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FACTORS EFFECTING PERMEABILITY

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INFLUENCE OF LIME ADDITIVE

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BY

SUHA ULUÇAY

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A B S T R A C T

Permeability is an important property of soils. Testing of compacted impervious clays requires better testing techniques than those used in conventional permeameters. GEONOR permeameter solves many problems associated with permeability testing. Saturation of samples is achieved by exerting high pore pressures while the effective pressure may be kept constant. Due to the effects explained by Boyle's law and Henry's Law, the entrapped air in the voids will be dissolved.

Affects of different variables on permeability are analyzed through a set of experiments. The results obtained are quite reliable. The most effective factor came out to be the soil type, followed by water content.

A second set of experiments, in which the two important factors of the first experiment and lime content are run, and the results obtained show that lime content is a significant factor on permeability.

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INTRODUCTION

Permeability of soils depends upon various factors. Some of these factors are seen to be more pronounced in some soils and less in others. The physical properties, mineralogy and other characteristics of soils play important roles on the extent of the influence of these factors on permeability.

In the hydrolic works of our times, the importance of earth dams is increasing rapidly. This fact necessitates a more careful study of soil properties and better techniques of soil testing. It is very evident that permeability is one of the most important properties of soils which are to be used for constructing earth dams.

The problem of testing the permeability of impervious compacted clays has been a relatively difficult task, since the use of conventional permeability apparatus for highly impervious soils has many limitations. For example, constant head apparatus uses the principle of collecting the water which passes through the sample, this is not very practical for compacted clay since the quantity of water permeating through such a sample will be very small and a considerable portion of it may evaporate.

Besides these instrumental difficulties, there are other difficulties involved with imitating the natural conditions.

The GEONOR permeameter overcomes these difficulties and provides accurate measurability of the permeability values. There are three important advantages of the GEONOR

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perme ameter:

- 1- Almost 100 % saturation of the sample
- 2- Full drainage control facilities
- 3- Ability to apply any desired effective stresses on the sample

Thus it is very easy to create any set of conditions on the sample.

Another interesting point to be analyzed would be the effect of a stabilizer on the values of permeability. Lime is a stabilizer being used recently to increase the binding of particles of soil in subgrade and surface of roads. However today, there is scant information on the effect of lime on the permeability of soils.

To get effective results for the factors influencing permeability and the extent to which permeability is effected by the addition of lime, a statistical analysis method, namely Variance analysis may be used. This method enables the evaluation of the effect of this variables with a relatively few number of experiments.

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THEORY OF PERMEABILITY

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A- Flow of water through soil

It is a known fact that the properties of soils depend to a large degree on the amounts of pore water they contain. The facility with which water is able to travel through the pores also has much significance in many types of engineering problem. This property, called the permeability, is one of the most important of soil properties.

The rate of settlement of a layer of saturated compressible soil subjected to load is dependent upon the permeability. The sustained rate of flow from wells is dependent upon the permeability of the aquifer. The permeability of the soil will determine the spacing of wells and amount of water to be pumped in lowering ground water to facilitate excavation for construction purposes. It also will affect the amount of loss from reservoirs, through, under and around dams. Permeability is a factor in the need for and design of filters to prevent piping or uplift, and to control the hydrolic stability of slopes of earth materials.

In hydraulics it is shown that flowing water may assume either of two characteristic states of motion. In "laminar flow" each particle travels along a definite path which never intersects the path of any other particle. In "turbulent flow" the paths are irregular and twisting, crossing and recrossing at random. The fundamental laws that determine the state existing for any given case were determined by Reynolds. He

states that if $\frac{v_c D \gamma_w}{\eta g}$ is below 2000 the flow is laminar.

Thus for tubes of very small diameters, the critical velocity is relatively high and therefore the flow is usually laminar. We may safely say that the flow in soils is therefore laminar, unless the soil particles are very coarse.

The pore channels of a soil mass are so narrow and tortuous, so irregular in cross section, and so complex in their interconnection and subdivision that an analysis of the flow through individual pores is not possible. However, in engineering problems involving seepage through soils, it is not the flow through individual pores that is of interest. Instead, the flow desired is the combined flow through all pores of an element of volume which is sufficiently large to give a typical representation of the soil mass as a whole. These macroscopic or statistical average properties are of interest in connection with permeability investigations.

The law for flow through soils is named after Darcy, who after a great deal of experimentation demonstrated that the rate of flow is proportional to the gradient. Darcy's Law is written

$$Q = k i A$$

or

$$\frac{Q}{A} = v = k i$$

The area A in the above eqn is the total cross-sectional area of the soil mass, across which the discharge Q occurs. In any cross section through a soil sample this total area A will consist of area within solids A_s and void area A_v . It is worth noting that the void ratio also may be expressed as the area ratio A_v/A_s . Since the velocity v in

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the equation given above is equal Q divided by the "total" area-not the void area through which the liquid is actually flowing- it should be noted that v must be a superficial velocity, Careful distinction between the superficial velocity v and the seepage velocity v_s is important. The discharge may be written

$$Q = A v = A_v v_s$$

and since $A_v = n A$ it follows that $v = n v_s$.

The term k is Darcy's coefficient of permeability, and is bet defined as the constant of proportionality between the superficial velocity v and the gradient i . Darcy's eqn shows that k has the dimensional units of a velocity, and it may be called the superficial velocity per unit of gradien

B- Measuring Permeability

1- Conventional Methods :

The various types of apparatus which are used in soil laboratories for determining coefficients of permeability of soils are called permeameters. They are of two basic design the constant head type and the variable head type. In an apparatus in which the head remains constant, the quantity of water flowing through a soil sample of known area and length in a given time can be measured. Head water and tail water levels can be kept constant by overflows. The head loss is the difference between the elevations of head and

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tail water surfaces. The area and length of the sample, A and L , are measured. The tail water is caught in a graduate, and the rate of discharge, Q , is measured. From Darcy's Law,

$$k = \frac{Q L}{h A}$$

In highly impervious soils the quantity Q is small, and accurate measurements of its value are not easily obtained. Therefore the constant head permeameter is principally applicable to relatively pervious soils. Instruments operating under variable head furnish more accurate determinations of the permeability of impervious soils. The essential characteristic of the method is that the quantity of percolating water is measured indirectly by observations on the rate of the water level in the standpipe above the specimen. The length L and area A of the sample, and the area a of the standpipe, must be known. Darcy's law for this case can be written

$$-a \frac{d h}{d t} = k \frac{h}{L} A$$

or

$$-a \int_{h_0}^{h_1} \frac{d h}{h} = k \frac{A}{L} \int_{t_0}^{t_1} dt$$

whence

$$k = \frac{a L}{A t_1} \ln \frac{h_0}{h_1}$$

where h_0 is hight of water at time zero and h_1 at time t_1 . All the quantities on the right having been measured, k is readily found.

2- GEONOR permeameter for compacted clays :

Experimental determination of the permeability of compacted soils is in general complicated by the fact that the samples are not initially fully saturated and it is a difficult and time-wasting process to saturate the samples. The errors implied in conventional permeability tests on not fully saturated samples are, in the first place, due to incorrect measurements of the flow or water resulting from the change in volume of the entrapped air. In the second place the gas bubbles will have a tendency to accumulate in that end of the sample where water emerges, causing a clogging resulting in erroneous permeability measurement.

Solution to a similar problem caused by entrapped air in measurement of pore pressures in samples subjected to undrained triaxial shear tests, lead the manufacturers to use the same method in saturating the samples before measuring their permeability. To solve the above problem, back pressure was applied resulting in a compression of the gas bubbles and a saturation of the sample. A similar technique is applied to the permeability tests. The saturation of the sample is being achieved by increasing the pressure in the pore fluid. Two laws of physical chemistry demand that air bubbles reduce in volume and weight of dissolved air in water increase. First of these laws is Boyle's law and is written,

$$V = \frac{k}{p}$$

where V = volume
p = pressure
k = constant

Boyle states that at constant temperature, the volume of a gas decreases when pressure is applied and that it is inversel

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proportional to the applied pressure. If the gas is an ideal gas, at 0°C, 28 liters of gas at 1 atmosphere becomes 3 liters at 8 atmospheres (9). The above equation is that of a hyperbola and naturally the plot of V versus p (at constant temperature) does not give a zero volume. That is to obtain zero volume one has to apply infinite pressure. This means that increase of pressure has limited help from decreasing of volume point of view. However, there is also the second effect; Henry's Law. Henry's Law involves with the solution of gasses in liquids. It states that the partial pressure of the solute is proportional to its mole fraction in the solution; thus is written

$$P_{\text{solute}} = K N_{\text{solute}}$$

In an ideal solution Henry's law is an exact law, and moreover the proportionality constant K becomes identical with the vapor pressure of the pure solute. Values of K for two largest components of air, namely Nitrogen and Oxygen are 6.51×10^7 and 3.30×10^7 respectively for 25°C and water being the solvent. The unit of K is millimeters of pressure of the gas divided by the mole fraction of gas in solution (9).

As we can see from the information given above, saturation of the samples with the explained method can be realized. To each degree of saturation, there corresponds a certain additional pressure which will cause a saturation if applied to the pore fluid of the sample. If the pore pressure is increased in steps (e.g. 1, 2, 3, 4... kilograms per cm^2) and for each step the permeability determined, we will find that after a certain point the value of permeability will show no change how ever high the pore pressure is made. The

entrapped air is then, compressed and dissolved and the measured permeability is a true value corresponding to full saturation under the applied effective stresses.

L. Bjerrum in his paper (12) gives the results of an investigation of the permeability of a sandy clay which was to be used for the core of an earth dam at Innset, Norway. The samples for the permeability tests were compacted in a special mould using the same compactive effort per unit volume as in the Proctor test. Fig.1 shows their observed permeabilities of a sample compacted at a moisture content 3 percent wet of optimum and consolidated under the pressure 1.0 kg/cm^2 . The initial degree of saturation was 59 percent. The pore pressure was increased step wise to the values 2, 4, 6, 8 and 10 kg/cm^2 , and for each value the permeability was measured by tests of the constant head type. The apparatus was the former model of the same instrument manufactured at the same institution. As seen from the plot, the permeability increases with the pore pressure from 2.5×10^{-6} at zero pore pressure to $15 \times 10^{-6} \text{ cm. per sec.}$ which is reached at the pore pressure of 8 kg/cm^2 .

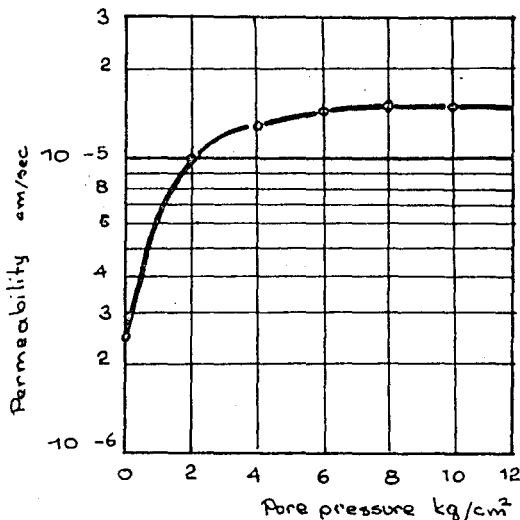


Fig. 1 : Results of permeability measurements plotted against the pore pressure

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The GEONOR permeameter is capable of measuring permeability in both methods, either by constant head or by falling head. A constant head permeability may be determined by pulling the mercury column over to one side and up to the top of the scale. This will create an over pressure in the system; in other words, hydrolic gradient through the sample. If the column of mercury is kept on one side of the U-tube, the hydrolic gradient will be constant. Although the mercury column will displace with respect to the plastic tube, this does not mean that the head is falling, since the head created is due to the difference in densities of equal lengths of mercury and water columns at each side of the U-tube. This difference remains constant as long as the string of mercury does not turn to the other arm of the U-tube. The formula to determine the value of permeability for constant head may be derived from Darcy's law;

$$V = k i$$

or $Q = A k i$

$$k = \frac{Q}{A i}$$

$$Q = \frac{a L}{t} \quad \text{where } a = \text{area of pla}$$

where a = area of plastic tube in cm^2
 L = movement of mercury column in cm
 t = time elapsed in seconds

then $k = \frac{a L}{t} \frac{1}{A i}$

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here i is the hydrolic gradient. According to the explanation given above

$$i = \frac{H}{h} \frac{\gamma_{Hg} - \gamma_w}{\gamma_w}$$

where H = length of the mercury column in cm.
 γ_w = the density of water in gm./cm³
 γ_{Hg} = the density of mercury in gm./cm³
 h = length of the sample in cm.

thus we obtain

$$k = \frac{a L}{t} \frac{h}{H} \frac{1}{A} \frac{\gamma_w}{\gamma_{Hg} - \gamma_w}$$

and the unit of k is cm/sec.

Similarly the relation for a falling head may be written as

$$k = \frac{a h}{2 A t} \frac{\gamma_w}{\gamma_{Hg} - \gamma_w} \log_e \frac{H_o}{H_t}$$

where H_o = is the difference in height between two ends of the mercury column forming a U-shape

H_t = the difference at time t

C- Factors Affecting Permeability

Taylor gives a theoretical equation for the flow of water through soils (1) :

$$Q = \left(D_s^2 \frac{\gamma_w}{\mu} \frac{e^3}{1 + e} C \right) i A$$

where D_s = diameter of the spherical grain which has the same ratio of volume to surface area as holds collectively for all grains of a given soil

γ_w = unit weight of water

μ = coefficient of viscosity

e = void ratio

C = constant including shape factor also

i = hydrolic gradient

A = area

Comparison of the above equation with Darcy's Law gives:

$$k = D_s^2 \frac{\gamma_w}{\mu} \frac{e^3}{1 + e} C$$

From the terms on the right-hand side of this equation, the following outline of the factors which affect permeability may be prepared. The first four factors are indicated by the four terms of the equation in the order given. The final factor is known from earlier explanations.

1- The permeability of a given soil depends on the second power of a dimension representative of the average grain size ; this is represented by the term D_s^2 , designating the square of the diameter of the sphere of equivalent volume-area ratio, which is a constant for any given soil.

2- It depends on properties of the pore fluid, as shown by the term γ_w/μ .

3- It depends on the void ratio. The factor C may also depend somewhat on void ratio, and thus may have to be included in void ratio considerations ; therefore $C e^3 / (1 + e)$ represents the void ratio effect.

4- It depends on shapes and arrangement of pores, on

the soil structure, as represented by the composite shape factor C.

5- It depends on the amount of undissolved gas within the pore water.

Bjerrum in his paper (12) gives test results which show that water content is a factor affecting permeability of compacted clays. For a typical case, for samples compacted with a water content 4 to 5 percent below optimum, up to 10 times higher permeabilities are measured in the saturated samples.

D- Notes on Lime Stabilization

Lime has been used with varying degrees of success for stabilization of soils. Generally the use of lime is restricted to warm or moderate climates, since lime-stabilized soils are susceptible to breakup under freezing and thawing. According to two sources (7 , 3), the addition of lime generally brings about a decrease in soil density, change the plasticity properties of soil, and increase soil strength. The action of lime in soil is explained by three basic reactions. The first of these reactions is alteration of the water film surrounding the clay minerals.

A second process by which lime will change a soil is that of coagulation, or flocculation, of the soil particles. The amount of lime ordinarily used in construction (5 to 10 per cent by weight) results in a concentration of calcium ion greater than that actually needed (3).

The third process through which lime affects soils is reaction of the lime with soil components to form new

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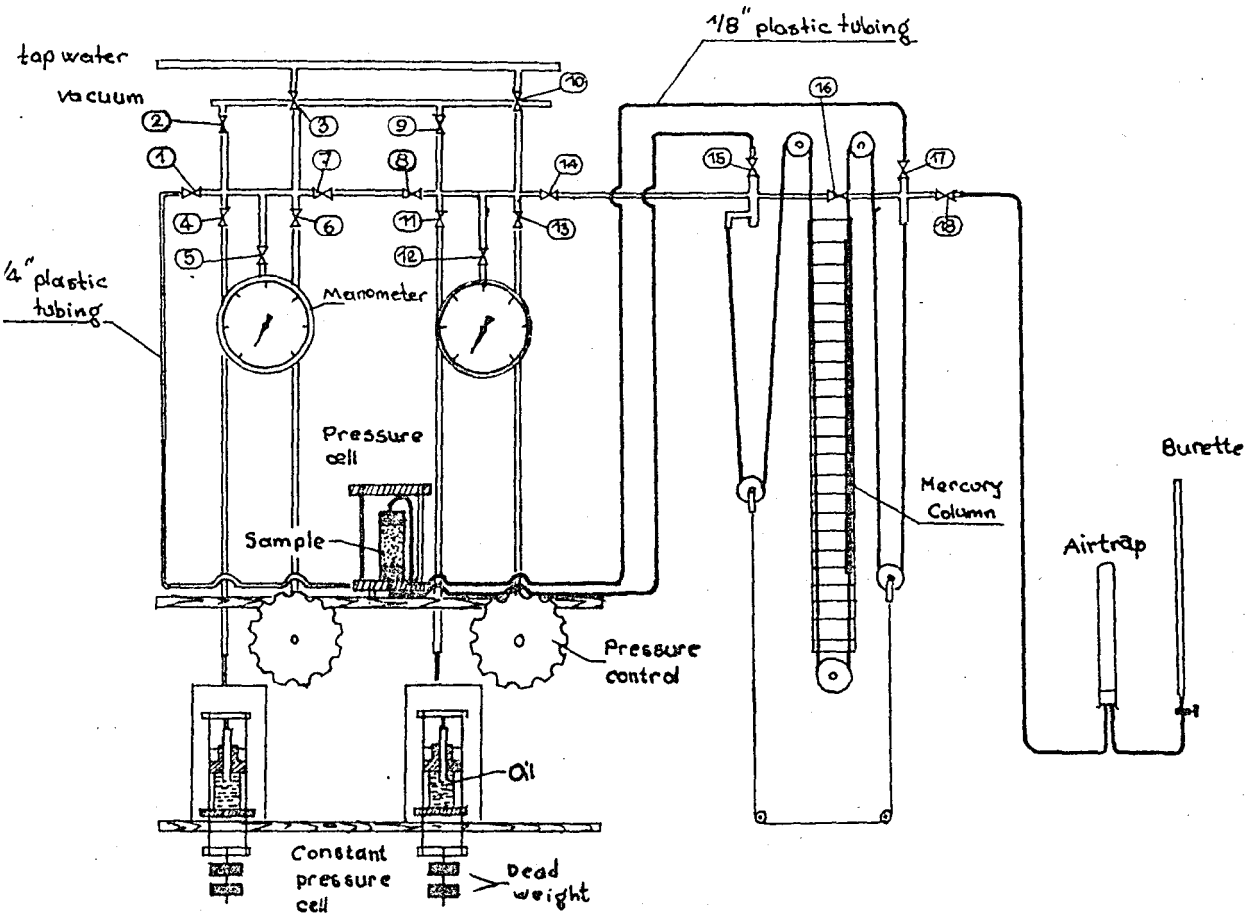
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chemicals. The two principal components of soil which react with lime are alumina and silica. This reaction is a long term reaction and one that results in greater strengths if lime soil mixtures are cured for a period of time. This is also known as pozzolanic action.

Experiments of Whitehurst and Yoder (3) show that the degree to which lime will react with soil depends on such variables as quantity of lime, soil type, and the length of time the lime-soil mixture is cured.

One of the most important functions of lime is that it changes the soil's plasticity appreciably. For Soils which have low plasticity, lime increases both the liquid-and plastic limit values and also the plasticity index. For high plasticity soils, however, the lime generally decreases the liquid limit and increases the plastic limit, which changes in turn bring about a decrease in plasticity index. Admixtures of lime therefore, make a soil more friable and granular (3).

As a result of the above discussion we may conzi clude that addition of lime to soils will probably increase the permeability,



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MATERIALS AND APPARATUS

A- Soils To Be Investigated :

1- Description of the soils and their origin :

Three fine grain soils from different places of the Bosphorus region are used in the experiments. They were recieved from Soil Mechanics Laboratory of Istanbul Technical University where extensive research and experimentation has been going on these soils. They are named after their origins as "Topser - Sarı, Kilyos - Esmer, Paşabahçe - Kırmızı". Identification of these soils were thoroughly made by the above mentioned laboratory (5) and their physico-Chemical properties were determined (6). Stabilization of these Bosphorus clays with lime is one of the researches that needs to be mentioned (7). Dr. Remzi Ülker of Technical University in his doctoral thesis (5), describes these clays as :

"Topser - Sarı"clay: Has yellow color. It is found in thick layers, generally under red clays. It has been noted that this clay has undergone deformations while it had a high consistancy. It contains quartz sandstone blocks upto diameters of 10-15 cm. The fissures of the layers are filled with bands of a red, lower plasticity clay.

It is usually seen above the level of +20.00 and disappears above +60.00.

The clay has low plasticity and contains silt and fine sand of quartz. Also flattened pebbles are present in a scattered manner. It contains almost no organic matter.

"Kilyos - Esmer" clay : Has dark-brown color. They have been formed as a result of breaking and transportation of clayey schists. The thickness of the layers depend upon the topografy and erosion conditions. At some places maximum thickness goes upto 8.0 meters. It contains little amount of

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silt and organic matter. These clays have not undergone much changes besides erosion. They are mostly seen upto +25.00 meters elevation and they constitute the filling material of the valleys.

"Paşabahçe - Kırmızı" clay: Is found towards the inner parts of the Paşabahçe valley. The layers have a thickness of 8 to 10 meters.

The clay has high consistancy and the beds contain small pockets of quartz. The clay contains much aluminium and iron, thus the color is dark red.

2- Properties of the soils:

Dr. Remzi Ülker in his doctoral thesis at the Technical University gives the physical and chemical properties of these soils as :

Soil Property	Topser-Sarı	Paşabahçe-Kırmızı	Kilyos-Esmer
Type	Low-plasticity clay	Low-plasticity clay	High-plasticity clay
L.L.	34.5	37.9	84.2
P.L.	21.6	19.8	42.6
S.L.	17.9	13.0	17.0
Ip	12.9	18.1	41.6
n	1.74	2.13	1.70
s	2.77	2.72	2.81
e	0.77	0.50	1.41
n	0.435	0.334	0.585
sat.	1.93	2.14	1.74
PH	5.8	5.3	5.6

His granulemetric analysis results are given in the appandix.

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The mineralogy of these clays have been determined at the Technical University of Istanbul and also in U.S.A. at Harmondsworth Road Research laboratory. The results are given in a paper by Mehmet Tümay and Ergün Toğrol (6). In the paper they summarize the results of five different methods which are : liquid limit/plasticity index diagram method, by finding liquid limit using different pore fluids, by finding ion exchange capacity, by using electron microscope and finally by x-ray diffraction method. The conclusion that they make is that the predominant clay mineral in "Topser-Sarı" is montmorillonite, in "Paşabahçe-Kırmızı" is kaolinite and illite and in "Topser-Sarı" is kaolinite (plus some illite) .

B- Lime used as additive

Hydrated powdered calcitic lime was used through the second set of experiments. It was provided from the limewell of the college. The dirt on the surface of the pieces were cleaned and it was dried in the oven at about 130° C thus the composition of the compound was not altered. If drying is made at temperature as high as $800-1000^{\circ}$ C, then calcium hydroxide changes into calcium oxide. Really one does not call this process drying any more but ignition.

After 24 hours lime was taken from the oven and was cooled in the desiccator. It was crushed into powder form and mixed with the soil samples at specified quantities.

C- Apparatus :

1) Description of the apparatus

The apparatus is named as " m-45 Permeameter for Compacted Clays" by its manufacturer, Norwegien Geotechnical

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Institute; "GEONOR AS". The apparatus may be divided into three main groups (See Fig.) :

- 1- The cell pressure system,
- 2- The pore pressure system,
- 3- The measuring panel.

The cell pressure and the pore pressure systems are essentially identical. In addition to the valves and the pipe system, each system is equipped with a screw control, a constant pressure cell and a Bourdon gauge to measure the pressure. The measuring panel consists mainly of plastic tubing and five pulleys. This tubing is later on filled partly with mercury which produces the hydrolic gradient on the sample. The measuring of the rate of fall of mercury column is done against the metric scale on the panel.

The ends of this plastic tubing are connected to a simplified triaxial cell in which the sample is subjected to pressures and differential head.

At the righthand side of the measuring panel, there is a burette to measure volume changes (if consolidation is being made). Also an air trap is mounted before the burette.

2- Preparation of the apparatus for the test:

First the apparatus has to be deaired and then filled with water. This can be done very easily since the author has provided a tank for water reservoir for the apparatus. Before doing anything the pressure controls are screwed in completely. The reservoir has to be filled with distilled water which is previously boiled and then cooled. This tank is connected to the apparatus by a plastic tube at valve 10. This valve is opened together with valves 14,16 and 18. The water from the reservoir will come to valve 18,

from there into the burette. One has to wait until no air bubbles come out but water only. Then valve 16 is closed thus the 1/8 inch plastic tubing (mounted over the pulleys) is also filled with water. Then valve 18 is closed and valves 8, 7 and 1 are opened, valve 10 still being open. After air bubbles stop coming, valve 1 can be closed. Valve 6 is then opened and the left pressure control is screwed out. Valve 10 is closed and valve 1 is opened and the pressure control is screwed in. This last operation is repeated several times until nomore air bubbles are seen to come out of valve 1. The same process is applied for filling the right screw this time valve 14 is kept closed through out.

The Bourdon gauges are filled in a different manner and one by one. The left gauge is dismantled from its place and its inside is filled with water by the help of a thin plastic tube which is pushed into the hole. Then valves 10, 8, 7 and 5 are opened and the gauge is mounted while water is coming from valve 5. The second gauge is filled in the same manner.

The last part to be filled with water is the constant pressure system. But before this, the cells are filled with oil by the procedure which is explained further below. Assuming the cells to be filled with the oil, we fill the line connecting them to the system as follows: valve 4 is opened together with the valves 7, 8 and 10. The screw connecting the plastic tube to the cell is opened and water is let to flow out until air bubbles do not come any more. Then it is connected to the cell while water is still flowing out. Then the piston is pulled up slowly so that some water enters into the cell. Special care must be taken not to bring water in contact with the piston since the piston is not stainless will rust. The line to the second constant pressure cell is also filled the same way.

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The second job is to fill the mercury into the plastic tubing of the measuring panel. Some clean mercury is precisely weighed (approximately 27 to 30 grams). Some water is added onto it to prevent entry of air into the tube during suction. The right end of the plastic tubing is dismantled from the pin-type connection onto which it is attached. The end of the tube is dipped into the cup of mercury and water, and by using one of the pressure controls, some water is ejected out. Then the piston is screwed out slowly so that mercury is sucked into the tube uniformly. After all mercury is sucked in, some water is also sucked so that the mercury column is retained between water columns. One thing of prime importance here is that no air must be present in the tube before mounting the plastic tube before mounting it to its place. To realize this valves 13 and 14 are opened together with valve 16. when valve 10 is opened water starts flowing out from the open end of the pipe system (where the tubing is to be mounted). Also the right pressure control is screwed in so that water comes from the free end of the plastic tubing. The tube is mounted while water is flowing out from both ends; the pipe-end and the tube-end.

Filling of oil into the constant pressure cells is done in the procedure given below. The oil to be used must conform with the following specifications :

Specific gravity	0,9 gm/cm ³ max.
Viscosity:	
Redwood	1400 at 70° F
	170 at 140° F
	64 at 200° F

Saybolt Universal	
Sec SSU	570 at 100° F
	66 at 210° F
Engler	
	49 at 20° C
	85 at 50° C

Also the oil should have good demulsibility, oxidation stability and anti foam properties.

After searching in the market, the oil was provided from B.P. Company, whose classification number for the oil is HL-150.

To fill the oil into the cell, one has to pour the oil into the container which is at the top of the cell. Then by closing the lower outlet of the cell with the finger, opening the upper inlet and moving the piston up and down, the oil is sucked into the cell. All the air will be pushed out in this way. One must be very careful not to harm the pistons in any way, since they are extremely delicate.

3- Function of each part of the apparatus :

a- Pressure Control System-Is made of a stainless steel cylinder and a piston with a screw ram. There are two of them on the apparatus. The whole control of the pressure of the system is achieved by these pistons. The screws are lubricated with graphite, thus no additional lubrication is necessary. The apparatus had soft plastic tubing connecting these cylinders to the copper pipe system. The author replaced them with hard plastic tubing which do not deform as much as the former ones.

b- Measuring panel- In this part the plastic tubing is of prime importance. In it, we fill the mercury which produces the differential head. The mercury gets dirty if the tubing is not clean. Also it sticks on the walls of the plastic tubing. Therefore it is required that the tube be cleaned very well before the filling of mercury. The author has done the following related to this problem. The tube is dismantled at both ends. Tap water is passed through it for half an hour. Then a dilution of Lissapol-N, which is an extremely high wetting agent, is passed for at least ten times. This agent enables the water to wet the walls of the tubing completely so that perfect cleaning becomes possible. But it is required that the tubing is to be rinsed with water for at least 15 minutes. Afterwards alcohol is circulated through the tubing which is followed by another rinsing with water. The manufacturer advises to use an agent which they name as "Tetra". However it was not possible to find out what this agent was.

It is mentioned above that the mercury produces the differential head. This is possible since the specific gravity of mercury is very high with respect to water. Now if there is mercury on one arm of a U-tube and water on the other arm, surely there is a pressure difference between the two ends of the tube.

c- The pipe system - Consists of copper pipes and valves. The valves are of "Klinger" type which are excellent in leakproofing. If a valve is found to be leaking, one only has to tighten the bolt-head of the valve. The valves are lubricated with graphite thus other lubrication not required. The pipe system is made of copper pipes. To prevent corrosion of the pipes mercury should strictly be prevented from entry

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into the pipe system. One uses distilled water in the system to prevent scaling after long periods of use. Before using the apparatus, if it has not been used for quite a long time, thorough flushing of all the pipe system is compulsory. Otherwise the dirt which accumulates inside the pipes, pollutes the mercury very rapidly.

d- Bourdon gauges- There are two of these gauges, and they are coupled with the cell pressure and the pore pressure systems. They are quite sensitive and have divisions down to 100 gm/cm^2 . The most important fact concerning with these gauges is that they must be deaired completely. The method to be followed to achieve this was explained in section (b) of this part.

e- Constant pressure cells- The function of the constant pressure cells is to maintain any desired pressure at constant level. This is achieved by hanging weights on the yoke of the cell. When the pressure in the system drops due to any reason, the oil displaces the lost water, that is the piston moves down, thus the pressure is brought back to the same level. The piston has an area of exactly 2 cm^2 , so to provide a pressure of 4 kg/cm^2 , one has to hang 8 kg.s of dead weight on the yoke. An important point to note here is that the piston and the bushing must be exactly in the vertical position, otherwise friction forces interfere with the operation of the pistons. To use a spirit level and to adjust the bushing into vertical position by the three screws under the cell is recommended.

These cells are very sensitive and the pistons and the bushings are manufactured with extremely low tolerances. However, according to the manufacturer as it was impossible

to make these parts with the wanted surface hardness in stainless steel, they were made of a type of steel which may corrode and must thus be kept away from water. Here one problem arises which is that the manufacturer advises no water to be let into these cells. However it was found by the author that once oil gets into the plastic tubing which connect the cells to the system, then it starts creeping up towards the copper tubing and this results with the danger of oil mixing with the system water and even with the mercury. To prevent this, the author opened holes on the lower board plate of the apparatus and made both of the plastic tubings form a goose-neck at their middle lengths. The quantity of oil was so adjusted that even when the piston was at its lowest position, the oil stayed on the upper portion of the nearer end of the goose-neck, thus it did not climb upwards due to its lower specific gravity.

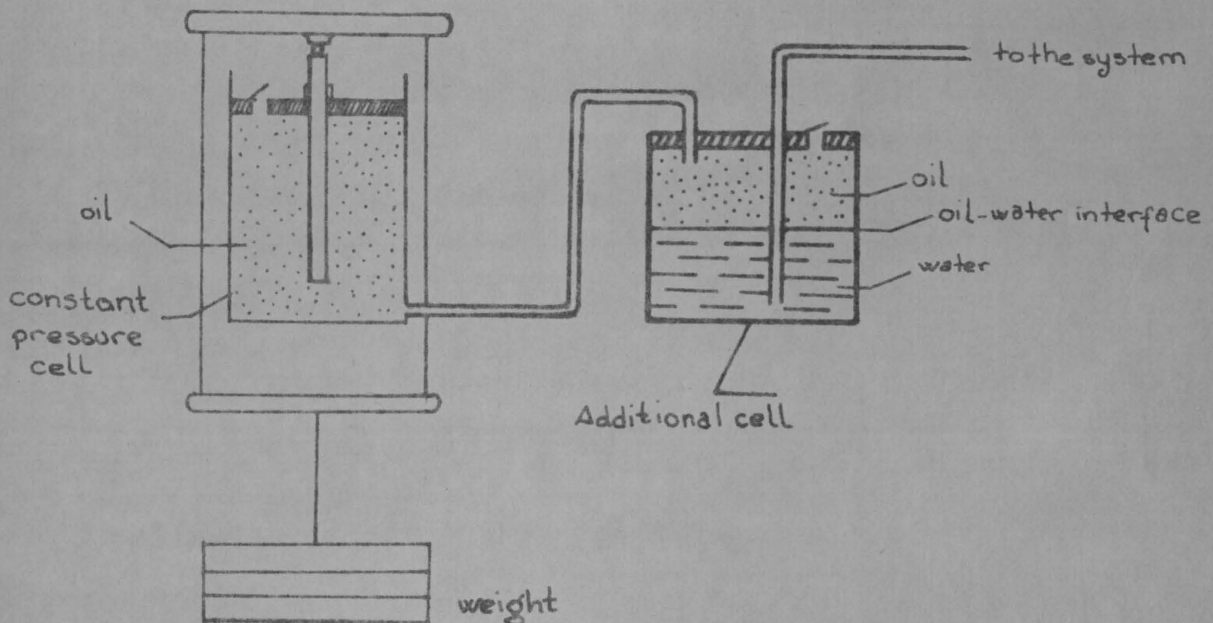


Fig. : Additional cell for constant pressure system

However, even this measure was found not to be enough to solve the above mentioned problem. The author planned for a small modification in the apparatus which he was unable to have constructed for his experimentation, but a sketch of it was found useful to be given here, in case any other person using the same apparatus faces the same problem. In the above modification, the new cell is used to provide possibility for oil and water to have a large area of interface and in such a way that the oil always constitutes the upper layer. If the crosssectional area of the cell is designed accordingly, the maximum displacement of the piston may be compensated by movement of the interface within few centimeters. Since the oil has good demulsibility, its emulsification in the water will not be possible.

f- The testing cell- Is made of stainless steel and consists of two parts. The upper part is a perpex cylinder with a steel cap plate. The plate has an air outlet valve on it. This cylinder is mounted on a base plate which has four outlets. One outlet is connected to valve 1 and provides for the connection to the cell pressure system. There are two outlets on the pedestal and these are the connection to the bottom of the sample. Upon correspondence with GEONOR it was told to the author that one of these outlets was extra and the two outlets could be connected by a T connection. However the author found use in having a valve mounted on one of these outlets for other purposes. The bottom plate has one more outlet which is the connection to the top of the sample. There is a short plastic tube from this outlet to the perpex cap on the sample. When a

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membrane is put around the sample, one is able to apply all-around pressure and pore pressure independent from each other which is the main function of the cell.

The cell should be cleaned by washing thoroughly after each test. Detergents or cleaning powder may be used but then the cell must be rinsed very well. Also the outlets should be flushed with water each time.

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EXPERIMENTAL PROCEDURE

A- Program of the Experimentation

It is decided that before analyzing the effects of lime on permeability, factors affecting the values of permeability should be determined. Therefore four factors are chosen and such that they are independent from each other. These factors are :

- 1- Compactive effort
- 2- Grain size distribution
- 3- Soil type
- 4- Water content

The experiments are to be run at three different levels of each variable, in such a combination that nine experiments shall be performed. The combinations of the levels of each variable are made according to a format ; "Greko-Latin Square", which is a matrix used to perform the Variance Analysis method of statistics.

The variance analysis will give the relative importance of each of the factors.

Then a second set of experiments must be performed, this time the variables being the lime-content and the important factors of the first analysis. A second variance analysis is made to find out if the lime-content has any significant effect on permeability or not.

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B- Compaction of samples

As it is determined to take compactive effort and water content as two of the variables in the first analysis, it is compulsory to make compaction experiments for each soil and at each level of compactive effort. For the permeability measurements, the compaction of the specimen is made in a special mould which has rather smaller dimensions than that of a standard Proctor mould. For the permeability measurements with the GEONOR Permeameter, Bjerrum (12) recommends that the compaction be completed in four layers, each layer having a thickness of 2.5cm. Actually the mould has a length of 10 cm. and a diameter of 5.05 cm. which means a cross-section of 20 cm^2 . The drop hammer weighs 1514 gm. and falls from a height of 21.2. cm. Since the energy for each compactive effort is known, it is easy to calculate the number of blows, of this special hammer, corresponding to those energies. This has been done (see Appendix for calculations) and the results are as follows:

Compactive Efford	Conditions	Energy	Equivalent Blows
Standard Proctor	5.5 lb, 3 layers, 25 blows	$6.050 \frac{\text{gm-cm}}{\text{cm}^3}$	10
Modified Proctor I	10 lb, 3 layers, 25 blows	$16.400 \frac{\text{gm-cm}}{\text{cm}^3}$	26
Modified Proctor II	10 lb, 3 layers, 55 blows	$36.200 \frac{\text{gm-cm}}{\text{cm}^3}$	57

The compaction experiments were performed and the curves obtained are given in the next pages. The values of maximum dry density and optimum water content are tabulated in the

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$$\Delta \rho_d \left(\frac{\text{gm}}{\text{cm}^3} \right)$$

1.95

1.90

1.85

1.80

1.75

1.70

~TOPSER~

1.65

MODIFIED PROCTOR I

w (%)



1.60

0.0

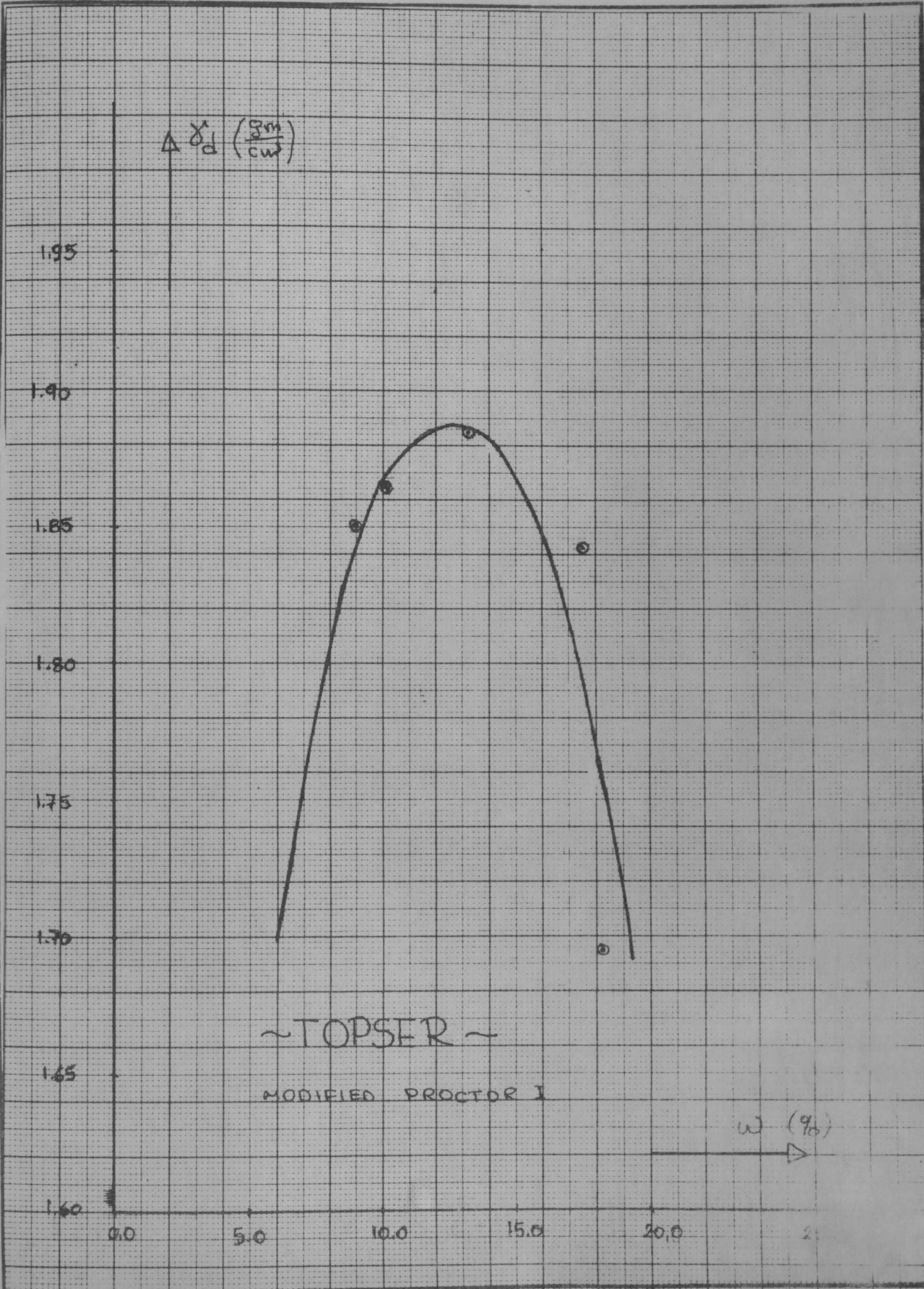
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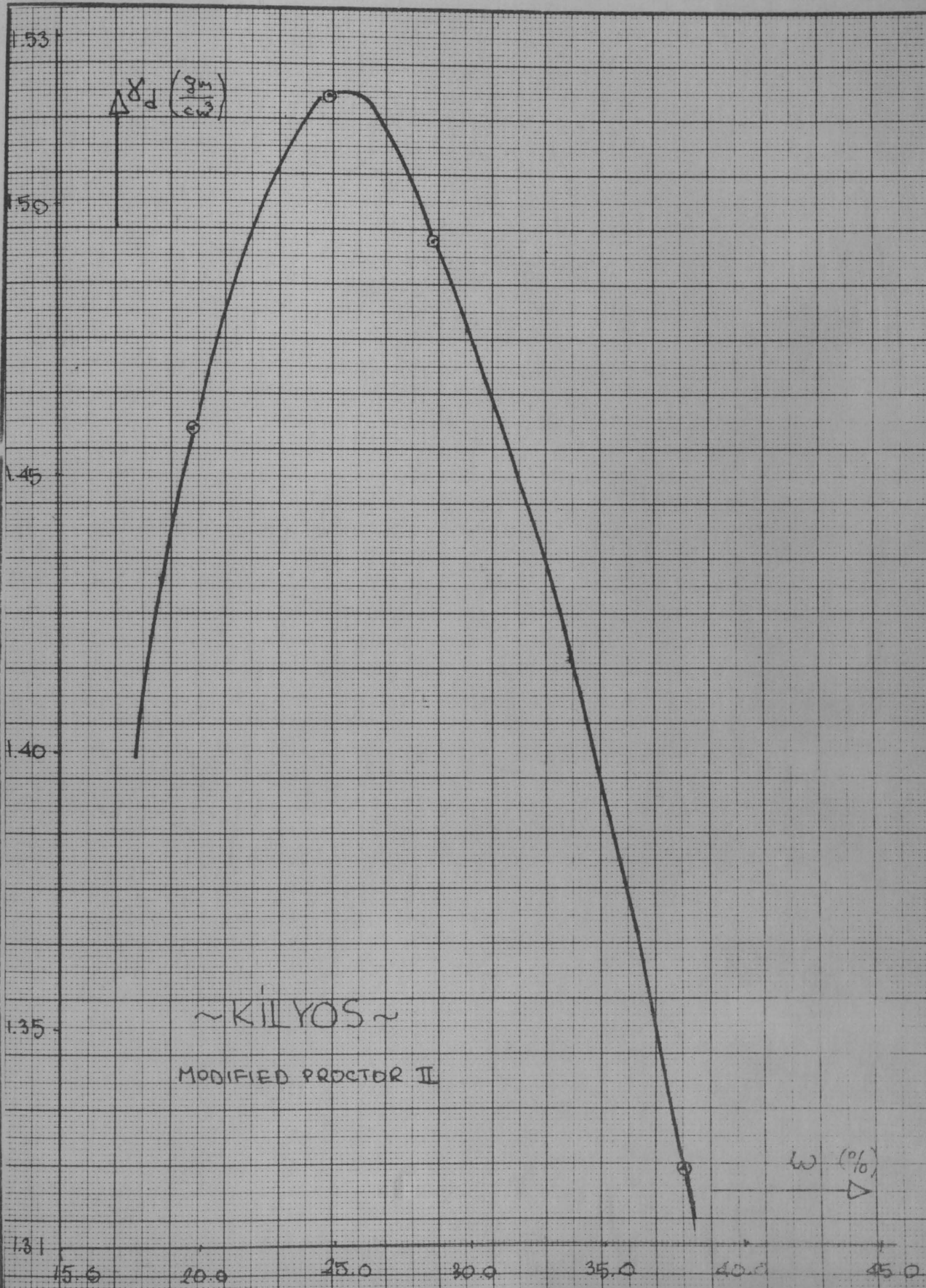
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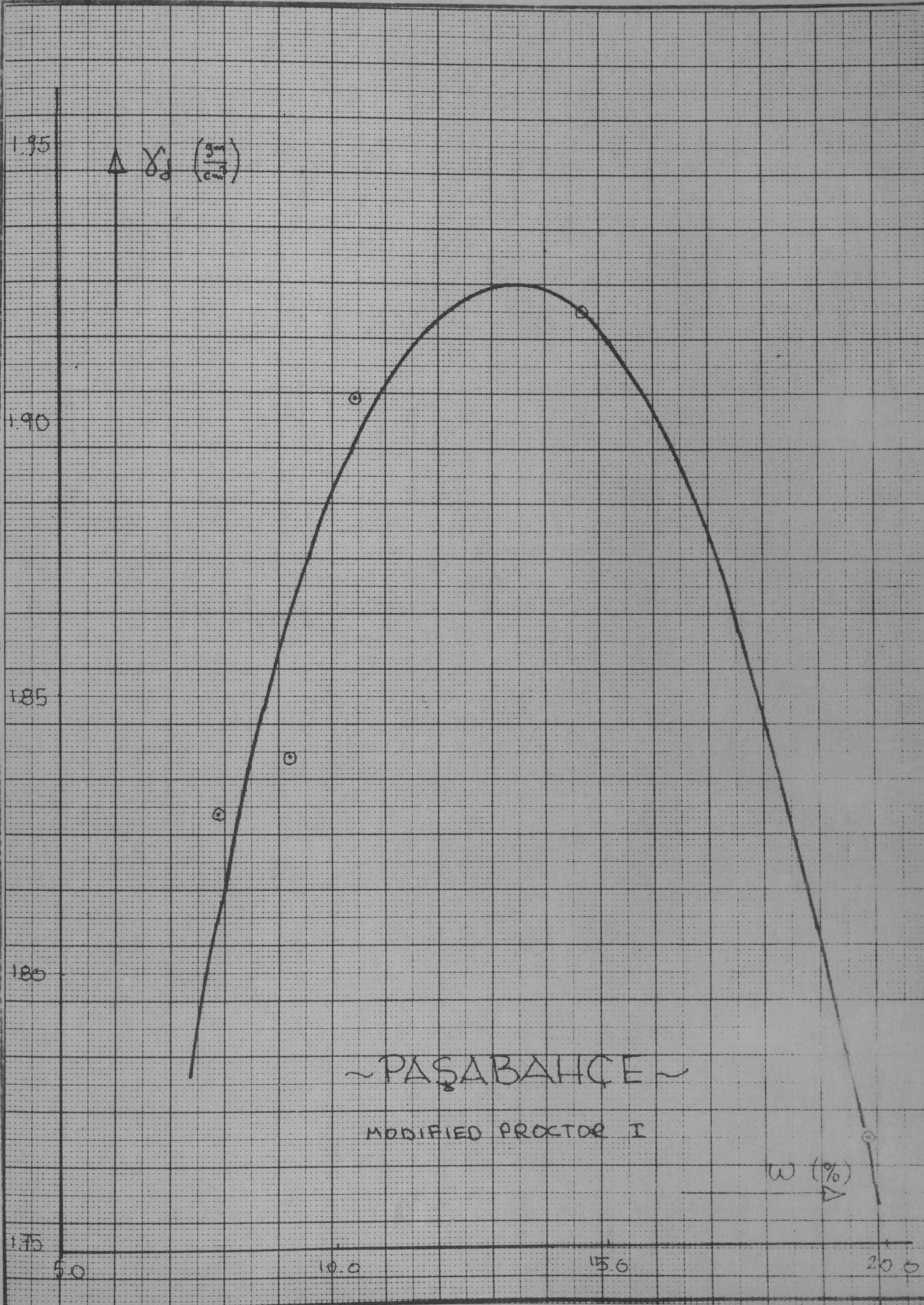
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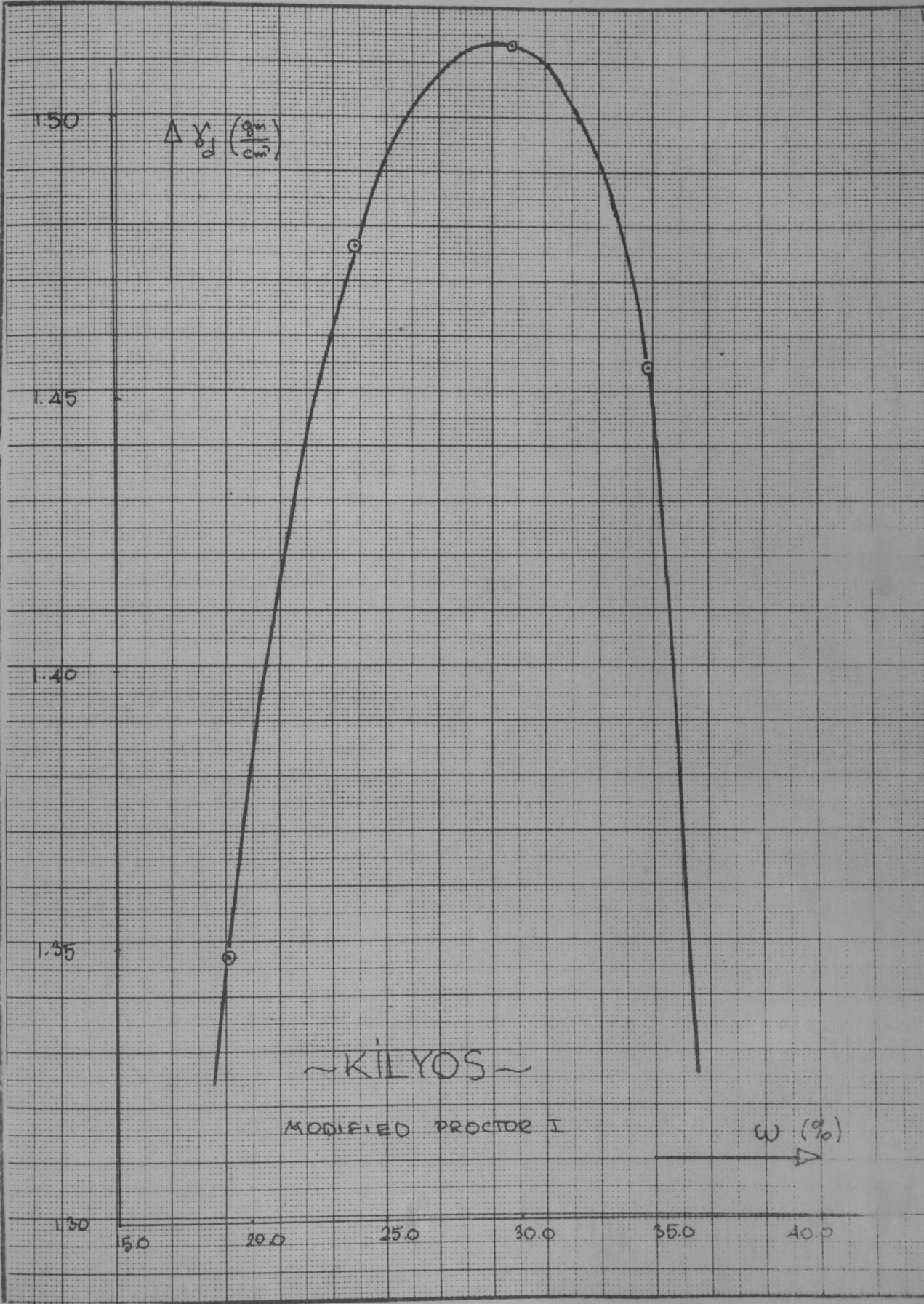
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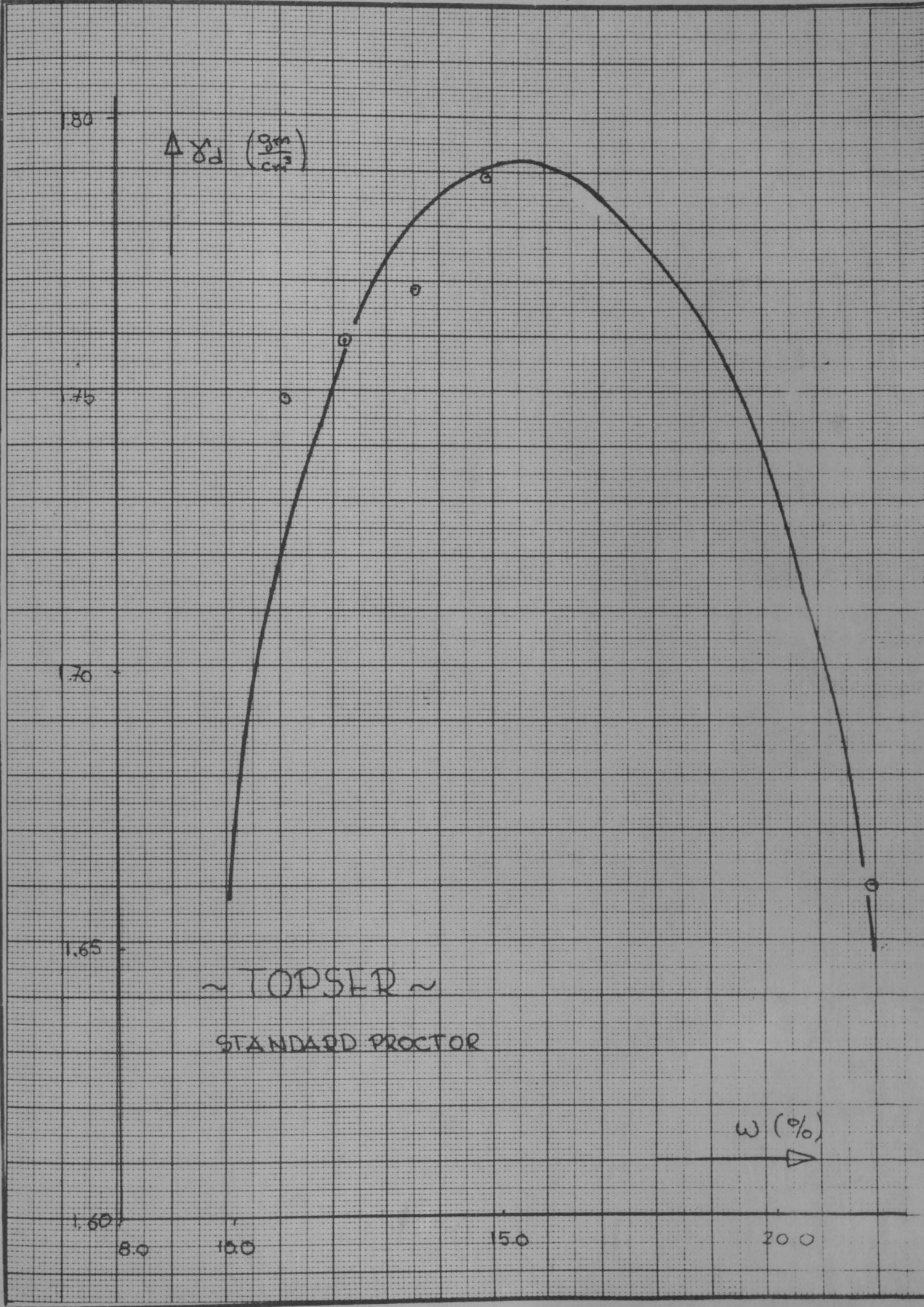
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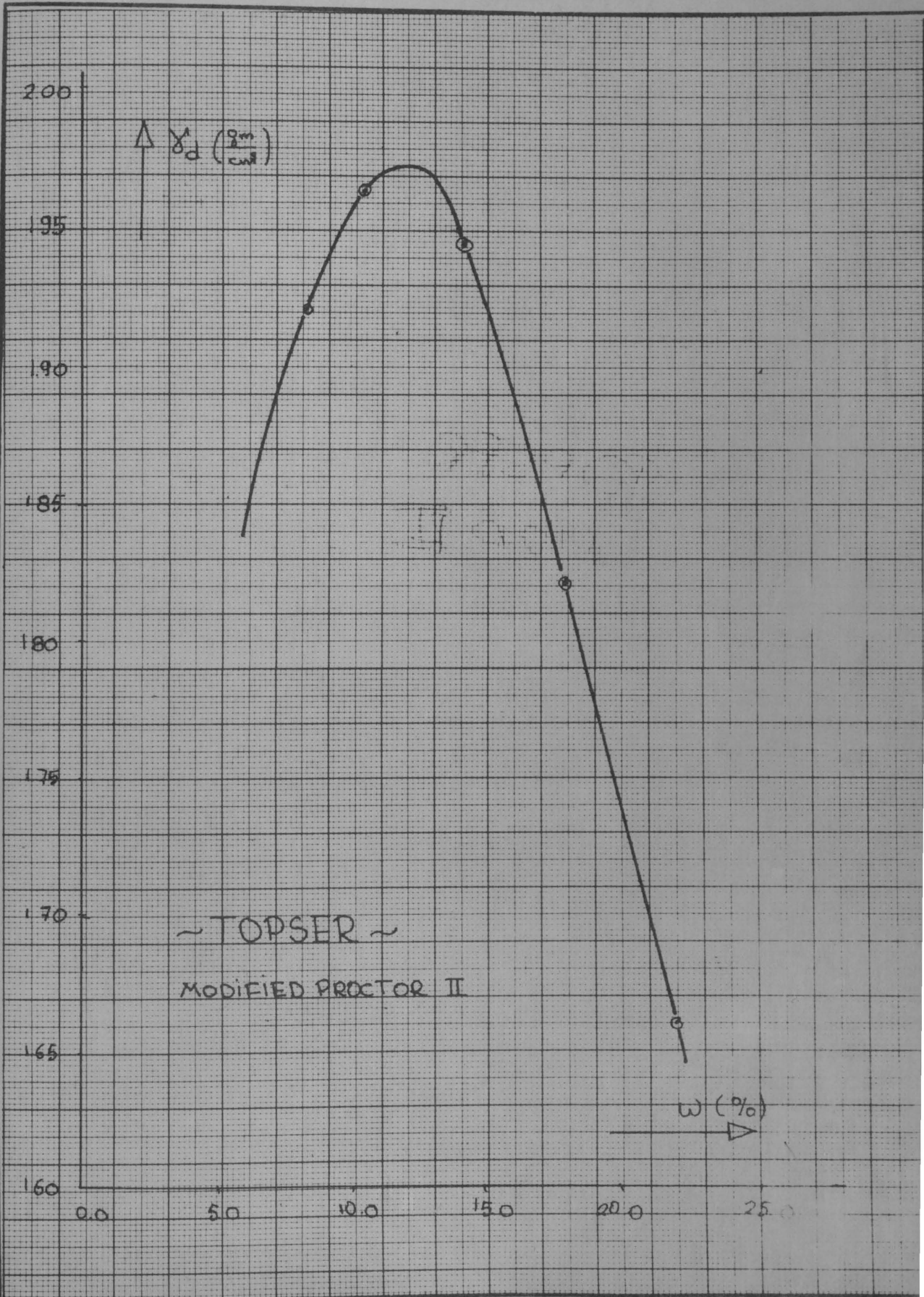
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1.40

1.35

1.30

1.25

1.20

1.15

1.10

1.05

1.00

$\Delta \gamma_d \left(\frac{\text{gm}}{\text{cm}^3} \right)$

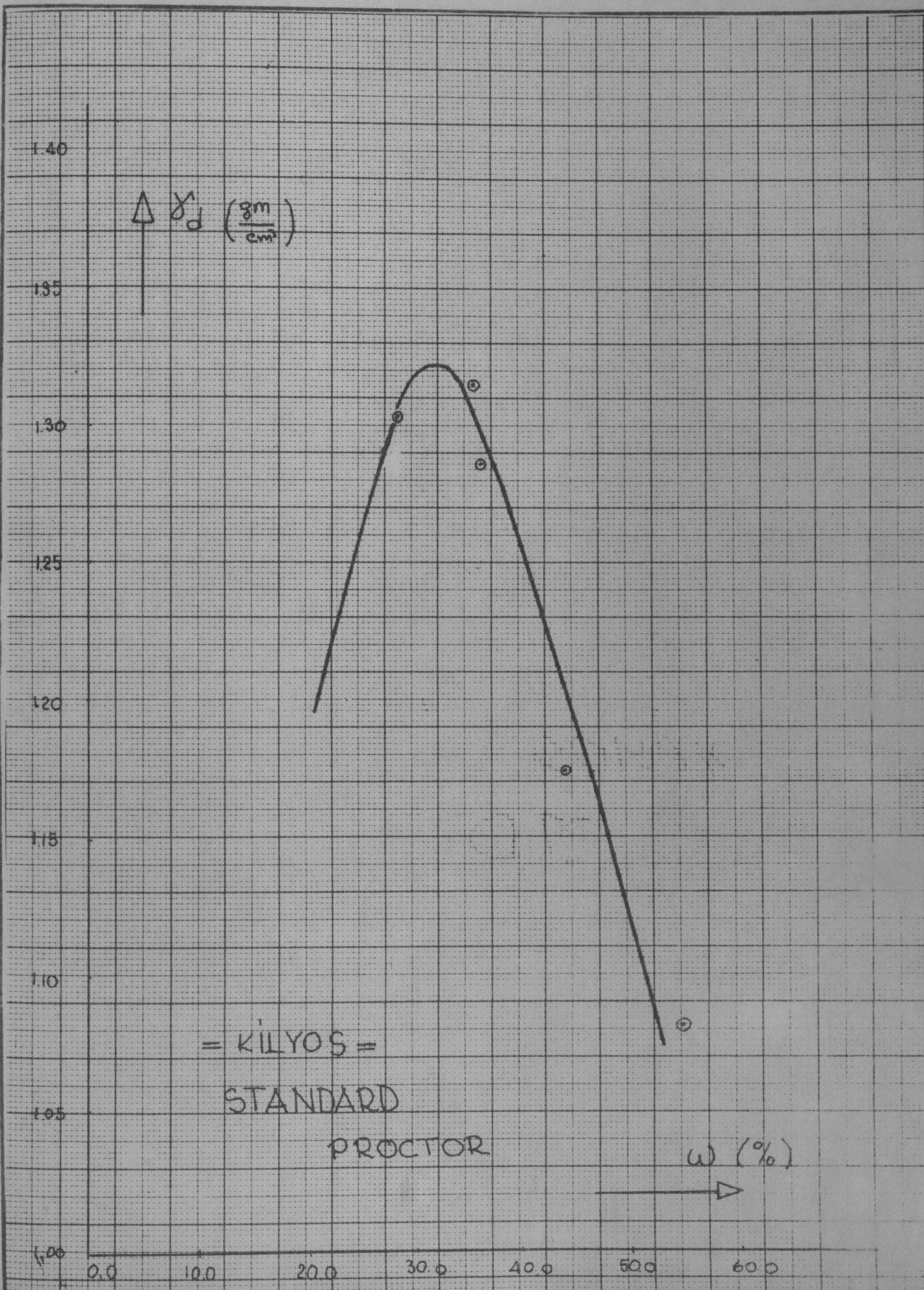
= KILYOS =

STANDARD

PROCTOR

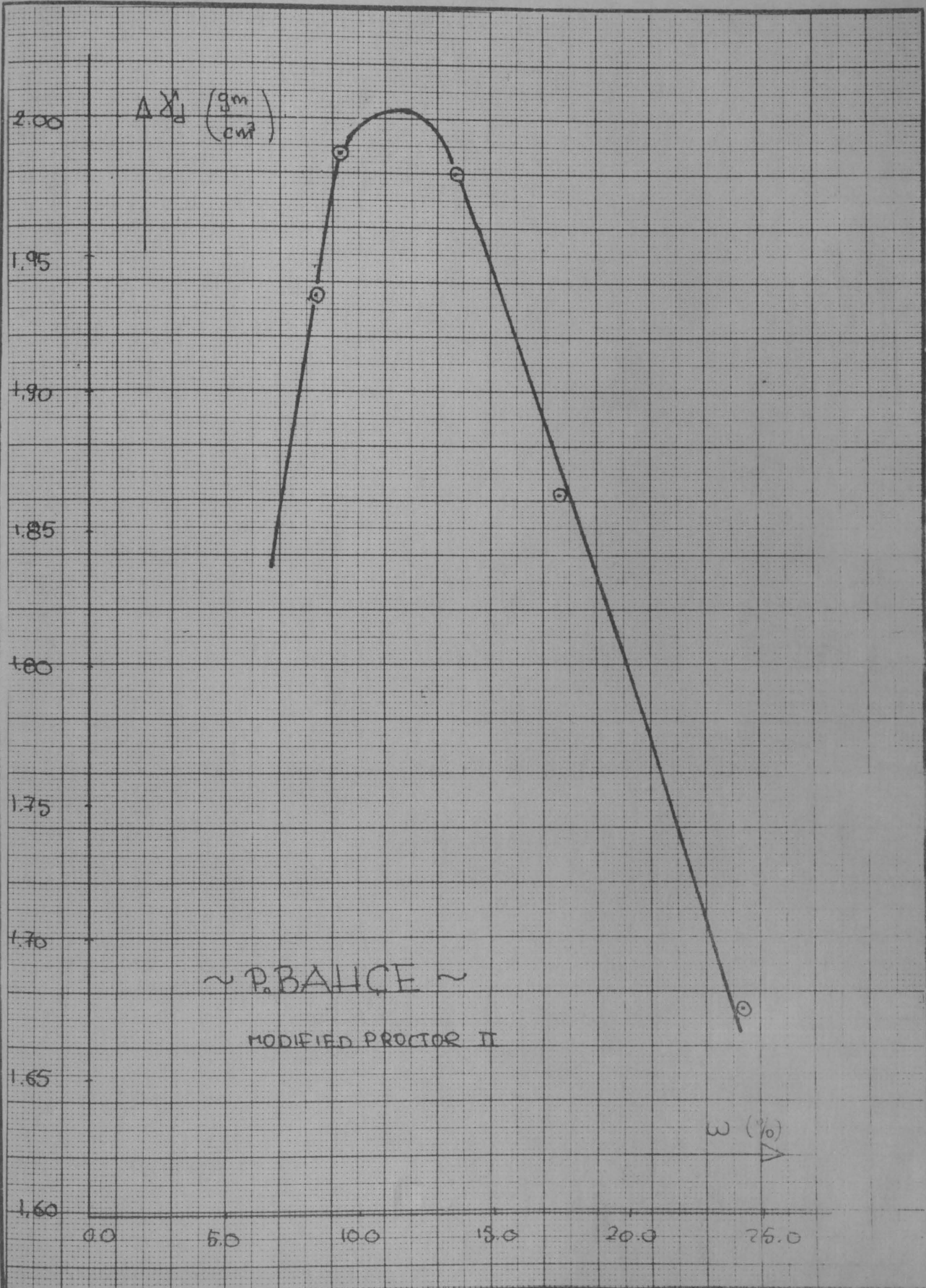
w (%)

0.0 10.0 20.0 30.0 40.0 50.0 60.0



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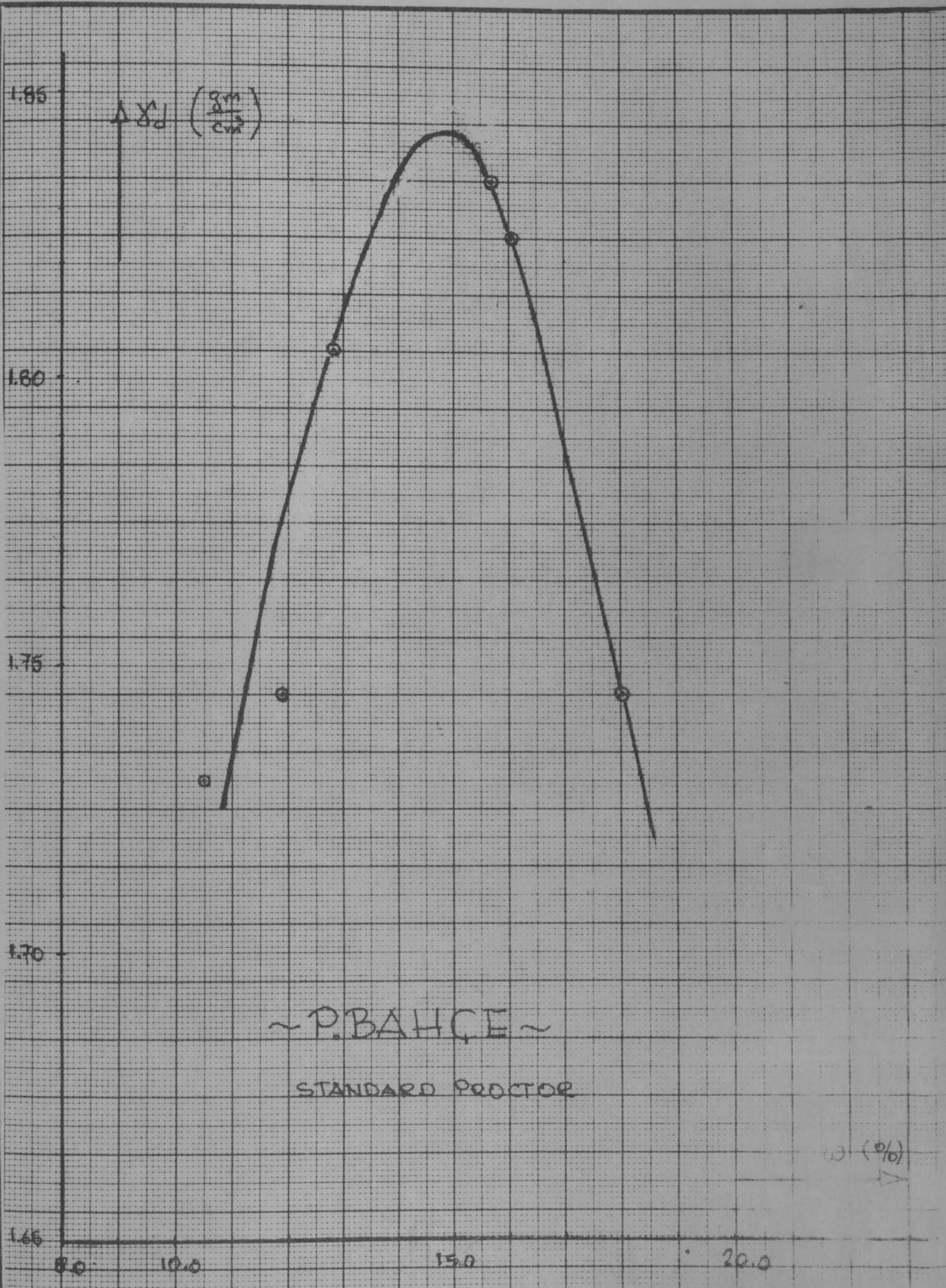
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C- Measurement of Permeabilities

1- Arrangement of variables :

The first set of experiments are made to evaluate the important factors effecting permeability. The levels of each variable are as follows :

Soil type :

- 1- High Plasticity clay with montmorillonite calay mineral (Kilyos esmer)
- 2- Lower plasticity clay with kaolinite and illite clay mineral (Paşabahçe-Kırmızı)
- 3- Low plasticity clay with kaolinite clay mineral (Topser-Sarı)

Compactive effort :

- 1- Standard Proctor;
Energy per unit volume= 12.360 ft.lb/cu.ft.
- 2- Modified Proctor I ;
Energy per unit volume= 33.750 ft.lb/cu.ft.
- 3- Modified Proctor II;
Energy per unit volume= 74.250 ft.lb/cu.ft.

Water content :

- 1- Dry side of dry density curve (3-4 %)
- 2- Optimum of dry density curve (± 0.5 %)
- 3- Wet side of dry density curve (3-4 %)

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Granulometry :

- 1- Below No. 16 sieve
- 2- Below No. 40 sieve
- 3- Below No.100 sieve

The arrangement of these variables at their various levels according to the greko-Latin Square gives us the following Matrix :

Compactive effort	10 Blows 4 Layers	26 Blows 4 Layers	57 Blows 4 Layers
water content			
Dry	Paşabahçe - 16	Kilyos - 40	Topser - 100
Optimum	Kilyos -100	Topser - 16	Paşabahçe - 40
Wet	Topser - 40	Paşabahçe - 100	Kilyos - 16

2- Permeability testing :

Testing of permeability of a soil sample with the GEONOR permeameter requires some preparation before measuring the permeability. The steps are as follows :

a- Moulding the sample- is made in the special mould of the apparatus and the compaction is completed in four equal layers. The thickness of each layer is checked with the special measuring rod. If the layer thickness is uneven,

then the work done per unit volume will be uneven. This influences the permeability. To determine the density, the top collar is removed and the sample is trimmed on the top. The bottom piece may be removed if the sample is not loose, before weighing.

Since the permeameter is used to measure the permeability of clayey soils, a height of the samples is recommended to be kept around 5 cm. However the mould has a height of 10 cm., therefore ejecting the sample and trimming it down to 5 cm. is necessary. To be able to do this the author has had three wooden pistons made, which have different lengths; 2.5 cm. of compacted soil is ejected out of the mould and the surface trimmed. Then another 2.5 cm. of soil is ejected, this time out of the other end of the mould, and again the surface is trimmed. Thus, the sample inside the mould has about 5 cm. of length. The longest ejector is used to eject the sample completely out of the mould. Now, the sample is ready for testing.

b- Mounting of the sample- First a piece of cylindrical rubber collar (actually a piece of inner tube of a bicycle tire) is mounted around the pedestal on the bottom plate of the testing cell. The end of the rubber is protruded about 4 mm. upwards. A similar tube is mounted on the cap which comes onto the top of the sample. The thin plastic tubings which are in connection with the valves 15 and 17 are coupled to the bottom piece, and the top and the bottom pieces are saturated. The saturated filter stones are fastened to the top and bottom piece and the protruding portion of the rubber collars are used to cover the sides of the stones, so that they do not harm the membrane when mounting. Two filter papers are

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cut and placed on the filter stones. The sample is then measured and placed on the bottom piece. The cylinder for mounting the rubber membrane is placed around it and the top piece is put on the sample. The rubber membrane is released to surround the sample and the top and bottom pieces. The O-rings are fastened to the bottom and top pieces with the help of a split cylinder.

Now, the sample is ready to be tested. Valve 1 is opened together with the valves 7, 8 and 10. When the air inlet at the top of the cell is opened, water starts filling into the cell from the tank.

c- Consolidation- When no air is left in the cell, water starts flowing out from the air inlet of the cell. Then the air inlet and the valves 10, 7 and 8 are closed. The cell pressure is gradually raised and kept at 10 kg/cm^2 . Valve 18 is opened and the sample is let to consolidate under this all-around pressure.

d- Saturating the sample- When the movement of water in the burette stops, this means that detectable consolidation has stopped. Then the pore pressure is started to be raised. For the experiments carried through out the work, the pore pressure was kept at 8.0 kg/cm^2 . The sample is subjected to these pressures for at least 24 hours before any measurements on permeability are made. A pore pressure as high as the above value is enough to saturate the samples by dissolving the air in the voids.

e- Measuring of Permeability- is done when the saturation of the sample is achieved. In all the experiments

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performed, the constant head method is used. The mercury column is pulled to one side of the U-tube after valve 16 is closed. The rate of fall of the mercury column is observed for several times. When one gets at least three equal rates of fall consecutively, the value may be accepted.

3- Permeability with Lime as additive

For the second set of experiments, two most important variables of the first set ; namely soil type and water content are selected with additive Lime as the third variable. This time the Variance Analysis format is "Latin Square" since there are only three variables. The variables again are used at three levels, the levels of the first two variables being the same as in the first set of experiments. The third variable, lime additive, is used at the following levels:

- 1- 0 % Lime added
- 2- 2 % Lime added
- 3- 5 % Lime added

The experiment arrangement matrix is given below.

Lime added Water Content	0 %	2 %	5 %
Dry	Paşabahçe	Kilyos	Topser
Optimum	Topser	Paşabahçe	Kilyos
Wet	Kilyos	Topser	Paşabahçe

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The energy per unit volume was taken as Proctor Modified I, and the granulometry as below number 16 sieve.

The procedure followed in testing was identical as in the first set of experiments. The data and the results are given and discussed in the next chapter.

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DATA, ANALYSIS AND
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A- Data and Analysis

1- Values of permeability obtained from the first set of experiments which were performed to determine the factors effecting permeability:

Soil	Water Content	Compactive Effort	Granulo- metry	Permeability 10^{-9} cm/sec
Topser	Wet	Std.Proct.	- 40	11.6
"	optimum	Mod.Proct.I	- 16	11.6
"	dry	Mod.Proct.II	-100	17.5
Paşabahçe	dry	Std. Proct.	- 16	20.6
"	wet	Mod.Proct.I	-100	8.8
"	optimum	Mod.Proct.II	- 40	7.4
Kilyos	optimum	Std.Proct.	-100	2.4
"	dry	Mod.Proct.I	- 40	0.8
"	wet	Mod.Proct.II	- 16	3.1

The data of these experiments are given in the next pages. Calculations are included in the appandix.

To determine the effect of these variables on permeability, Variance Analysis has been made. The details of analysis are given in the appandix.

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The Results of Variance analysis made for determining the effective factors on permeability :

Source	Sum of squares	Degrees of Freedom	Mean Square	F
Soil type	1025-780= 245	2	123	8.2
Granulometry	820-780= 40	2	20	1.3
Water content	840-780= 60	2	30	2.0
Comp.Effort	811-780= 31	2	15	

F value of 8.2 is between 0.2 and 0.1 significance levels (8), that is, there is 80 to 90 percent evidence that the corresponding variable; soil type has effect on permeability. From the F values we deduce that the factors may be listed according to ascending importance as

First - Soil type

Secund- Water Content

Third - Granulometry

Fourth- Compactive Effort

2- Values of permeability obtained from the second set of experiments which were performed to determine the

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effect of lime content on the permeability :

Soil type	Water Content	Lime added	Permeability 10^{-9} cm/sec
Topser	optimum	0	11.6
"	wet	2 %	19.2
"	dry	5 %	19.8
Paşabahçe	dry	0 %	8.8
"	optimum	2 %	9.7
"	wet	5 %	14.0
Kilyos	wet	0 %	3.1
"	dry	2 %	4.7
"	optimum	5 %	6.7

Since granulometry and compactive effort were found to be insignificant in the first analysis, it is justified to use those values from the first set which give the necessary combinations of the two variables; soil type and water content, lime added being equal to zero. With the values given above, a second variance analysis has been made whose details are given in the appendix.

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The results of Variance analysis made for determining the effect of lime on permeability:

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Soil type	1320-1100= 220	2	110	73.5
Percent Lime added	1137-1100= 37	2	19	12.7
Water content	1103-1100= 3	2	1.5	

This analysis shows that soil type is again the most important factor, but lime additive is the second important factor which effects the permeability.

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B- Discussion of the Results :

The two sets of experiments reveal very important facts about the permeability of soils. When the experimentation was being programmed, the author was in the opinion that compactive effort might have come out to be an important factor. However, the analysis showed that water content was a more important factor than the compactive effort. Granulometry has almost no effect on the permeability, However, it is a well known fact that grain size is one of the most important factors in permeability. Actually, the test result does not fall into contradiction with this fact since the granulometry we used in these experiments is a deceiving one. When we sieve the soil through number 40 sieve, we are not separating soil particles of diameters larger than 0.42 mm. but "lumps" of soil which are greater than this mesh size. The soils are 50 to 80 percent silt and clay in reality (see Appandix). Thus it is very reasonable that grain size does not appear to be an effective variable.

Soil type, is the most important factor according to both of the sets of experiments. This result may be attributed to various effects. First of these is the properties of the predominant clay mineral in the soil. It has been shown that the water held by the clay particles is in a physical state different from that of liquid water. Ralph E. Grim (10) states that " The film of nonordinary, or so-called nonliquid, water is best developed and appears to reach its greatest thickness on the basal plane surfaces of the expanding lattice minerals of the montmorillonite group." This quotation explains why the permeability of Kilyos-Esmer whose ^{clay} predominant clay mineral is montmorillonite, is so low when compared to the

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other soils, some portions of voids being blocked by non-flowing water.

The second important factor to influence the permeability is the water content. This fact requires little discussion since it is long known in soil mechanics that the dry density; that is the packing of the soil particles is related to water content with the so-called Proctor relation. Thus if the water content is at the wet or the dry side of the optimum water content, the packing of the soil particles will not be as close as at optimum, the permeability will be higher.

An important point to note that in a similar work (11), the water content has been found to be the influencing factor after a great number of experiments in which the soil was not a variable.

The second set of data give a higher significance level for the soil type variable. This also is a confirming evidence that shows the result obtained in the first set is quite reliable.

The effect of Lime on the permeability is clearly seen upon inspecting the second Variance analysis results. The F test gives a value of 12.7, which from tables shows a significance level of 80-90 %. This is a good evidence that this factor is an effective factor on permeability. Water content, the second important factor as obtained from the first set of experiments falls below the lime content which also shows that lime content is really an important factor in permeability of soils.

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CONCLUSIONS AND RECOMMENDATIONS

Two important conclusions can be derived from the results of the experiments :

- 1- Soil type and water content are the most important factors influencing permeability,
- 2- Addition of lime increases the permeability of soils.

These two conclusions enable us to evaluate some of the soil engineering problem from a new point of view.

One of the results of the first set of experiments reveals that compactive effort has little significance on the value of permeability, This would mean for example that a controls engineer should not insist on the exact amount of compaction that a contractor should apply at the construction of the core of a dam, but be more careful that the right water content be attained.

The fact that lime increases the permeability may find many uses in engineering applications. The drainage field of a septic tank may be treated with lime, so that the percolation of the effluent water is increased. If it is desired to make an impervious strata more pervious, lime treatment may be used by mixing lime with the impervious soil so that improvement of permeability of soils can be achieved in place. The positive effect of lime on permeability may also find use in highway engineering. The subgrade and the surface of roads may be treated with lime so that better drainage is provided. The addition of lime also has a positive effect on the strength of the soils, thus it is

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desirable to be used at highway constructions.

Also, when the permeability is higher, the water will drain and freezing in winter followed by a spring break-up of roads will be avoided.

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A P P E N D I C E S

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CALCULATIONS:

Calculation of Permeability values

The formula for the constant head was given:

$$k = \frac{ah}{A} \cdot \frac{L}{t} \cdot \frac{1}{H} \cdot \frac{\gamma_w}{\gamma_{Hg} - \gamma_w}$$

KİLYOS, STANDARD PROCTOR:

$$k = \frac{0.034 \times 0.5}{20} \cdot \frac{4.7}{34 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 2.398 \times 10^{-9}$$

KİLYOS, MODIFIED I :

$$k = \frac{0.034 \times 0.1}{20} \cdot \frac{5.05}{21 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 0.832 \times 10^{-9}$$

KİLYOS, MODIFIED II :

$$k = \frac{0.034 \times 0.35}{20} \cdot \frac{5.05}{20 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 3.062 \times 10^{-9}$$

PAŞABAĞCI, STANDARD PROCTOR:

$$k = \frac{0.034 \times 0.7}{20} \cdot \frac{5.1}{6 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 20.6 \times 10^{-9}$$

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LİME STABILİZASYON

KİLYOS, % 2

$$k = \frac{0.034 \times 0.4}{20} \cdot \frac{5.1}{900} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 4.71 \times 10^{-9}$$

KİLYOS, % 5

$$k = \frac{0.034 \times 0.7}{20} \cdot \frac{5.1}{1110} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 6.68 \times 10^{-9}$$

TOPSER, % 2

$$k = \frac{0.034 \times 1.0}{20} \cdot \frac{5.1}{540} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 19.6 \times 10^{-9}$$

TOPSER, % 5

$$k = \frac{0.034 \times 4.50}{20} \cdot \frac{5.1}{240} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 19.8 \times 10^{-9}$$

PAŞABAĞCI, % 5

$$k = \frac{0.034 \times 0.95}{20} \cdot \frac{5.1}{720} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 14 \times 10^{-9}$$

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PAŞABAHÇE, MODIFIED I :

$$k = \frac{0.034 \times 0.3}{20} \cdot \frac{5.1}{6 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 8.83 \times 10^{-9}$$

PAŞABAHÇE, MODIFIED II :

$$k = \frac{0.034 \times 0.5}{20} \cdot \frac{5.05}{12 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 7.38 \times 10^{-9}$$

TOPSER, STANDARD PROCTOR :

$$k = \frac{0.034 \times 0.4}{20} \cdot \frac{5.1}{6 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 11.55 \times 10^{-9}$$

TOPSER, MODIFIED I :

$$k = \frac{0.034 \times 0.4}{20} \cdot \frac{5.1}{6 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 11.55 \times 10^{-9}$$

TOPSER, MODIFIED II :

$$k = \frac{0.034 \times 0.6}{20} \cdot \frac{5.05}{6 \times 60} \cdot \frac{1}{65.2} \cdot \frac{1}{12.55} = 17.45 \times 10^{-9}$$

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
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P. BAHÇE N MOD. PROCTOR I

Detm.n No.	1	2	3	4	5		
Cont.r No.	51	52	53	54	55		
Cont+wet soil (gm)	183.96	191.10	193.12	164.70	162.02		
Cont+dry soil (gm)	172.47	177.24	177.29	146.93	139.70		
wt. cont.r (gm)	11.49	13.86	15.83	17.77	22.32		
wt. water (gm)	26.52	26.74	26.34	26.50	26.51		
wt. dry soil (gm)	145.95	150.50	150.95	120.43	113.19		
water content w (%)	7.90	9.20	10.50	14.70	19.70		
wt. compacted soil + mold	1893	1901	1921	1939	1922		
wt. mold (gm)	1499	1499	1499	1499	1499		
wt. soil	394	402	422	440	423		
volume of mold (cm ³)	200	200	200	200	200		
$\gamma_d = \frac{W}{V(1+w)} \left(\frac{\text{gm}}{\text{cm}^3} \right)$	1.83	1.84	1.91	1.92	1.77		

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
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P. BAHÇE ~ MOD. FROCTOR I

Detm.n No.	1	2	3	4	5		
cont.r No.	13	7	9	12	11		
cont + wet soil (gm)	175.34	179.36	158.15	151.73	184.51		
cont + dry soil	163.63	163.12	139.68	132.11	173.62		
wt. cont.r (gm)	11.71	16.24	18.47	19.62	10.89		
wt. water (gm)	42.18	44.11	34.33	40.74	44.08		
wt. dry soil (gm)	121.55	119.01	105.35	81.37	129.54		
water content w (%)	9.30	13.60	17.50	24.20	8.40		
wt. compacted soil + mold	1934	1949	1937	1911	1919		
wt. mold (gm)	1499	1499	1499	1499	1499		
wt. soil	435	450	438	412	420		
volume of mold (cm ³)	200	200	200	200	200		
$\frac{w}{1+w} \left(\frac{gm}{cm^3} \right)$	1.989	1.981	1.863	1.655	1.936		

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
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P.BAHÇE ~ STD. PROCTOR

Detmn. No.	1	2	3	4	5	6	7
Cont.r No.	10	11	12	13	14	15	16
Cont.+wet soil (gm)	178.05	158.90	159.10	142.35	170.80	251.00	75.25
Cont.+dry soil (gm)	165.80	148.80	148.20	129.80	155.70	229.40	69.15
wt. cont.r (gm)	49.20	64.00	63.20	40.40	61.60	110.40	30.20
wt. water (gm)	12.25	10.10	10.90	12.55	15.10	21.60	6.10
wt. dry soil (gm)	116.60	84.80	85.00	69.40	94.10	119.00	38.95
water content w (%)	10.50	11.90	12.80	18.10	16.05	18.2	15.7
wt. compacted soil + mold	1881	1900	1906	1912	1923	1925	1923
wt. mold (gm)	1499	1499	1499	1499	1499	1499	1499
wt. soil	382	401	407	413	424	426	424
volume of mold (cm ³)	200	200	200	200	200	200	200
$\rho_d = \frac{W}{V(1+W)} \frac{(gm)}{(cm^3)}$	1.725	1.792	1.805	1.749	1.815	1.181	1.833

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KILYOS ~ STD. PROCTOR

Detm.n No.	1	2	3	4	5		
Cont.r No.	3	4	2	13	7		
Cont + wet soil (gm)	90.56	100.96	111.87	133.91	138.97		
cont + dry soil	74.34	75.43	86.79	113.33	114.01		
wt. cont.r (gm)	16.22	25.53	25.08	20.54	24.96		
wt. water (gm)	29.47	31.35	30.24	42.18	44.11		
wt. dry soil (gm)	44.87	44.08	56.55	71.15	69.90		
water content w (%)	36.20	57.90	44.40	28.80	35.70		
wt. compacted soil + mold	1849	1841	1839	1835	1856		
wt. mold (gm)	1499	1499	1499	1499	1499		
wt. soil	350	342	340	336	357		
volume of mold (cm) ³	200	200	200	200	200		
$\gamma_d = \frac{W}{V(1+w)} \left(\frac{gm}{cm^3} \right)$	1.285	1.082	1.175	1.303	1.315		

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KILYOS ~ MOD. PROCTOR I

Detm.n No.	1	2	3	4	5		
Cont.r No.	7	13	9	11	101		
Cont wet soil (gm)	142.75	129.62	120.96	124.84	136.65		
cont dry soil (gm)	120.21	112.79	98.57	103.05	118.70		
wt. cont.r (gm)	22.54	16.83	22.39	21.49	17.95		
wt. water (gm)	44.09	42.16	34.26	44.05	25.59		
wt. dry soil (gm)	76.12	70.63	64.31	59.00	93.11		
water content w (%)	29.60	23.80	34.80	36.50	19.30		
wt compacted soil + mold	1870	1844	1868	1861	1821		
wt. mold (gm)	1499	1499	1499	1499	1499		
wt. soil (gm)	371	345	369	362	322		
volume of mold (cu)	200	200	200	200	200		
$\gamma = \frac{W}{V(1+w)} \left(\frac{gm}{cu} \right)$	1.54	1.477	1.505	1.325	1.348		

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ROBERT COLLEGE GRADUATE SCHOOL
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KILYOS N MOD . PROCTOR II

Detm.n No.	1	2	3	4	5		
Cont.r. No.	9	12	12	11	9		
Cont.wet soil (gm)	133.98	144.01	135.09	131.26	125.44		
cont.dry soil (gm)	117.45	123.38	114.00	111.01	100.35		
wt. cont.r (gm)	16.53	20.63	21.09	20.25	25.09		
wt. water (gm)	34.28	40.74	40.75	44.08	34.28		
wt. dry soil (gm)	83.17	82.64	73.25	66.93	66.07		
water content w (%)	19.90	25.00	28.80	30.30	38.00		
wt. compacted soil + mold	1845	1880	1883	1883	1864		
wt. mold (gm)	1499	1499	1499	1499	1499		
wt. soil (gm)	346	381	384	384	365		
volume of mold (cm ³)	200	200	200	200	200		
$\rho_d = \frac{W}{V(1+w)} \left(\frac{gm}{cm^3} \right)$	1.459	1.520	1.493	1.473	1.324		

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
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TOPSER ~ MOD. PROCTOR I

Detm.n No	1	2	3	4	5		
Cont.r. No	6	7	9	11	13		
Cont+wet soil (gm)	135.69	151.00	140.59	149.69	161.30		
Cont+dry soil (gm)	127.62	141.17	128.20	134.84	143.05		
wt. cont.r (gm)	8.07	9.83	12.39	15.85	18.25		
wt. water (gm)	37.24	44.10	34.31	44.06	42.16		
wt. dry soil (gm)	90.38	97.07	93.89	90.78	100.89		
water content w (%)	8.95	10.05	13.20	17.50	18.20		
wt. compacted soil + mold	1900	1910	1926	1931	1900		
wt. mold (gm)	1499	1499	1499	1499	1499		
wt. soil (gm)	401	411	427	432	401		
volume of mold (cm ³)	200	200	200	200	200		
$\gamma_d = \frac{W}{V(1+w)} \left(\frac{gm}{cm^3} \right)$	1.840	1.865	1.885	1.843	1.695		

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, İSTANBUL

TOPSER ~ MOD. PROCTOR II

Detm. n No.	1	2	3	4	5		
Cont. r No.	51	52	53	54	58		
cont + wet soil (gm)	183.41	175.09	170.30	151.24	152.55		
cont + dry soil (gm)	171.31	161.06	152.54	132.61	129.90		
wt. cont. r (gm)	12.10	14.03	17.76	18.63	22.65		
wt. water (gm)	26.51	26.68	26.30	26.51	26.48		
wt. dry soil (gm)	144.80	134.38	126.24	106.10	103.42		
water content w (%)	8.26	10.40	14.10	17.60	21.90		
wt compacted soil + mold	1914	1933	1943	1927	1903		
wt. mold (gm)	1499	1499	1499	1499	1499		
wt. soil (gm)	415	434	444	428	404		
volume of mold (cu ³)	200	200	200	200	200		
$\gamma_d = \frac{W}{V(1+w)} \left(\frac{\text{gm}}{\text{cu}^3} \right)$	1.920	1.963	1.945	1.821	1.660		

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

TOPSER ~ STD. PROCTOR

Detm. n No.	1	2	3	4	5		
Cont. r. No.	2	1	3	5	101		
Cont + wet soil (gm)	98.00	109.00	96.40	96.15	133.56		
Cont + dry soil (gm)	90.60	100.9	88.30	87.75	114.39		
wt cont. r (gm)	740	8.10	8.10	8.40	19.17		
wt. water (gm)	30.00	27.70	29.20	31.70	25.59		
wt dry soil (gm)	60.60	73.20	59.10	56.00	87.70		
water content w (%)	12.20	11.10	13.60	15.00	21.80		
wt. comp. pack soil + mold	1893.5	1887.5	1901.0	1911.0	1904.0		
wt. mold (gm)	1499.0	1499.0	1499.0	1499.0	1499.0		
wt. soil (gm)	394.5	388.5	402.0	412.0	405.0		
volume of mold (cu ³)	200.0	200.0	200.0	200.0	200.0		
$\gamma_g = \frac{W}{V(1+w)} \left(\frac{gm}{cu^3} \right)$	1.76	1.75	1.77	1.79	1.66		

THESIS

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P. BAHÇE KIRMIZI

Lime Content = 5%

Wet

Cell Press. σ_3 (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.7	360	
"	"	0.95	720	
"	"	0.95	720	
"	"	1.5	1140	
"	"	0.95	720	
"	"	1.3	1770	
"	"	0.95	720	
		0.95	720	
		0.95	720	
		0.95	720	

$$a = 0.034 \text{ cm}^2$$

$$h = 5.1 \text{ cm}$$

$$A = 20.0 \text{ cm}^2$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$w =$$

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

TOPSER SARI

Lime content = 2 %

Cell Press. σ_3 (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	1.8	8.70	
"	"	1.0	5.10	
"	"	1.0	5.40	
"	"	1.0	5.40	
"	"	1.0	5.40	

$a = 0.034 \text{ cm}^2$ $w =$
 $A = 20.0 \text{ cm}^2$
 $h = 5.1 \text{ cm}$
 $H = 65.2 \text{ cm}$ at $U_{av} = 8.0$

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

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KILYOS ESMER

Lime Content = 2 %

Dry.

Cell Press. σ_3 (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.6	900	
10.0	8.0	0.8	1800	
10.0	8.0	0.4	900	
10.0	8.0	0.4	900	
10.0	8.0	0.4	900	

$$a = 0.034 \text{ cm}^2$$

$$h = 5.1 \text{ cm.}$$

$$A = 20.0 \text{ cm}^2$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$W =$$

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, İSTANBUL

TOPSER SARI

Lime content = 5 %

Dry.

Cell Press. σ_3 (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	time t (sec)	Permeability k (cm/sec)
10.0	8.0	2.4	120	
"	"	2.35	120	
"	"	4.60	240	
"	"	4.80	240	
"	"	4.55	240	
"	"	4.55	240	
"	"	4.50	240	
"	"	4.50	240	
"	"	4.50	240	

$a = 0.034 \text{ cm}^2$

$A = 20.0 \text{ cm}^2$

$h = 5.1 \text{ cm}$

$H = 65.2 \text{ cm}$ at $U_{av} = 8.0$

w

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

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KILYOS ESMER

Lime Content = 5 %

Optimum.

Cell Press. σ_3 (kg/cm ²)	Average Pore Press. $U_{av.}$ (kg/cm ²)	Movement of Hg' Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.4	360	
"	"	0.3	360	
"	"	0.6	810	
"	"	0.6	900	
"	"	0.65	1020	
"	"	0.65	1020	
"	"	0.7	1110	

$$a = 0.034 \text{ cm}^2$$

$$A = 20.0 \text{ cm}^2$$

$$h = 5.1 \text{ cm}$$

$$H = 65.2 \text{ cm at } U_{av.} = 8.0$$

$$w =$$

T H E S I S

ROBERT COLLEGE GRADUATE SCHOOL
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TOPSER SARI

Standard Proctor

- #40

Wet

Cell Press. (kg/cm ²)	Average Pore Press U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.3	360	
"	"	0.9	360	
"	"	0.5	360	
"	"	0.4	360	
"	"	0.4	360	
"	"	0.8	360	
"	"	0.5	360	
"	"	0.5	360	
"	"	0.4	360	
"	"	0.4	360	
"	"	0.4	360	11.55×10^{-9}

$h = 5.1 \text{ cm}$

$a = 0.034 \text{ cm}^2$

$A = 20.0 \text{ cm}^2$

$H = 65.2 \text{ cm at } U_{av} = 8.0$

$w = 18.4 \%$

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
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P. BAHÇE KIRMIZI

Modified - II

- #40

Optimum

Cell. Press. (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.5	360	
"	"	0.35	360	
"	"	0.35	360	
"	"	0.5	600	
"	"	0.5	600	
"	"	0.5	660	
"	"	0.5	690	
"	"	0.5	780	
"	"	0.5	870	
"	"	0.5	720	
"	"	0.5	720	
"	"	0.5	720	7.38×10^{-9}

$$a = 0.034 \text{ cm}^2.$$

$$A = 20.0 \text{ cm}^2.$$

$$h = 5.05 \text{ cm.}$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$w = 10.3 \%$$

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ROBERT COLLEGE GRADUATE SCHOOL
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TOPSER SARI

Modified - I

- # 16

Optimum

Cell Press. (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.9	360	
"	"	0.7	360	
"	"	0.45	360	
"	"	0.40	360	
"	"	0.45	360	
"	"	0.30	360	
"	"	0.40	360	
"	"	0.40	360	
"	"	0.40	360	
"	"	0.40	360	
"	"	0.40	360	
"	"	0.40	360	
"	"	0.40	360	11.55×10^{-9}

$$h = 5.1 \text{ cm.}$$

$$a = 0.034 \text{ cm}^2$$

$$A = 20.0$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$\omega = 12.4 \%$$

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
BEBEK, ISTANBUL

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KILYOS ESMER

Standard Proctor

- # 100

Optimum

Cell Press (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.3	360	
"	"	0.2	360	
"	"	0.15	360	
"	"	0.15	360	
"	"	1.0	3240	
"	"	0.3	1200	
"	"	0.2	720	
"	"	0.5	2040	2.398×10^{-9}

$$a = 0.034 \text{ cm}^2$$

$$h = 4.7 \text{ cm}$$

$$A = 20.0 \text{ cm}^2$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$w = 32.3 \%$$

THESIS

ROBERT COLLEGE GRADUATE SCHOOL
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KILYOS ESMER

Modified - I

-# 40

Dry

Cell Press. (kg/cm ²)	Average Pore Press. u_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.2	360	
"	"	0.15	360	
"	"	0.1	360	
"	"	0.1	360	
"	"	0.1	360	
"	"	0.1	360	
"	"	0.3	1080	
"	"	0.1	1260	
"	"	0.1	126	
"	"	0.1	1260	0.832×10^{-9}

$$a = 0.034 \text{ cm}^2$$

$$h = 5.05 \text{ cm}$$

$$A = 20.0 \text{ cm}^2$$

$$\omega = 24.6 \%$$

$$H = 65.2 \text{ cm at } u_{av} = 8.0$$

THESIS

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P. BAHÇE KIRMIZI

standard Proctor

-# 16

Dry

Cell Press. σ_3 (g/cm ²)	Average Pore Press U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	1.1	180	
"	"	1.2	180	
"	"	0.7	180	
"	"	0.4	180	
"	"	0.8	360	
"	"	0.7	360	
"	"	0.7	360	
"	"	0.7	360	
"	"	0.7	360	20.6×10^{-9}

$$h = 5.1 \text{ cm.}$$

$$a = 0.034 \text{ cm}^2.$$

$$A = 20 \text{ cm}^2.$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$w = 11.4 \%$$

THESIS

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TOPSER SARI

Modified - II

- # 100

Dry

Cell. Press. (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Height of Hg Column L (cm)	Time t (sec)	Permeability K (cm/sec)
10.0	8.0	0.9	360	
"	"	0.8	"	
"	"	0.7	"	
"	"	0.7	"	
"	"	0.65	"	
"	"	0.65	"	
"	"	0.6	"	
"	"	0.6	"	
"	"	0.6	"	
"	"	0.6	"	
"	"	2,4	1240	17.45×10^{-9}
"				

$$a = 0.034 \text{ cm}^2$$

$$h = 5.05 \text{ cm}$$

$$A = 20.0$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$w = 6.01 \%$$

THESIS

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KILYOS ESMER

Modified - II

- # 16

Wet

Cell. Press. (kg/cm ²)	Average Pore Press. U_{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.2	360	
"	"	0.4	720	
"	"	0.1	360	
"	"	0.3	840	
"	"	0.2	600	
"	"	0.35	1200	
"	"	0.35	1200	
"	"	0.35	1200	3.062×10^{-9}

$$a = 0.034 \text{ cm}^2$$

$$A = 20.0 \text{ cm}^2$$

$$h = 5.05 \text{ cm}$$

$$H = 65.2 \text{ cm at } U_{av} = 8.0$$

$$W =$$

T H E S I S

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P. BAHÇE MODIFIED I

-# 100

Wet

Cell Press. (kg/cm ²)	Average Pore Press. U _{av} (kg/cm ²)	Movement of Hg Column L (cm)	Time t (sec)	Permeability k (cm/sec)
10.0	8.0	0.90	360	
"	"	0.50	360	
"	"	0.45	360	
"	"	0.35	360	
"	"	0.30	360	
"	"	0.30	360	
"	"	0.30	360	
"	"	0.30	360	8.83 × 10 ⁻⁹

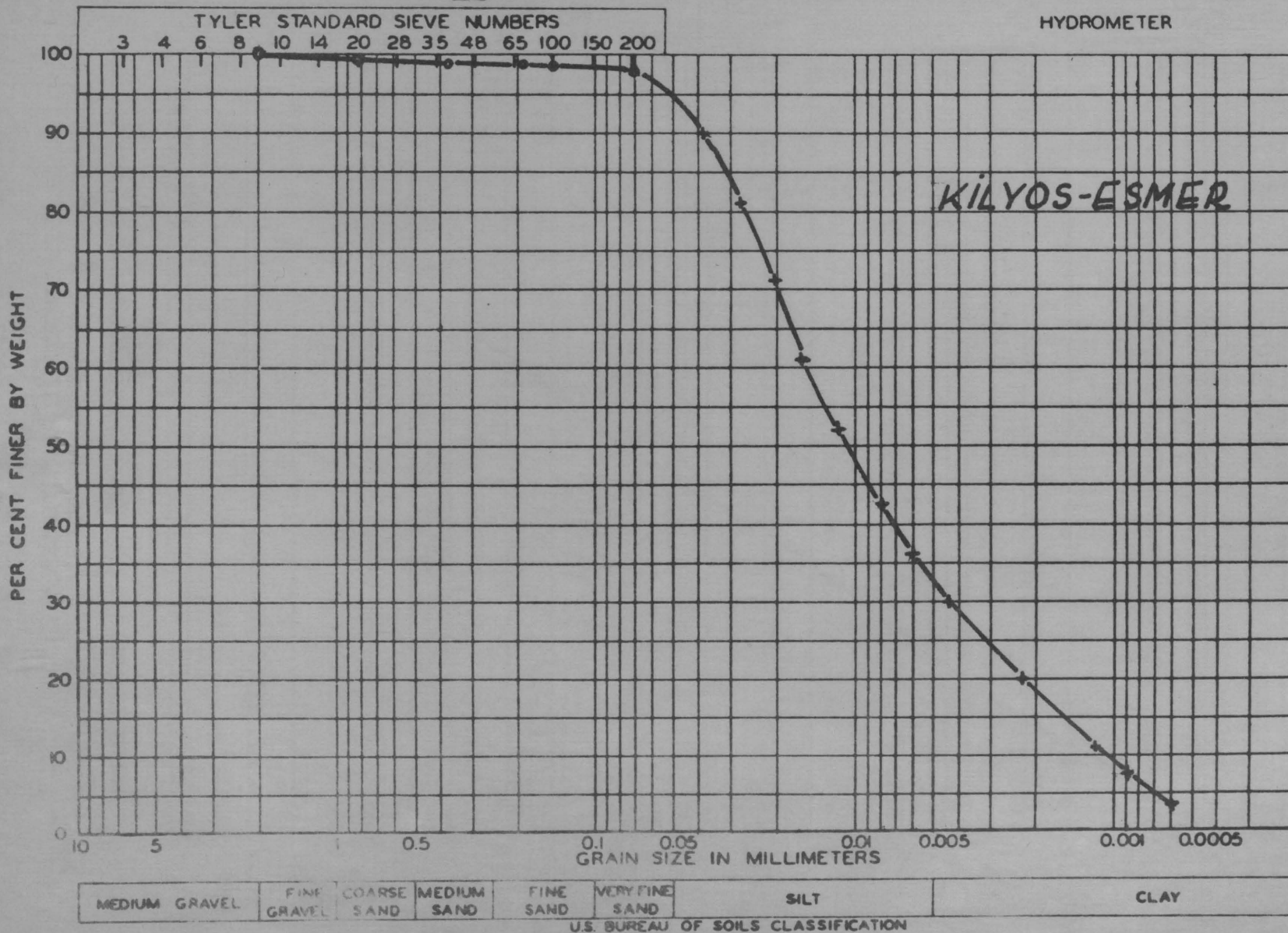
$h = 5.1 \text{ cm}$

$a = 0.034 \text{ cm}^2$

$A = 20 \text{ cm}^2$

$H = 65.2 \text{ cm}$ at $U_{av} = 8.0$

$w = 16.9 \%$



THESIS

ROBERT COLLEGE GRADUATE SCHOOL
 BEBEK, ISTANBUL

TOPSER-SARI

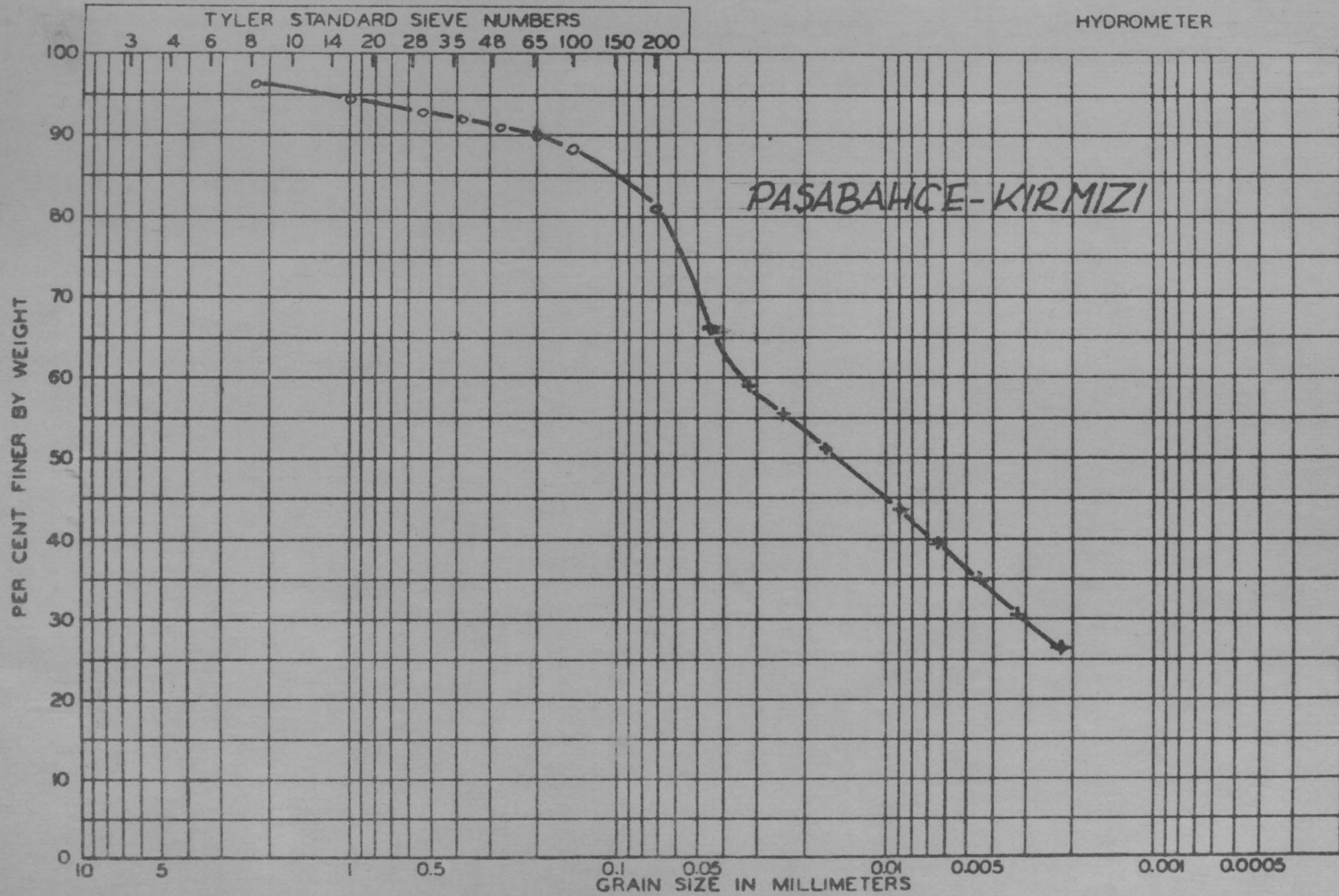


MEDIUM GRAVEL FINE GRAVEL COARSE SAND MEDIUM SAND FINE SAND VERY FINE SAND SILT CLAY

U.S. BUREAU OF SOILS CLASSIFICATION

HYDROMETER

TYLER STANDARD SIEVE NUMBERS
3 4 6 8 10 14 20 28 35 48 65 100 150 200



MEDIUM GRAVEL	FINE GRAVEL	COARSE SAND	MEDIUM SAND	FINE SAND	VERY FINE SAND	SILT	CLAY
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U.S. BUREAU OF SOILS CLASSIFICATION

THESIS

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