that the amount of heave in open systems decreases with increase in pressure and the maximum load which may be lifted increases with decrease in particle size, but with much decrease in size of particle, the material would become highly impermeable. The limit to the load which may be lifted by frost heaving in an open system is not due to the inability of the ice crystals to grow under higher pressure but due to the failure of the water supply. This was proved by Taber who conducted experiments by supplying water under pressure larger than atmospheric pressure. His load was 14 kg/cm^2. He obtained a total thickness of ice 2 to 3 cm. while in the experiments with water at atmospheric pressure he did not find any ice lenses.

(b) Load and Capillary Pressure

After having conducted numerous laboratory experiments, Beskow summarized his findings on the effect of load capillary pressure as follows (1):

"The rate of frost heaving for a given soil is inversely proportional to the square of the pressure (sum of load and capillary pressure), after the pressure exceeds a certain but not large value. The reason for this "initial pressure increment" is that when the pressure approaches zero, the theoretical rate of frost heave does not approach infinity but a limiting, but quite large, value".

Some of his results are shown in Fig.6, Fig.7 and Fig.8 (1).

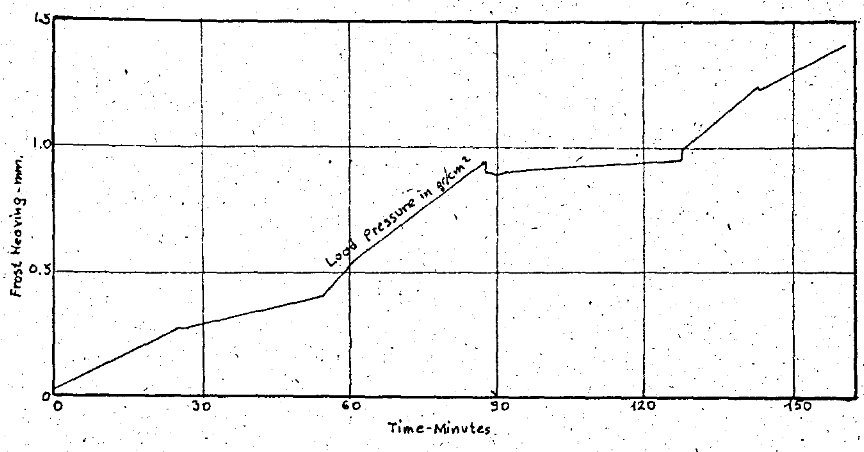


Figure 6. Diagram showing frost-heaving at different pressures (load or capillary). Soil-specimen: pure fraction, 0.01 - 0.005 mm. particle size

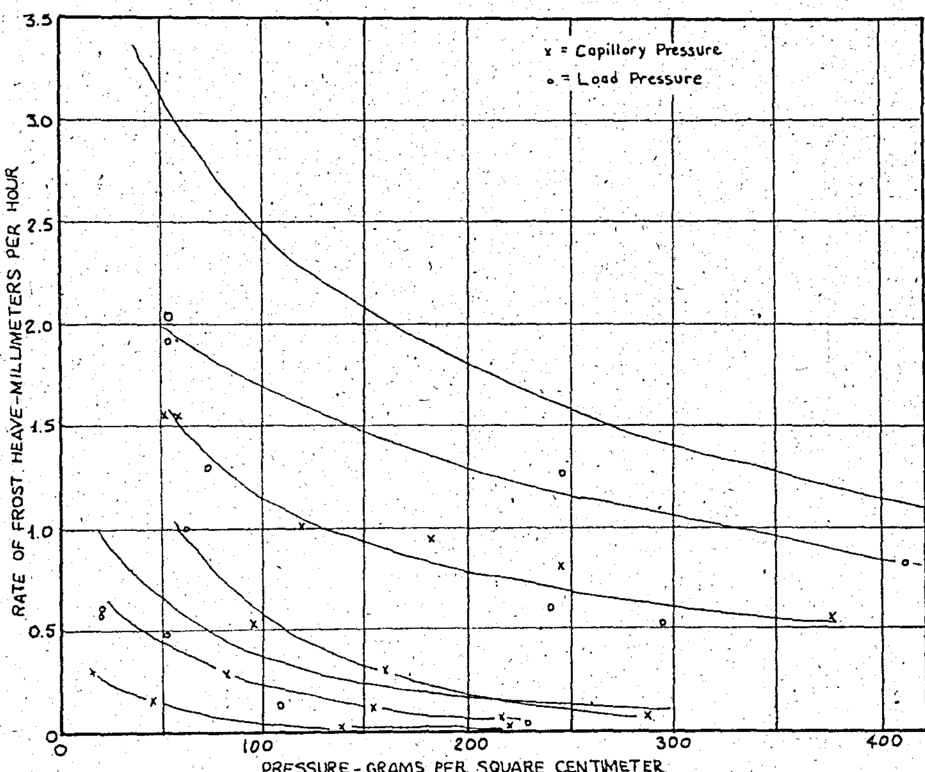


Figure 7. Frost-heaving rate as a function of pressure for some natural soils

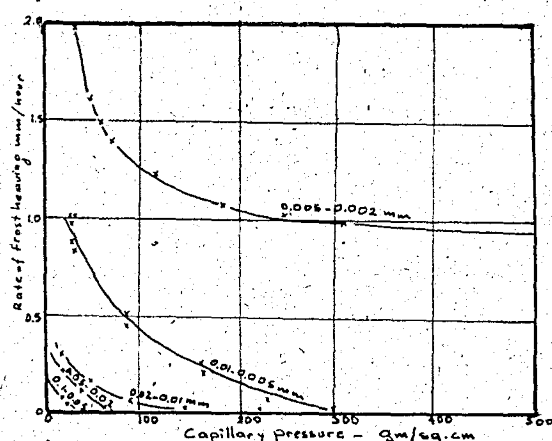


Figure 8 . Diagram of frost heaving rate as a function of pressure.

3. Influence of Physical Characteristics and Properties of Soil on Frost Action

(a) Influence of grain size distribution

The type of soil asit effects the kind of water included, has a large effect on soil freezing and heaving. In cohesionless soils, having little capillarity, no detrimental frost heaves are likely to accur. Freezing of the originally contained water in the pores is not followed by drawing extra water from the below particles and strata. Cohesive water particles do not exist in amounts sufficient to cause excessive segregation of ice. On the other hand, in silts where we find low cohesion and high capillarity, appreciable amounts of heaves are obtained. In the clayey soils, due to cohesion, and large amount of adsorbed water, capillary water will travel very slowly. Therefore, when we have low ground water table, in the absence of lateral seepage, ice segregation is limited by contained water in dense clays.

The table below shows the rise of water in grains of different sizes. (3)

RISE OF WATER IN GRAINS OF DIFFERENT SIZES

Diameter of grain mm.	Rize in 24 hr. inches	Max, rise inches	Period for max. rise. days
5 to 2	0.87	1.0	3
2 - 1	2.13	2.6	4
1 - 0.5	4.53	5.2	4
0.5 - 0.2	8.43	9.7	8
0.2 - 0.1	14.80	16.9	8
0.1 - 0.05	20.87	41.5	72
0.05 - 0.02	45.39	78	53
0.02 - 0.01	19.09		
0.01 - 0.005	11.22		
0.005 - 0.002	5.63		
0.002 - 0.001	2.17		

Burton and Benkelman made detailed analysis (1) of 156 heaves. They showed that 94 occured in layers at pockets of fine textured material such as silt, very fine sand and silt, or silty clay, clay or sandy clay surrounded by coarser, better drained material. The results of the heaves are

	Average heave
5.5% silts	6 in.
32 % in very fine sand and silt	5 in.
4.3 % in very fine sand	4 in.
30 % in clay	
8 % in silty clay	5 in.
17 % in sandy clay	3 in.

As can be seen that those material having high capillarity is causing detrimental frost heaving. The only cure for this is to replace the matérial with materials having favaroble the drainage characteristics. As for the coarser materials the elimination of frost heaving can be accomplished by providing adequate drainage conditions at the basis of foundations.

(b) Moisture movement and moisture retention in soils

Detrimental frost action cannot be conceived without water movements into the zone of freezing. The process of water movement is fundemental to water gain heaving on freezing, as well as reduction in load carrying capacity following thawing of frost (1). It includes movements of water through a range of complete saturation to a condition of partial saturation where the quantity of moisture flow is not significant. The process of moisture flow depends on many factors: grain composition, shape and grain size distribution (7, 8, 10), these influencing the size and shape of soil pores. It is also depending on soil density, initial water content and soil structure, because these factors effects the nature of the pore spaces.

Many investigators have classified the water in the soil into three categories: (a) Gravitational or free water, (b) Capillary water, (c) Adsorbed water. Since the act of excessive heaving is made possible by movement of capillary water to the zone of freezing, we will be mainly interested with the capillarity.

(b-1) Many authors and investigators have refrained from the explanation of existance of capillarity water as described by the rise of water above a free surface in a small diameter capillary tube. They have supported their arguments that there is no free surface existing in a soil mass after the soil has frozen as it is in the case of a capillary tube. But the concept of capillary tube analogy is a useful one, only when one takes into account the relative complexity and irregularity of the small capillarities in the soil mass.

To be able to visualise the mechanics of capillary phenomena occuring in voids of a dry, cohensionless sand, we simplify the problem by considering the rise of water in capillary tubes. Figure 9 shows a capillary tube immersed in a vessel containing water.

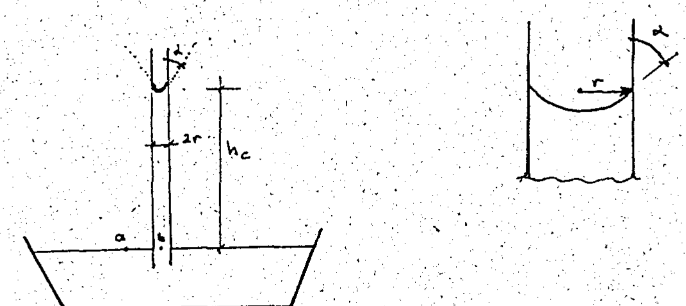


Fig. 9

At point a we have atmospheric pressure. Since point b is at the same elevation as point a, the pressure is the same as at point a. To be able to raise a water column above the free surface, there should exist some kind of transactions of forces existing in the tube. Of the radius of the tube is r, the rise of water is h_c and α is the contact angle between the tube and water surface. from the equilibrium of forces in vertical direction, we can write.

$$\cos\alpha \cdot 2\pi r T_s = \pi r^2 h_c \gamma_w$$

$$h_c = \frac{2 T_s}{\gamma_w r} \cos\alpha$$

or

$$h_c = \frac{2T_s}{\gamma_w} \frac{1}{r} \cos\alpha$$

As we see it from this equation for a given temperature and given enclosing tube, the capillary rise is inversely proportional to the radius of the tube. The smaller the tube size, the higher the capillary there will be.

The following table gives the tension T_s in the surface film water in contact with air for different temperatures(7).

T(°C)	0°	10°	20°	30°	40°
T_s(gr.per cm)	0,0756	0,0742	0,0727	0,0711	0,0695

Lets consider a colomn of dry sand whose lower end is immersed in a water tank. As soon as it is immersed, capillary action due to surface tension between the sand and water is going to take place. Lets denote the distance the water is going to rise as h_c (Assuming that the portion that water has risen is completely saturated, and above portions as dry). Since h_c represent a capacity of water to rise in soil, it can be denoted as capillary potential. Capillary water flowing in the sand, is under the action of this potential, or head.

Since flow of water in soil is determined by Darcy's law. We can write

$$v = k.i$$

where v = discharge velocity

k = permeability of soil

i = hydraulic gradient.

At a given time t, the capillary water in the sand is at an elevation z. Assuming that the vertical component of surface tension at the upper boundary of saturated section for any elevation, the hydraulic head with respect to the base of the colomn, located at the free level is $h_c - z$

and hydraulic gradient being hydraulic head divided by distance travelled,

$$i = (h_c - z)/z$$

the rate dz/dt is the rate at which water is flowing in the sand colomn, which is equal to seepage velocity v_s

$$v_s = \frac{v}{n} \quad \text{or} \quad v_s = \frac{dz}{dt}$$

if we combine the equations

$$\frac{dz}{dt} = v_s = \frac{v}{n}$$

$$v_s = \frac{k.i}{n}$$

$$\frac{dz}{dt} = \frac{k}{n} \cdot \frac{h_c - z}{z}$$

from which we get

$$h_c - z - h_c \operatorname{Log}(h_c - z) = \frac{k}{n} t + c$$

at $t = 0$ $z = 0$

$$c = h_c - h_c \operatorname{Log} h_c$$

Thus we obtain, substituting the values above.

$$t = \frac{n h_c}{k} \left[\operatorname{Log} \frac{h_c}{h_c - z} - \frac{z}{h_c} \right]$$

Therefore, as we see from this equation, the time required for the capillary climb is limited by the soil permeability.

(b-2) The Approximate Relation between the Permeability and Capillary Head

An approximate relationship between the permeability and the capillary head of a soil can be developed by a comparison of flow and capillarity relationship for soil capillaries and capillary tubes. This approximate relation as given in reference (8) is

$$k = A \frac{n}{B h_c^2}$$

where $A = \frac{T_s^2}{2 \mu \gamma_w}$ is related to the water properties

and $A = 290$ cc/sec at T 20^oC

B is a factor depending on soil, it generally varies between 20 and 300. The range of values of B/n is from 50 to 600.

PHYSICO - CHEMICAL PROPERTIES OF SOIL

As it has been shown by Taber and by other investigators that water in fine clay soil freezes at several degrees below °C. This fact is best explained by super cooling of the water adjacent to the films around the particles. It is necessary to remove more heat, thus reduction in temperature, so as to be able to introduce the water molecules in the film to the growing crystal. And the amount of heat removed, thus the amount of energy expended, varies with the nature of the forces between the water molecules in the film and the soil molecules. Thus the supercooling is directly effected by the minerological composition of clay particles.

CHAPTER II

MATERIAL AND APPARATUS

A. Soils to be investigated

Soil fractions and various combinations of them are taken. These are given in a list form below.

1.	100 %	- 50 + 100	
2.	100 %	-100 + 200	
3.	100 %	-200	
4.	50 %	- 50 + 100	by weight
	50 %	-100 + 200	
5.	50 %	-100 + 200	by weight
	50 %	-200	
6.	50 %	- 50 + 100	by weight
	50 %	-200	
7.	25 %	- 50 + 100	by weight
	75 %	-100 + 200	
8.	75 %	- 50 + 100	by weight
	25 %	-100 + 200	
9.	25 %	-100 + 200	by weight
	75 %	-200	
10.	75 %	-100 + 200	by weight
	25 %	-200	
11.	25 %	- 50 + 100	by weight
	75 %	-200	

12. 75 % - 50 +100 by weight
25 % -200

In the experiments to determine the saturation capillary head a void ratio is provided to the specific soil at hand. This void ratio is then kept the same in all other experiments, like in permeability and in freezing tests.

-200 denotes the fraction passing No.200 sieve having an opening 0.074 mm.

-50 +100 denotes the fraction passing No.50 sieve and retaining on No 100 sieve.

-100 +200 denotes the fraction passing No.100 sieve and retaining on No.200 sieve.

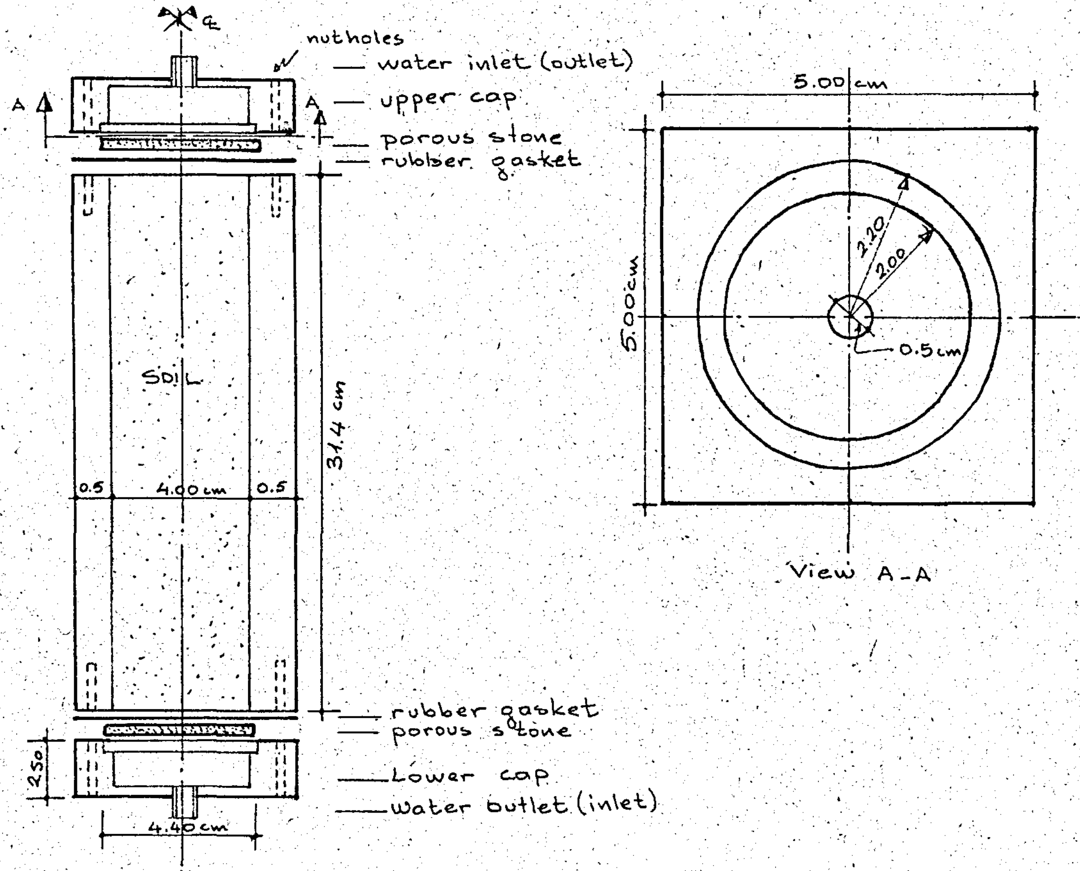
In the experiments performed, the portion below 0.05 mm. was not seperated from -200 sieve portion. Since this portion and diameter sizes smaller than these portions consists of clay particles, experimental considerations of the grain size effects are effected by the adsorbed water. And this introduces some errors in the experimental results.

B. <u>Apparatus</u>

1) Description and preparation of apparatus for tests

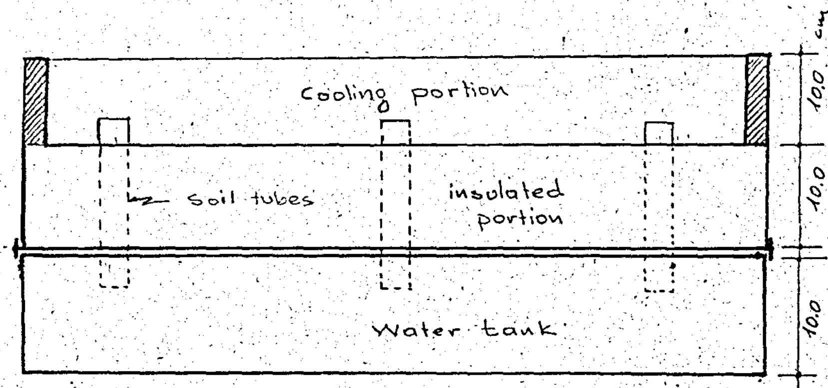
Tests of saturation capillary heads were performed in an apparatus manufactured in the laboratory. In designing this apparatus, the apparatus described in ref. (19), was taken as a model.

The figure below shows the different sections of this apparatus.

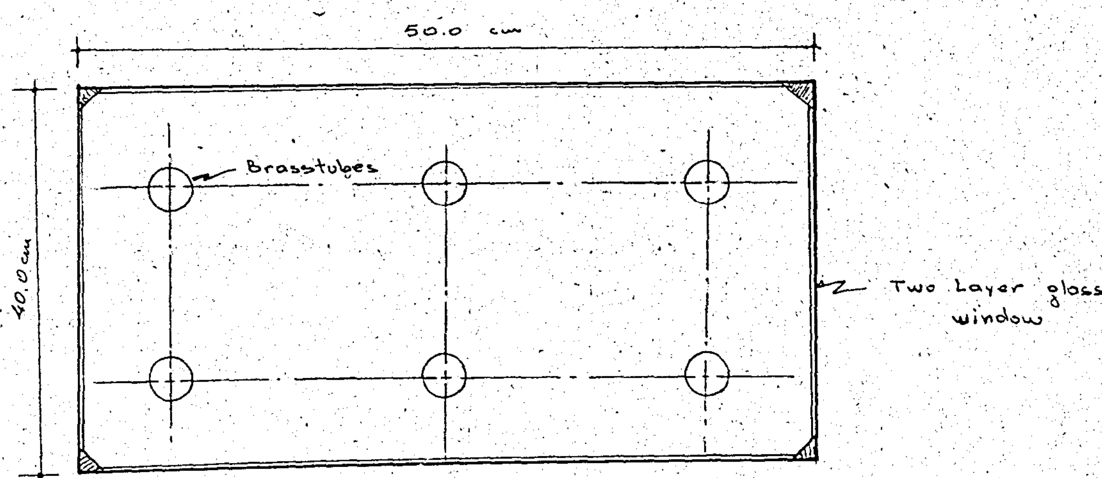


The apparatus is produced from a transparent synthetic glass. Its commercial name is "far glass". The reason for choosing a transparent material is to be able to have a control on the different stages of experiments, to be able to see the phenomena occuring in the soil during the measurement of capillary heads.

Freezing tests were performed in a freezing chamber constructed for this purpose. It is consisted of three parts. Lower part is a water tank to which is attached inlets and outlets to have a water circulation in the tank so that the temperature changes will essentially be zero. This portion represents the ground water level occuring in nature. Middle part contains the insulating material surrounding the brass tubes containing soil samples. Top portion is the section which is being cooled by cold air above it. Cooling the samples were performed by means of dry ice and the air temperatume obtained was around -20°C for a 10 hour long interval. The figure of the apparatus and its various parts are shown below.

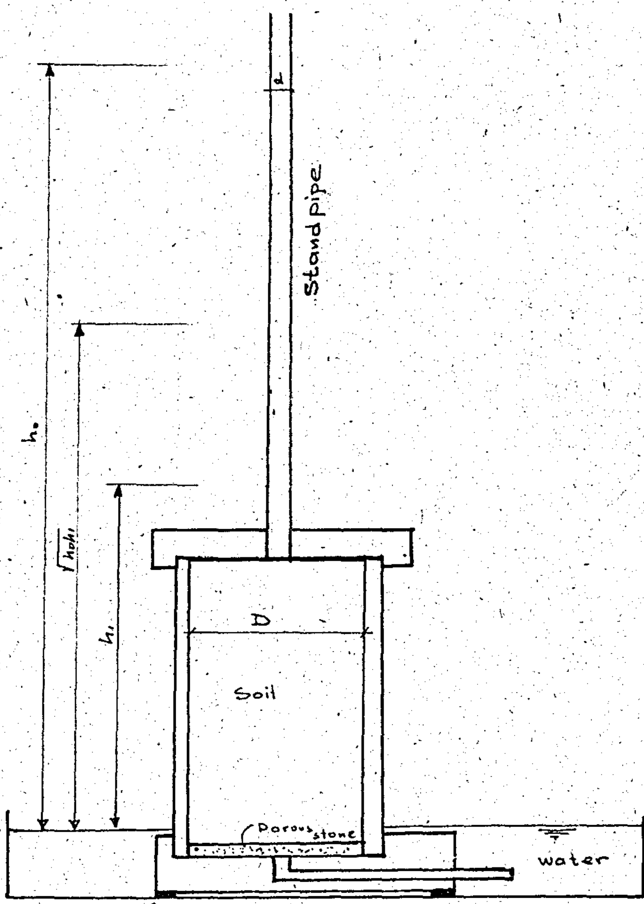


Side View



Top view

Permeabilities of the soil samples are obtained in a standard falling head permeameters in the laboratory. Its standpipe containes 10 ml. of water at T = 20°C. The figure below shows the figure of the falling head permeameter and its various portions.



d = internal diameter of standpipe

a = internal cross-sectional area of stand-pipe $= \pi d^2/4$

D = internal diameter of soiltube

A = cross-sectional area of soil sample $= \pi D^2/4$.

H = length of soil sample

V = volume of soil sample $= (\pi D^2/4)(H)$

CHAPTER III

EXPERIMENTATION

Capillary Head Test

Measurement of saturation capillary heads were measured in the apparatus produced in the laboratory. This apparatus was designed in a similar fashion like the one described in ref. (19).

Procedure of the experiment.

1. Cleaning the tube
2. Weighing the tube
3. Filling the layers in 2 cm. thicknesses at the same time compacting the soil put.
4. Putting filter paper on top of the soil.
5. Placing the upper cap of the tube
6. Weighing it to an accuracy of 0.1 gm.
7. Measuring the length of the soil
8. Connecting top portion to vacuum, bottom water supply.
9. Applying vacuum, until water is seen to be coming out through the porous stone at the top cap.
10. Applying head to the soil at the bottom tube by lowering the water tank 2cm./5 min.

Measuring the distance from the bottom of the soil sample to the water level in the water tank, as soon as first air buble is seen to be coming out of the porous stone, at the bottom of the soil sample.

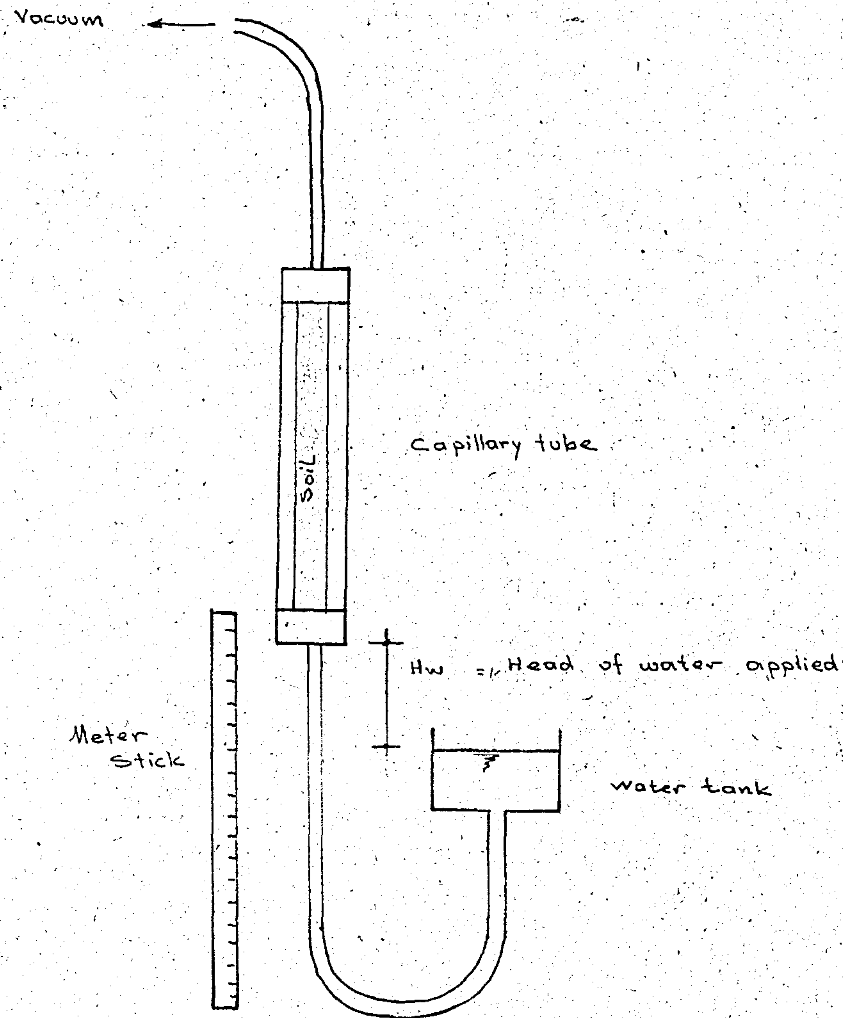
In the case of very fine grained particles and low void ratios, this head comes out to be very high. In that case saturation capillary head comes out to be very high. For this, we use mercury instead of water. Saturation capillary heads of different samples with different void ratios were measured. They are plotted on a e vs. H_{cs} scale. In this graph, however there are certain errors involved due to.

1. Although we are considering the void ratio as a parameter, wetted perimeter has an effect to change the saturation capillary heads.
2. Minus 200 portion contains clay particles, which has adsorbed water films around, as well. This also has an effect on the saturation capillary head, not being related to void ratio of soil. In the figure, on page 38, the set-up of the apparatus, during saturation and during measurement of saturation capillary heads is shown.

Picnometer calibration

To be able to measure the specific gravities of the different soil sample, we have to, first, calibrate the picnometer. The picnometer used has a volume of 200 ml. at 20°C.

The procedure of the experiments is as follows:



Set-up for measuring
Saturation capillary head

In case of high capillary heads :

$H_{cs} = H_w + (13.6)(\ell)_m$ where ℓ_m is the effective length of mercury colomn

1. Cleaning the picnometer
2. Putting water into it so that the bottom of the water in the picnometer is at the same level as the line on it.
3. Measure temperature of water, (at room temperature.)
4. Weigh picnometer and water to an accuracy of 0.01 gm.
5. Heat the picnometer slowly, at the same time stiring the water in it to have uniform temperature distribution in it.
6. Add, or take out some water, (as necessity arises) so that the bottom of the meniscus is at the same level as the level of line on the picnometer.
7. Weigh the picnometer to an accuracy of 0.01 gm.
8. Repeat the steps 5 to 7, within temperature range of 20°-30°C until you get 4 more points.
9. Plot (weight of water + weight of picnometer) vs. temperature. °C

Determination of Specific Gravities

1. Weigh tare to an accuracy of 0.01 gm
2. Weigh tare + soil.
3. Put soil into the picnometer + water system.
4. Heat it slowly by applying partial vacuum so that all air entrapped will bubble out.
5. Adjust the level of bottom of meniscus to the same level as hair line on the picnometer, at the same time cooling and stirring the water and soil to bring it to the temperature range of picnometer calibrations.

6. Measure the temperature of water + soil.

Calculations and data are shown in appendix.

Specific gravity of a soil is :

$$G_s = \frac{W_s \, G_T}{W_s - W_1 + W_2}$$

Permeability Determinations

1. Clean the permeameter.
2. Measure the length of the tube in which soil is put
3. Measure the internal diameter of the tube in which soil is put.
4. Calcbrate the amount of soil to be put to have the void ratio as in the case of saturation capillary heads.
5. Weigh the oven dry soil equal to the amount found in item 3.
6. Put the soil in 1 cm. layers.
7. Make sure that the soil put just fills up to the top of the tube.
8. Put filter paper on top of the soil.
9. Assemble the top portion of permeameter.
10. Saturate the soil slowly by applying head to the bottom of soil sample.
11. Make sure that no air bubble is coming out of the standpipe, by tapping to the tube.
12. Mark the distances h_o, $\sqrt{h_o h_1}$, h_1

13. Measure the temperature of the distilled water used in the permeability experiment.

14. Measure the time from h_o to $\sqrt{h_o h_1}$ and from $\sqrt{h_o h_1}$ to h_1. If they do not agree within 2-3%, empty the tube and refill it. Repeat the steps 6-14 until you get the contition above.

15. Calculate the permeability according to

$$k = 2.3 \frac{a\,L}{A(t_1 - t_o)} \text{Log} \frac{h_o}{h_1}$$

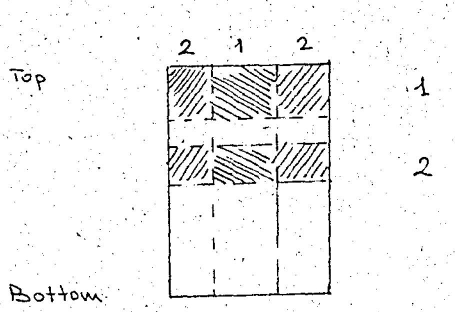
Calculations and data pertaining to this experiment are given in the appendix.

Freezing Experiments

Freezing of the samples were performed in the following manner.

1. Prepare the freezing chamber for the experiment.
2. Measure the diameter of tubes.
3. Calculate volume of soil to be put into a height of 12 cm. so as to have the same void ratios as in capillary and permeability experiments.
4. Weigh the necessary amounts of ovendry soil.
5. Place the soil in 2 cm. thickness, gradually compacting it so that it fills a height of 12 cm. (soil put is partially saturated).
6. Freeze the soils by dry-ice gradually at a rate of 2 °C/hr. until the temperature of -20°C is reached.
7. Maintain -20°C temperature for 10 hours.
8. Measure heaves, if any present.
9. Measure the final moisture contents after freezing.
10. Repeat steps 1-9 with full saturation at smaller void ratios

Measurements of the moisture contents (as shown in appendix) are done according to the notation in the figure below.



Soil sample taken out of brass tube

CHAPTER IV

Data, Analysis and Discussion

A- Data and Analysis

I- Results of the saturation capillary heads determinations are given below in a listed form

Void ratio	I.I58	0.935	I.I25	I.02I	0.872
H_{cs} (cm)	28	40	322	28	58I
Void ratio	0.7I0	0.930	0.839	0.889	0.920
H_{cs} (cm)	6I6	24	23.5	238	I44
Void ratio	0.980	0.752			
H_{cs} (cm)	270	23.5			

The plot of void ratio vs. saturation capillary heads are given in the appendices.However,this is an attempt and the purpose of plotting these values is not to derive a general relation between the void ratio and saturation heads but,instead, to indicate the type of behaviour it tends to demonstrate.Since,the phenomena is too complicated to be expressed only in terms of single variable,void ratio.

2- Permeabilities of the same soils are determined at the same void ratios as in the case of saturation capillary head determinations.They demonstrate a scattered distribution on e vs. log.k scale.Since,we have a change in the soil samples, permeability vs e relation is not easy to express, graphically.

3- During the first set of freezing experiments ,soil initially was not fully saturated.Percent saturation of these soils are given below:

Sample no	I	2	3	4	5	6
% saturation	49.5	83,5	93.0	8I.0	82.5	75.0

We could not obtain any frost heaving as a result of partial saturation of the samples.This is to be expected. Since,excessive heaving is due to the growth of ice lenses fed by the water with the combined action of capillarity and permeability.

During the second set of freezing of the same soil samples void ratios of the samples are decreased compared with the void ratios originally.Using the same amount of soil,but this time compacting it into a height of I2 cm instead of I3 cm,securing at the same time , full saturation.They are frozen in the deep-freeze of the refrigirator in the laboratory,at a temperature of -20 degree centigrade for ten hours.This time again,although ice lencing was obtained, they did not have any chance to grow up due to rapid freezing conditions.The formation of ice strata is observed in sample number three which is consisted of pure minus 200 portion.The calculation below shows,approximately, the time required for sample number three to freeze from plus I5 degrees centigrade down to minus I5 degrees centigrade.

$k = 2.90 \times 10^{3}$ cal/cm-sec°C   for 100% saturated silty-clay unfrozen

$c_{ps} = 0.22$ cal/gm-°C

$c_{pw} = 1$ cal/gm-°C

$$Q_{required} = \int_{+15}^{-15} V_s \rho_s c_{ps}\, dT + \int_{+15}^{-5} V_w \rho_w c_{pw}\, dT$$

$$\frac{dQ}{dt} = q = KA \frac{\Delta T}{\Delta x}$$

$$Q_{req} = (201)(0.22)(-30) + (76.5)(1)(-30) = 3800 \text{ cal}$$

$$q = 2900 \times \frac{\pi}{4} \overline{4.04}^2 \times \frac{(-30)}{12} \doteq 100000 \text{ cal}$$

$$\Delta t = \frac{3800}{100000} \approx 0.038 \text{ sec} \quad (\text{very small})$$

k_{soil} = (permeability) is around the range of 10^{-4} cm/sec. That is the water will travel 0.4 cm/hour.

B- Discussion:

Results of capillary head determinations reveals that a certain relation exist between the void ratio of the soil samples and their saturation capillary potential heads. As the grain sizes are made smaller or by combining different soil fractions, the capillary passages are decreased in size this in turn effecting the capillary heads. Of course, by simple reduction of grain sizes does not express much. One, also has to compact it properly so that all extra voids beyond minimum are eliminated.

As the size of soil grain get smaller, an error is introduced due to the film formations around clay particles. This fact was not and could not be considered in our experiments.

Determination of permeabilities was done simply to obtain a relative a measure of them. Since they will be needed in the evaluation of freezing experiments.

In the first series of freezing experiments , no appreciable change of moisture content is observed. The reason is that soils was not fully saturated at the start of the experiments . In the secondset of freezing experiments, however, especially in sample number three which is composed of pure minus 200 , we observe a large change in moisture contents. But the lack of heave indicates that this content change is an internal one due to the migration of water from one portion of the soil to another portion. This regional change is an outcome of rapid freezing process. The photographs below are taken after the rapid freezing of soil number three.

Conclusion and Recommendations

To be able to have a better picture of the effect of grain size on frost heaving properties of various soils we have to increase the amount of experiments by extending the range of experiments for various void ratios for each soil. But this has a disadvantage with respect to the limitations of time. But, nevertheless, a certain picture of the phenomena was obtained with the experiments performed.

The freezing chamber has certain deficiencies with respect to the control of experiments. By improving the soil tubes, water tank below, and by installing thermo couples to the freezing chamber, these deficiencies can be eliminated and a better control of the experiments is possible.

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APPENDICES

CALCULATIONS

Capillarity Tests:

SAMPLE No: 1 100 % -50# +100#

Weight of capillary tube (empty) = 805 gm

Weight of capillary tube (filled) = 1292.50 gm

Weight of soil = 487.50 gm

Length of soil sample = 31.4 cm

D_{int} of tube = 4.0 cm

Volume of soil = $31.4 \times \pi \times \frac{4^2}{4}$ = 394 cm^3

G (Determined in specific gravity test) = 2.68

$$\gamma_{dry} = \frac{W_s}{V_{total}} = \frac{G\gamma_w}{1+e}$$

$$e = \frac{G\gamma_w}{W} V - 1 = \frac{2.68 \times 1 \times 394}{487.50} - 1 = 1.158$$

Saturation capillary head:

First run H_{cs} = 37 cm of water

Second run H_{cs} = 28 cm of water T_w = 22°C (of water)

Third run H_{cs} = 28 cm of water

SAMPLE No: 2 100 % $-100^{\#} + 200^{\#}$

Weight of capillary tube (empty) = 805.0 gm

Weight of capillary tube (filled) = 1308.0 gm

Weight of soil = 503.0 gm

Length of soil sample = 31.4 cm

D_{INT} of tube = 4.0 cm

Volume of soil = $31.4 \times \pi \times \frac{4^2}{4}$ = 394 cm^3

G_s (determined in the specific gravity test) = 2.48

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e}$$

$$e = \frac{G\gamma_w}{W_s} V_t - 1$$

$$e = \frac{2.48 \times 1}{503} 394 - 1 \qquad e = 0.935$$

Saturation capillary head:

First run H_{cs} = 40 cm of water

Second run H_{cs} = 41 cm of water

T_w = 22 °C (temperature of water).

SAMPLE NO: 3 100% −200#

Weight of capillary tube (empty) = 805.0 gm

Weight of capillary tube (filled) = 1278.5 gm

Weight of soil = 473.5 gm

Length of soil sample = 31.4 cm

Dint of tube = 4.0 cm

Volume of soil $= 31.4 \times \pi \times \frac{4^2}{4}$ = 394 cm^3

G_s (determined in the specific gravity test) = 2.58

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e}$$

$$e = \frac{G\gamma_w}{W_s} V_t - 1 = \frac{2.58 \times 1}{473.5} \times 394 - 1$$

$$e = 1.125$$

Saturation capillary head :

$$H_{cs} = H_w + 13.6\, \ell_m - H_w$$

$$H_{cs} = 50 + (71-50)\, 13.6 - (71-57)$$

$$H_{cs} = 322 \text{ cm of water}$$

$T_w = 22°C$ (Temperature of water)

SAMPLE No: 4

50% $-50^{\#}+100^{\#}$

50% $-100^{\#}+200^{\#}$ by weight

Weight of capillary tube (empty) = 805 gm

Weight of capillary tube (filled) = 1325 gm

Weight of soil = 520 gm

Length of soil sample = 31.4 cm

Volume of soil $= 31.4 \times \pi \times \frac{4.0^2}{4}$ = 394 cm^3

D_{INT} of tube = 4.0 cm

G_s (determined from sp. gravity test) = 2.67

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Longrightarrow e = \frac{G\gamma_w}{W_s} V_t - 1$$

$$e = \frac{2.67 \times 1}{520} \times 394 - 1 \qquad e = 1.021$$

Saturation capillary head :

First run H_{cs} = 28 cm of water

Second run H_{cs} = 28 cm of water

T_w = 22 °C (Temperature of water)

SAMPLE NO: 5 — 50 % $-100^{\#} + 200^{\#}$

50 % -200 by weight

Weight of capillary tube (empty) = 1008 gm

Weight of capillary tube (filled) = 1570 gm

Weight of soil = 562 gm

Length of soil sample = 31.3 cm

D_{INT} of tube = 4.0 cm

Volume of soil $= 31.3 \times \pi \times \frac{\overline{4.0}^2}{4}$ $= 393\ cm^3$

G_s (determined from sp. gravity test) = 2,68

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Longrightarrow e = \frac{G\gamma_w}{W_s} V_t - 1$$

$$e = \frac{2.68 \times 1}{562} \times 393 - 1 \qquad e = 0.872$$

Saturation capillary head :

$$H_{cs} = H_w + 13.6\, l_m - H_w'$$

$$H_{cs} = 71 + 13.6 \times 37.5 - 0$$

$$H_{cs} = 581 \text{ cm of water}$$

$T_w = 22°C$ (Temperature of water)

SAMPLE NO : 6 — 50 % $-50^{\#} + 100^{\#}$, 50 % $-200^{\#}$ by weight

Weight of capillary tube (empty) = 998 gm

Weight of capillary tube (filled) = 1595 gm

Weight of soil = 597 gm

Length of soil sample = 31.0 cm

D_{INT} of tube = 4.0 cm

Volume of soil $= 31 \times \pi \times \frac{4.0^2}{4}$ = 389 cm^3

G_s (Determined from sp. gravity test) = 2.63

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\,\gamma_w}{1+e} \implies e = \frac{G\,\gamma_w}{W_s} V_t - 1$$

$$e = \frac{2.63 \times 1}{597} \times 389 - 1 \qquad e = 0.710$$

Saturation capillary head :

$$H_{cs} = H_w + \ell_m \times 13.6 - H_w'$$

$$H_{cs} = 75 + (61.5 - 21) - 10$$

$$H_{cs} = 616 \text{ cm of water}$$

$T_w \doteq 20°C$ (Temperature of water)

SAMPLE No: 7 25 % $-50^{\#}+100^{\#}$
75 % $-100^{\#}+200^{\#}$ by weight

Weight of capillary tube (empty) = 805 gm
Weight of capillary tube (filled) = 1348 gm
Weight of soil = 543 gm
Length of soil sample = 31.4 cm
D_{int} of tube = 4.0 cm
Volume of soil = $31.4 \times \pi \times \frac{4.0^2}{4}$ = 394 cm^3
G_s (determined from sp. gravity test) = 2.66

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Rightarrow e = \frac{G\gamma_w}{W_s}V_t - 1$$

$$e = \frac{2.66 \times 1}{543} \times 394 - 1 \qquad e = 0.930$$

Saturation capillary head:

First run H_{cs} = 28 cm of water
Second run H_{cs} = 24 cm of water
Third run H_{cs} = 26 cm of water

T_w = 22°C (Temperature of water)

SAMPLE NO: 8 75 % $-50^{\#}+100^{\#}$
25 % $-100^{\#}+200^{\#}$ by weight

Weight of capillary tube (empty) = 810 gm
Weight of capillary tube (filled) = 1379 gm
Weight of soil = 569 gm
Length of soil sample = 31.4 cm
D_{int} of tube = 4.0 cm
Volume of soil = $31.4 \times \pi \times \frac{4.0^2}{4}$ = 394 cm^3
G_s (determined from sp. gravity test) = 2.66

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Rightarrow e = \frac{G\gamma_w}{W_s}V_t - 1$$

$$e = \frac{2.66 \times 1}{569} \times 394 - 1 \qquad e = 0.839$$

Saturation capillary head:

First run H_{cs} = 26.3 cm of water

Second run H_{cs} = 23.5 cm of water

Third run H_{cs} = 23.9 cm of water

T_w = 22 °C (Temperature of water)

SAMPLE NO: 9 25 % $-100^{\#} + 200^{\#}$
75 % $-200^{\#}$ by weight

Weight of capillary tube (empty) = 805 gm
Weight of capillary tube (filled) = 1351.90 gm
Weight of soil = 546.90 gm
Length of soil sample = 31.4 cm
D_{int} of tube = 4.0 cm
Volume of soil = $31.4 \times \pi \times \overline{4.0}^2/4$ = 394 cm³
G_s (determined from specific gr. test) = 2.63

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Rightarrow e = \frac{G\gamma_w}{W_s} V_t - 1$$

$$e = \frac{2.63 \times 1}{546.90} \times 394 - 1 \qquad e = 0.889$$

Saturation capillary head:

$$H_{cs} = H_w + 13.6\, \ell_m - H_w'$$

First run $H_{cs} = 37 + 13.6 \times 20 - 26 \Rightarrow H_{cs} = 260$ cm of water

Second run $H_{cs} = 40 + 17 \times 13.6 - 33 \Rightarrow H_{cs} = 238$ cm of water

T_w = 22 °C (Temperature of water)

SAMPLE NO: 10 75 % $-100^{\#} + 200^{\#}$
25 % $-200^{\#}$ by weight

Weight of capillary tube (empty) = 805 gm.
Weight of capillary tube (filled) = 1345 gm.
Weight of soil = 540 gm
Length of soil sample = 31.4 cm
D_{INT} of tube = 4.0 cm
Volume of soil = $31.4 \times \pi \times \frac{\overline{4.0}^2}{4}$ = 394 cm³
G_s (determined from specific gr. test) = 2.64

$$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Rightarrow e = \frac{G\gamma_w}{W_s} V_t - 1$$

$e = \frac{2.64 \times 1}{540} \times 394 - 1$ $\qquad e = 0.920$

Saturation capillary head :

$H_{cs} = H_w + \ell_m \times 13.6 - H_w'$

$H_{cs} = 56 + 9 \times 13.6 - 35$ $\qquad H_{cs} = 144$ cm of water

$T_w = 20°C$ (Temperature of water)

SAMPLE NO: 11 — 25 % $-50^{\#} + 100^{\#}$; 75 % $-200^{\#}$ by weight

Weight of capillary tube (empty) = 805 gm.
Weight of capillary tube (filled) = 1325 gm
Weight of soil = 520 gm
Length of soil sample = 31.4 cm
D_{INT} of tube = 4.0 cm
Volume of soil = $31.4 \times \pi \times \frac{\overline{4.0}^2}{4}$ = 394 cm^3
G_s (determined from sp. gravity test) = 2.62

$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Rightarrow e = \frac{G\gamma_w}{W_s} V_t - 1$

$e = \frac{2.62 \times 1}{520} \times 394 - 1$ $\qquad e = 0.980$

Saturation capillary head :

$H_{cs} = H_w + 13.6 \times \ell_m$

$= 32 + 13.6 \times 17.5$ $\qquad H_{cs} = 270$ cm of water

$T_w = 22°C$ (Temperature of water)

SAMPLE NO: 12 — 75% $-50^{\#} + 100^{\#}$; 25% $-200^{\#}$ by weight

Weight of capillary tube (empty) = 998 gm
Weight of capillary tube (filled) = 1595 gm
Weight of soil = 597 gm
Length of soil sample = 31.4 cm
D_{int} of tube = 4.0 cm
Volume of soil = $31.4 \times \pi \times \frac{\overline{4.0}^2}{4}$ = 394 cm^3

G_s (determined from sp. gravity test) = 2.66

$\gamma_{dry} = \frac{W_s}{V_t} = \frac{G\gamma_w}{1+e} \Rightarrow e = \frac{G\gamma_w}{W_s} V_t - 1$

$e = \frac{2.66 \times 1}{} \times 394 - 1$ $\qquad e = 0.752$

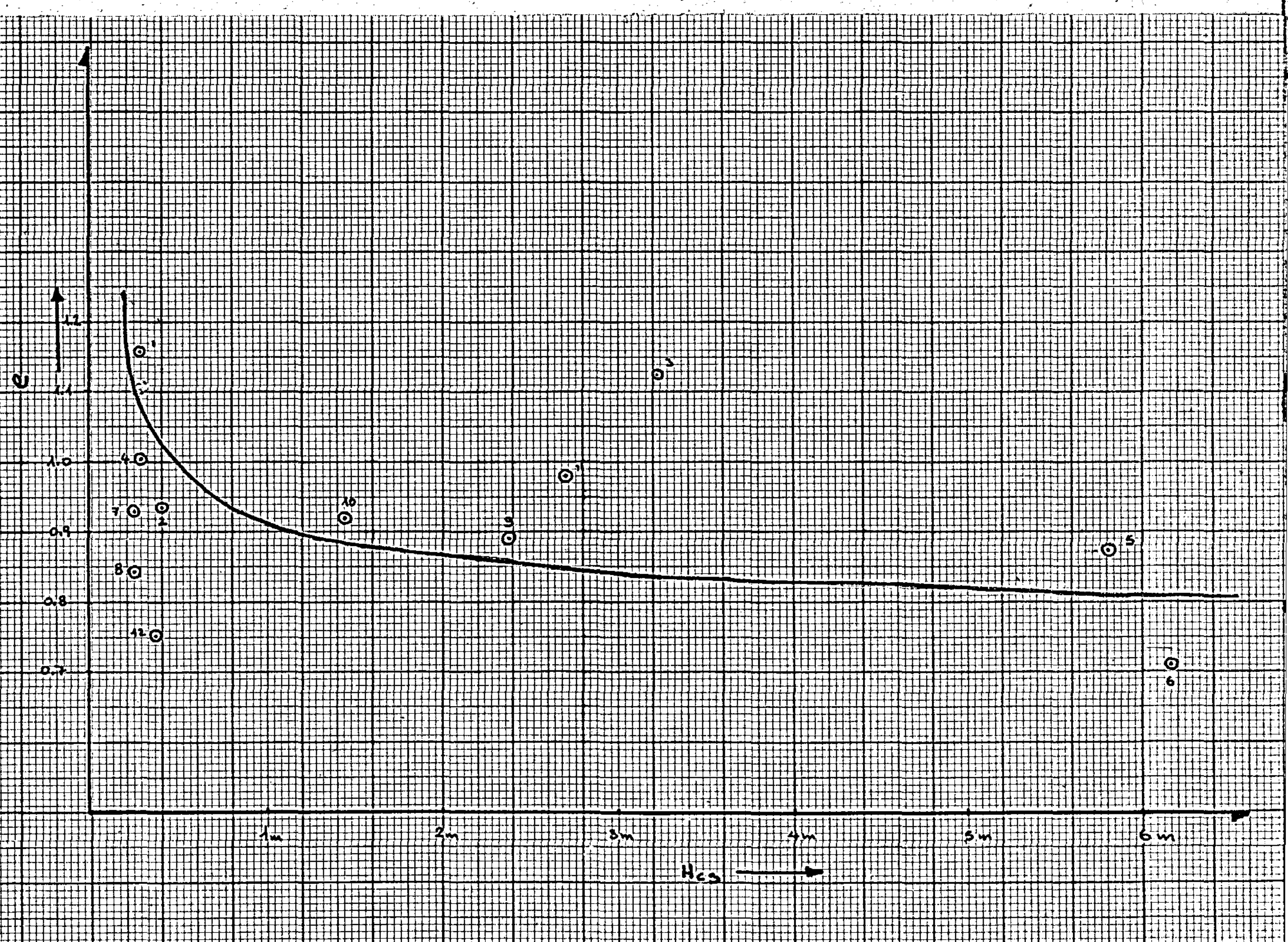
Saturation capillary head:

H_{cs} = 23.5 cm of water

T_w = 22°C (Temperature of water)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Void ratio e	1.158	0.935	1.125	1.021	0.872	0.710	0.930	0.839
H_{cs} (cm)	28	40	322	28	581	616	24	23.5

	(9)	(10)	(11)	(12)
Void ratio e	0.889	0.920	0.980	0.752
H_{cs} (cm)	238	144	270	23.5



PICNOMETER CALIBRATION

(Water+Picn.) wt gm.	660.78	659.95	660.15	660.20
T (°c)	23.8	29.8	28.8	28.0

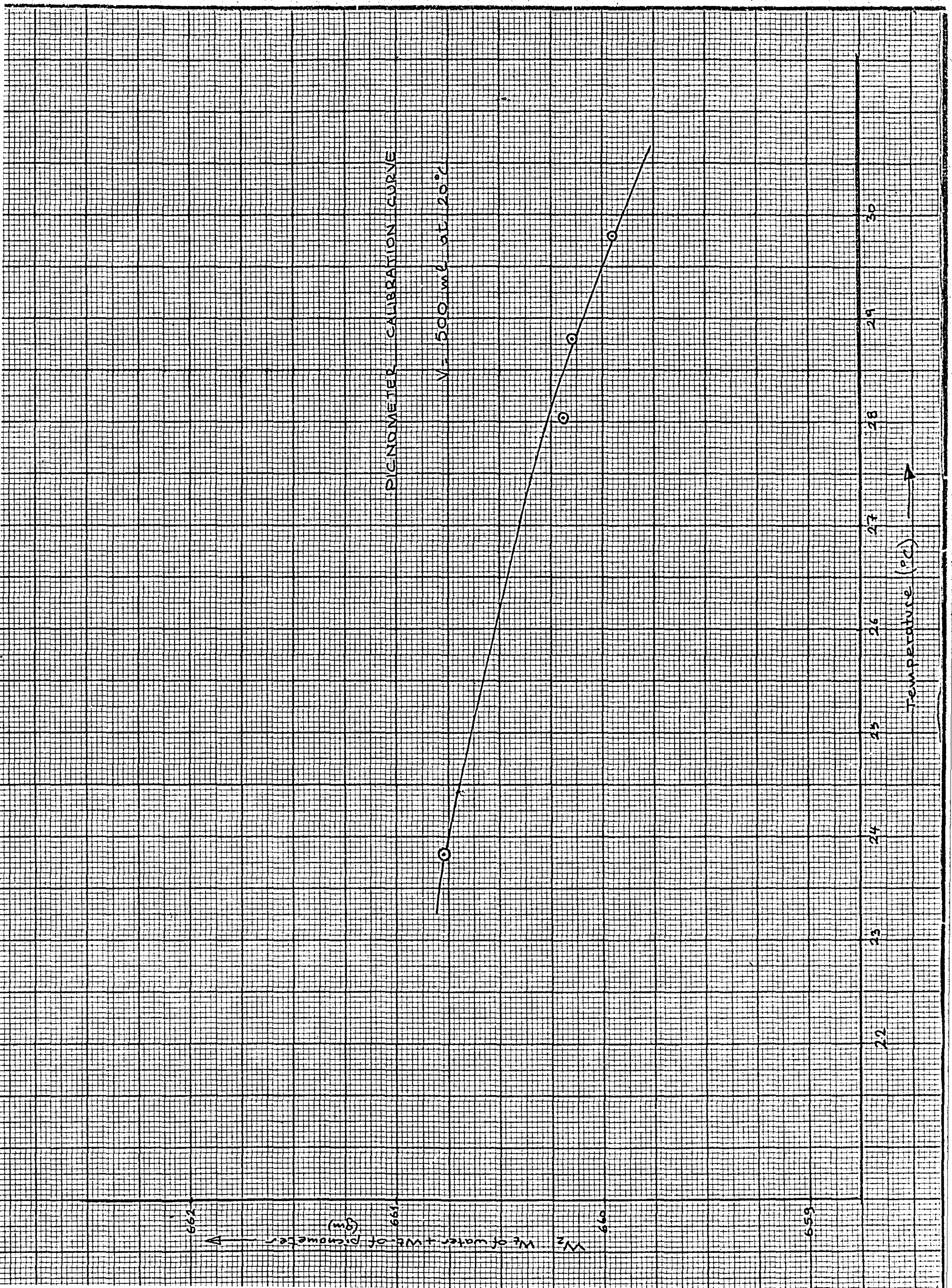
Picnometer calibration curve is given on the next page.

DETERMINATION OF SPECIFIC GRAVITIES

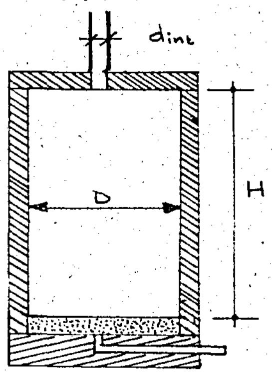
$$G_s = \frac{G_T W_s}{W_s - W_1 + W_2}$$

Sample No:	1	2	3	4	5	6
Tare wt. gm	461.95	460.97	527.25	460.95	460.95	462.00
(Tare + soil) wt. gm.	613.00	568.81	602.27	610.95	631.55	589.00
Soil wt W_s gm.	151.05	107.84	75.02	150.00	170.60	127.00
(Bo. + water + soil)$_{wt}$ W_1 gm	756.15	727.96	706.70	754.27	767.85	736.00
Temperature °C	25.2	26.5	24.9	26.0	28.0	27.0
(Bo. + water)$_{wt.}$ W_2 gm	660.62	660.46	660.65	660.52	660.25	660.40
Spec. gravity of water G_T	0.9971	0.9967	0.9971	0.9968	0.9963	0.9965
G_T W_s	150.60	107.20	74.88	149.65	169.70	126.50
$W_s - W_1 + W_2$	56.52	40.34	28.97	56.25	63.00	51.40
Spec. gravity of soil G_s	2.68	2.48	2.58	2.67	2.68	2.63

Sample No	7	8	9	10	11	12
Tare wt. gm.	112.60	528.03	527.25	527.25	528.05	527.25
(Tare + soil) wt. gm.	312.60	678.03	611.25	627.25	628.05	663.10
Soil wt. W_s gm.	200.00	150.00	84.00	100.00	100.00	135.85
(Bo. + water + soil)$_{wt}$ W_1 gm.	785.60	754.33	713.00	722.75	722.65	745.30
Temperature °C	26.0	25.8	23.0	26.0	24.2	26.8
(Bottle + water)$_{wt.}$ W_2 gm	660.52	660.55	660.85	660.52	660.72	660.42
Spec. gravity of water G_T	0.9968	0.9968	0.9976	0.9968	0.9973	0.9966
G_T W_s	199.36	149.50	83.90	99.68	99.73	135.35
$W_s - W_1 + W_2$	74.92	56.22	31.85	37.77	38.07	50.97
Specific gravity of soil G_s	2.66	2.66	2.63	2.64	2.62	2.66


PICNOMETER CALIBRATION CURVE
V = 500 ml at 20°C
Temperature (°C)
22
23
24
25
26
27
28
29
30
662
661
660
659
W₂ Wt of water + Wt of picnometer (gm)

PERMEABILITY CALCULATIONS



$H = 7.35\,cm$

$D = 3.32\,cm$

$d_{int} = 0.68\,cm$

$V = 7.35 \times \pi \times \frac{\overline{3.32}^2}{4}$ $\quad V = 63.5\,cm^3$

A = area of permeability apparatus (x-sectional)

$A = \pi \times D^2 \times \frac{1}{4}$ $\quad A = 8.65\ cm^2$

a = area of the tube above the main part (x-sectional area)

$a = \pi \times d^2 \times \frac{1}{4}$ $\quad a = 0.363\ cm^2$

Amounts of soils to be put into: Since we want to have the same void ratios as in the case of capillarity experiments,

$$\frac{W_c}{W_p} = \frac{G_s \gamma_w}{1+e_c}\ \frac{V_c}{V_p}\ \frac{1+e_p}{G_s \gamma_w}$$

$$\frac{W_c}{W_p} = \frac{V_c}{V_p}$$

SAMPLE NO: 1 $\quad$ 100% $-50^{\#}+100^{\#}$ by weight

$W_p = \frac{V_p}{V_c} W_c$ $\quad$ = weight of soil to be put

weight of soil $\quad W = \frac{63.5}{394}\ 487.5$ gm

$W_s = 78.5$ gm

$h_o = 36.5$ cm, 40.0 cm $\quad t_{h_o} = 0$, 0

$\sqrt{h_o h_1} = 32.5$ cm, 28.25 cm $\quad t_{h_o - \sqrt{h_o h_1}} = 6$ sec , 22 sec

$h_1 = 29.0$ cm, 20.00 cm $\quad t_{\sqrt{h_o h_1} - h_1} = 5$ sec , 23 sec

SAMPLE NO: 2 $\quad$ 100% $-100^{\#}+200^{\#}$ by weight

$W = \frac{63.5}{394}\ 503$ gm $\quad W_s = 83.2$ gm

$h_o = 30.0$ cm $\quad t_{h_o} = 0$

$\sqrt{h_o h_1} = 24.42$ cm $\quad t_{h_o - \sqrt{h_o h_1}} = 1$ min 10 sec

$\sqrt{h_1} = 20.0$ cm $\quad t_{\sqrt{h_o h_1}} - t_{h_1} = 1$ min 11 sec

SAMPLE NO: 3 — 100% $-200^{\#}$ by weight

$W_s = \frac{63.5}{394} \times 473.5$ $\quad W_s = 76.2$ gm.

$h_o = 23.5$ cm $\quad t_{h_o} = 0$

$\sqrt{h_o h_1} = 21.0$ cm $\quad t_{h_o - \sqrt{h_o h_1}} = 37$ min

$h_1 = 18.5$ cm $\quad t_{\sqrt{h_o h_1}} - t_{h_1} = 37$ min

SAMPLE NO: 4 — 50% $-50^{\#} + 100^{\#}$, 50% $-100^{\#} + 200^{\#}$ by weight

$W_s = \frac{63.5}{394} \times 520 = 84$ gm $\quad$ 42 gm $-50^{\#} + 100^{\#}$; 42 gm $-100^{\#} + 200^{\#}$

$h_o = 35.0$ cm $\quad t_{h_o} = 0$

$\sqrt{h_o h_1} = 26.4$ cm $\quad t_{h_o - \sqrt{h_o h_1}} = 31$ sec.

$h_1 = 20.0$ cm $\quad t_{\sqrt{h_o h_1}} - t_{h_1} = 30$ sec.

SAMPLE NO: 5 — 50% $-100^{\#} + 200^{\#}$, 50% $-200^{\#}$ by weight

$W_s = \frac{63.5}{393} \times 562$ $\quad W_s = 91$ gm $\quad$ 40.50 gm $-100^{\#} + 200^{\#}$; 40.50 gm $-200^{\#}$

$h_o = 36.5$ cm $\quad t_{h_o} = 0$

$\sqrt{h_o h_1} = 32.5$ cm $\quad t_{h_o - \sqrt{h_o h_1}} = 44$ min

$h_1 = 29.0$ cm $\quad t_{\sqrt{h_o h_1}} - t_{h_1} = 42$ min 40 sec.

SAMPLE NO: 6 — 50% $-50^{\#} + 100^{\#}$, 50% $-200^{\#}$ by weight

$W_s = \frac{63.5}{389} \times 597$ $\quad W_s = 97.5$ gm $\quad$ 48.75 gm $-50^{\#} + 100^{\#}$; 48.75 gm $-200^{\#}$

$h_o = 43.0$ cm $\quad t_{h_o} = 0$

$\sqrt{h_o h_1} = 26.7$ cm $\quad t_{h_o - \sqrt{h_o h_1}} = 25200$ sec (7 hours)

$h_1 = 16.5$ cm $\quad t_{\sqrt{h_o h_1} - h_1} = 25200$ sec (7 hours)

SAMPLE NO: 7

25% $-50^{\#} +100^{\#}$
75% $-100^{\#} +200^{\#}$ by weight

$W_s = \frac{63.5}{394} 543$ $W_s = 87.6$ gm

21.85 gm $-50^{\#}+100^{\#}$
65.75 gm $-100^{\#}+200^{\#}$

$h_o = 35.0$ cm $t_{h_o} = 0$
$\sqrt{h_o h_1} = 26.4$ cm $t_{h_o - \sqrt{h_o h_1}} = 6$ min. 22 sec
$h_1 = 20.0$ cm $t_{\sqrt{h_o h_1} - h_1} = 7$ min

SAMPLE NO: 8

75% $-50^{\#} +100^{\#}$
25% $-100^{\#} +200^{\#}$ by weight

$W_s = \frac{63.5}{393} 569$ $W_s = 90.5$ gm

68.90 gm $-50^{\#}+100^{\#}$
21.60 gm $-100^{\#}+200^{\#}$

$h_o = 24.0$ cm $t_{h_o} = 0$
$\sqrt{h_o h_1} = 19.6$ cm $t_{h_o - \sqrt{h_o h_1}} = 9$ min. 25 sec.
$h_1 = 16.0$ cm $t_{\sqrt{h_o h_1} - h_1} = 9$ min. 35 sec

SAMPLE NO: 9

25% $-100^{\#} + 200^{\#}$
75% $-200^{\#}$ by weight

$W_s = \frac{63.5}{393} 546.90$ $W_s = 87$ gm

22.1 gm. $-100^{\#}+200^{\#}$
64.9 gm. $-200^{\#}$

$h_o = 28.0$ cm $t_{h_o} = 0$
$\sqrt{h_o h_1} = 23.7$ cm $t_{h_o - \sqrt{h_o h_1}} = 2$ hours 24 min.
$h_1 = 20.0$ cm $t_{\sqrt{h_o h_1} - h_1} = 2$ hours 20 min.

SAMPLE NO: 10

25% $-200^{\#}$
75% $-100^{\#} +200^{\#}$ by weight

$W_s = \frac{63.5}{393} 540$ $W_s = 87.20$

21.80 gm $-200^{\#}$
65.40 gm $-100^{\#}+200^{\#}$

$h_o = 40.0$ cm $t_{h_o} = 0$
$\sqrt{h_o h_1} = 34.6$ cm $t_{h_o - \sqrt{h_o h_1}} = 12$ min 40 sec
$h_1 = 30$ cm $t_{\sqrt{h_o h_1} - h_1} = 13$ min 17 sec

SAMPLE NO: 11 — 25% $-50^{\#}+100^{\#}$; 75% $-200^{\#}$ by weight

$$W_s = \frac{63.5}{393}\,520 \qquad W_s = 84\ gm$$

21 gm $-50^{\#}+100^{\#}$
63 gm $-200^{\#}$

$h_o = 20.0$ cm — $t_{h_o} = 0$

$\sqrt{h_o h_1} = 17.1$ cm — $t_{h_o-\sqrt{h_o h_1}} = 22$ min

$h_1 = 15.0$ cm — $t'_{\sqrt{h_o h_1}-h_1} = 22$ min

SAMPLE NO: 12 — 75% $-50^{\#}+100^{\#}$; 25% $-200^{\#}$ by weight

$$W_s = \frac{63.5}{393}\,597 \qquad W_s = 96.5\ gm$$

24.1 gm $-200^{\#}$
72.4 gm $-50^{\#}+100^{\#}$

$h_o = 40.0$ cm — $t'_{h_o} = 0$

$\sqrt{h_o h_1} = 34.6$ cm — $t_{h_o-\sqrt{h_o h_1}} = 17$ min

$h_1 = 30.0$ cm — $t_{\sqrt{h_o h_1}-h_1} = 21$ min

$h_o' = 30.0$ cm — $t_{h_o'} = 0$

$\sqrt{h_o' h_1'} = 24.4$ cm — $t_{h_o'-\sqrt{h_o' h_1'}} = 12$ min 30 sec.

$h_1' = 20.0$ cm — $t_{\sqrt{h_o' h_1'}} - t_{h_1'} = 12$ min 30 sec

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For falling head permeability test

$$k = 2.3\,\frac{a\,L}{A\,(t_o - t_1)}\,\mathrm{Log}\,\frac{h_o}{h_1}$$

where
- a = cross-sectionally internal area of stand pipe, cm^2
- A = cross-sectional area of permeability tube, cm^2
- L = length of drainage through the soil, cm
- $t_o - t_1$ = time interval between h_o to h_1, sec

$$\frac{2.3\,a\,L}{A} = \frac{(2.3)\,(\pi)\,(0.68^2)\,(7.34)}{(4)\,(\pi)\,(3.32^2)} \times 4$$

$$= 0.710\ cm$$

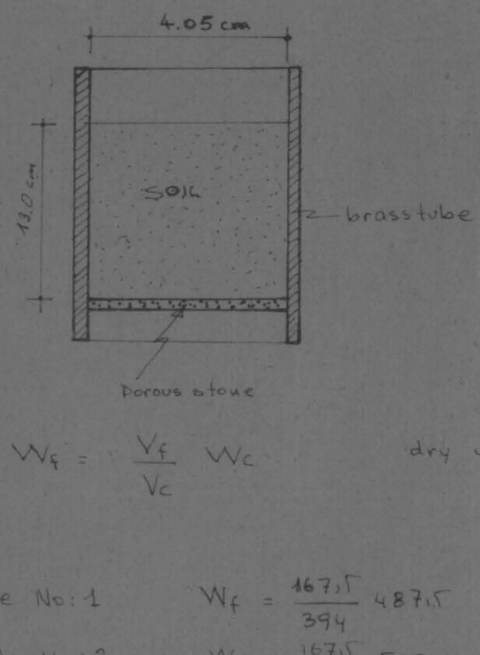
$$\therefore\quad k = 0.710\,\frac{1}{(t_o - t_1)}\,\mathrm{Log}\,\frac{h_o}{h_1}$$

at $T = 14°C$ in (1, 6)
at $T = 22°C$ in (2, 3, 4, 5, 7, 8, 9, 10, 11, 12)

Sample No	$t_1 - t_0$ (sec)	h_0 (cm)	h_1 (cm)	$\log h_0/h_1$	$\frac{1}{t_1-t_0} \log \frac{h_0}{h_1}$	k_T: $0.710 \frac{1}{t_0-t_1} \log \frac{h_0}{h_1}$	e	$k_{20°C}$
1	45	40	20	0.301	6.69×10^{-3}	4.74×10^{-3}	1.158	5.52×10^{-3}
2	141	30.0	20.0	0.176	1.25×10^{-3}	8.85×10^{-4} cm/sec	0.935	8.43×10^{-4}
3	4440	23.5	18.5	0.104	2.34×10^{-5}	1.67×10^{-5}	1.125	1.59×10^{-4}
4	61	35.0	20.0	0.243	3.99×10^{-3}	2.83×10^{-3}	1.021	2.69×10^{-3}
5	5200	36.5	29.0	0.100	1.92×10^{-5}	1.365×10^{-5}	0.872	1.30×10^{-5}
6	50400	43.0	16.5	0.421	8.35×10^{-6}	5.94×10^{-6}	0.710	6.91×10^{-6}
7	820	35.0	20.0	0.243	3.03×10^{-4}	2.15×10^{-4}	0.930	2.05×10^{-4}
8	1140	24.0	16.0	0.176	1.542×10^{-4}	1.095×10^{-4}	0.839	1.05×10^{-4}
9	17040	28.0	20.0	0.146	8.57×10^{-6}	6.08×10^{-6}	0.889	5.80×10^{-6}
10	1557	40.0	30.0	0.124	7.97×10^{-5}	5.66×10^{-5}	0.920	5.39×10^{-5}
11	2640	20.0	15.0	0.125	4.73×10^{-5}	3.31×10^{-5}	0.980	3.15×10^{-5}
12	2280	40.0	30.0	0.124	5.44×10^{-5}	3.86×10^{-5}	0.752	3.68×10^{-5}
(12)	1500	30.0	20.0	0.176	11.72×10^{-5}	8.34×10^{-5}	0.752	7.95×10^{-5} cm/sec

The points of e vs log k is given on the next page.

FREEZING TEST CALCULATIONS



$$V_s = \frac{\pi D_{int}^2}{4} h_s$$

$h_s = 13.0$ cm

$D_{int} = 4.05$ cm

$$V_s = \frac{3.14 \times \overline{4.05}^2}{4} 13$$

$$V_s = 167.5 \text{ cm}^3$$

$$\frac{W_c}{V_c} = \frac{W_f}{V_f}$$

$$W_f = \frac{V_f}{V_c} W_c$$

dry weight of soil to be put into freezing tube

		Soil weights	Moisture contents
Sample No: 1	$W_f = \frac{167.5}{394} 487.5$	$W_f = 207.0$ gm	$w = 21.35\%$
Sample No: 2	$W_f = \frac{167.5}{394} 503$	$W_f = 214.0$ gm	$w = 31.6\%$
Sample No: 3	$W_f = \frac{167.5}{394} 473.50$	$W_f = 201.0$ gm	$w = 35.4\%$
Sample No: 4	$W_f = \frac{167.5}{394} 570.0$	$W_f = 221.0$ gm	$w = 30.8\%$
Sample No: 5	$W_f = \frac{167.5}{394} 560.0$	$W_f = 239.0$ gm	$w = 26.9\%$
Sample No: 6	$W_f = \frac{167.5}{}$	$W_f = 254.0$ gm	$w = 21.0\%$


e. void ratio
1.300
1.200
1.100
1.000
0.900
0.800
0.700
10⁻⁶ 2 3 4 5 6 7 8 9 10⁻⁵ 2 3 4 5 9 10⁻⁴ 2 3 4 5 6 7 8 9 10⁻³ 2 3 4 5 6 7 8 9 10⁻²
K (cm/sec) at 20°C

MOISTURE CONTENT DETERMINATION

a) After freezing the samples

SAMP.No	(1) Tare wt (gm)	(2) (tare+wetsoil)wt	(3) (tare+drysoil)wt	(4) (2-3)(Ww)	(5) 4/(3-1) = w% (W_s)
11	13.50	27.35	24.01	3.34	31.70 %
12	10.75	36.06	30.16	5.90	30.30
13	10.62	27.98	23.98	4.00	29.90
14	14.32	39.62	33.56	6.06	31.50
21	13.40	22.91	21.02	1.89	24.80
22	16.16	32.08	28.65	3.43	27.45
23	14.36	27.32	24.05	3.27	33.60
24	14.36	31.00	26.76	4.24	34.20
31	13.64	27.44	24.00	3.44	33.25
32	13.64	36.12	30.18	5.94	35.90
33	13.83	28.00	24.15	3.85	37.30
34	13.83	32.03	27.05	4.98	37.70
41	14.32	23.52	21.50	2.02	27.20
42	13.09	30.61	26.60	4.01	29.65
43	13.74	30.40	26.73	3.67	28.25
44	13.76	46.64	39.27	7.37	29.60
51	14.35	28.23	25.05	3.18	29.70
52	13.16	41.41	35.50	5.91	26.50
53	13.17	30.73	27.15	3.58	25.60
54	13.44	48.58	41.40	7.18	25.60
61	13.59	24.15	22.35	1.80	20.55
62	13.80	41.37	36.35	5.02	22.55
63	13.81	27.58	24.90	2.68	24.20
64	14.34	36.50	32.17	4.33	24.30

b) Moisture contents, after free rise **and** comparison of the results with the initial moisture content and moisture content after freezing.

SAMPLE NO:	(1) Tare wt	(2) Tare+wet soil	(3) Tare+ dry soil	(4) $(3-1)=W_s$	(5) $(2-3)=W_w$	(6) $\frac{5}{4}=w_c\%$	(7) w_f %	(8) w_i %	(9) e	(10) K cm/sec
11	13.50	27.82	25.57	12.07	2.75	22.8	31.70	21.35	1.158	5.52×10^{-3}
12	10.75	32.76	29.30	18.55	3.46	18.6	30.30	21.35	1.158	5.52×10^{-3}
13	10.62	25.76	23.06	12.44	2.70	21.7	29.90	21.35	1.158	5.52×10^{-3}
14	14.32	31.80	28.67	14.35	3.13	21.8	31.50	21.35	1.158	5.52×10^{-3}
21	13.40	26.89	23.72	10.32	3.17	27.6	24.80	31.60	1.075	8.43×10^{-4}
22	16.16	38.97	33.73	17.57	5.26	29.9	27.45	31.60	1.075	8.43×10^{-4}
23	14.36	23.49	21.31	6.95	2.16	31.1	33.60	31.60	1.075	8.43×10^{-4}
24	14.36	34.28	29.39	15.03	4.89	32.5	34.20	31.60	1.075	8.43×10^{-4}
31	13.64	28.98	25.09	11.45	3.89	33.9	33.25	35.40	1.125	1.59×10^{-4}
32	13.64	35.01	29.50	15.86	5.51	34.7	35.90	35.40	1.125	1.59×10^{-4}
33	13.83	32.69	27.60	13.77	5.09	36.9	37.30	35.40	1.125	1.59×10^{-4}
34	13.83	35.70	29.79	15.96	5.91	37.0	37.70	35.40	1.125	1.59×10^{-4}
41	14.32	26.90	24.11	9.79	2.79	28.5	27.20	30.80	1.021	2.69×10^{-3}
42	13.09	33.10	28.58	15.49	4.52	29.2	29.65	30.80	1.021	2.69×10^{-3}
43	13.74	27.62	24.55	10.81	3.07	28.3	28.25	30.80	1.021	2.69×10^{-3}
44	13.76	34.35	29.72	15.96	4.63	29.0	29.60	30.80	1.021	2.69×10^{-3}
51	14.35	37.19	32.47	18.12	4.72	26.0	29.70	26.90	0.872	1.30×10^{-5}
52	13.16	39.90	34.26	21.10	5.64	26.70	26.50	26.90	0.872	1.30×10^{-5}
53	13.17	32.65	28.45	15.28	4.20	27.50	25.60	26.90	0.872	1.30×10^{-5}
54	13.44	32.40	28.30	14.86	4.10	27.60	25.60	26.90	0.872	1.30×10^{-5}
61	13.59	29.14	26.49	15.90	2.65	16.65	20.55	21.00	0.710	6.91×10^{-6}
62	13.80	38.42	34.14	20.34	4.28	21.00	22.55	21.00	0.710	6.91×10^{-6}
63	13.81	30.40	27.49	13.68	2.91	21.25	24.20	21.00	0.710	6.91×10^{-6}
64	14.34	38.90	34.57	20.23	4.33	21.40	24.30	21.00	0.710	6.91×10^{-6}

c) Second set of freezing tests:

Complete saturation is provided . H = 12 cm

Data before freezing

	G	V_t	W_s	$\frac{G V_t}{W_s}$	$e = \frac{G V_t}{W_s} - 1$	$\frac{G}{e}$	$\frac{W_w}{W_s} = G/e$	$\frac{W_w}{W_s} = w$ %	h from top of tube
1	2.68	154.5	207	2.06	1,000	2.68	77.2	37.3	3.60 cm
2	2.48	154.5	214	1,790	0,790	3.14	68.2	31.9	2.58
3	2.58	154.5	201	1,982	0,982	2.63	76.5	38.1	1,38
4	2.67	154.5	221	1,869	0,869	3.07	71.9	32.5	2.27
5	2.68	154.5	239	1,730	0,730	3.57	69.2	28.9	1,87
6	2.63	154.5	254	1,700	0,700	3.75	67.7	26.7	2,55

After freezing

	Tare wt	Tare + wet soil	tare + dry soil	W_w	W_s	$\frac{W_w}{W_s}$		h from top of tube
11	14.25	53.31	44.86	8.45	30.21	27.9	1	3.32 cm
12	13.77	58.80	48.85	9.95	35.08	28.4		3.30 cm
21	12.86	52.04	44.07	7.97	31.21	25.6	2	2.78 cm
22	13.64	61.44	51.10	10.34	37.46	27.6		2.70 cm
31	13.67	36.87	26.86	10.01	12.19	82.3	3	1.00 cm
32	14.32	58.78	43.86	14.92	29.54	52.0		0,82 cm
41	14.32	67.50	55.65	11.85	41.33	28.8	4	1.83 cm
42	13.42	56.17	46.82	9.35	33.40	28.0		1.83 cm
51	14.32	96.33	73.35	22.98	59.03	38.8	5	1.65 cm
52	13.08	67.29	54.48	12.81	41.40	31.0		1.60 cm
61	14.37	68.80	56.92	11.88	42.55	28.0	6	2.10 cm
62	13.44	81.05	67.34	13.61	53.90	25.2		2.10 cm