THE RELATION OF PORE SIZE DISTRIBUTION TO PERMEABILITY OF SOILS

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Arnold Klute

1948

This is to certify that the

thesis entitled

The Relation of Pore Size Distribution to Permeability of Soils

presented by

Arnold Klute

has been accepted towards fulfillment
of the requirements for

M.S. degree in Soil Science

Major professor

Date May 25, 1948

M-795

THE RELATION OF PORE SIZE DISTRIBUTION
TO PERMEABILITY OF SOILS

By

Arnold Klute

A THESIS

Submitted to the School of Graduate Studies of
Michigan State College of Agriculture and
Applied Science in partial fulfillment
of the requirements for the degree
of

MASTER OF SCIENCE

Department of Soil Science

1948

6/9/48
9-

ACKNOWLEDGEMENT

The writer expresses his appreciation to Dr. K. Lawton for his help and suggestions during the course of investigation.

TABLE OF CONTENTS

	page
Introduction	1
Review of Literature	1
Experimental Procedure	
Preparation of Samples	2
Pore Size Distribution Apparatus	3
Air Permeability Apparatus	6
Discussion and Results	6
Summary and Conclusions	15
Literature	16

INTRODUCTION

The relation of permeability of soils to their porosity and pore size distribution has been studied by various workers. The objective of most of these investigations has been a better understanding of the effect of the extent and nature of various sizes of soil pores upon permeability and subsequently to apply this knowledge in evaluating soil structure. In the work presented here the relationship of the pore size distribution of sand separates and soils to their permeability to air was studied.

REVIEW OF LITERATURE

According to Baver (2), Schubler and Schumaker were among the earliest workers to consider soil porosity and permeability. The concept of capillary and non-capillary porosity was introduced by Schumaker. His investigations included the study of air and water movement in soils and its relation to non-capillary porosity.

The fundamental equation for the flow of fluids through porous media was derived by Darcy (13) in 1856. Other equations relating the amount of water transmitted through a soil column to the porosity of the soil were developed by Slichter and Zunker (2). Slichter emphasized porosity as a factor to be considered in formulae for the flow of water through soils. Zunker's formula represents another attempt to modify Darcy's law in such a manner as to evaluate the significance of the amount and nature of the soil pore space. King (2), using Slichter's equation, attempted to determine the effective diameter of pores in the soil column by means of the rate of flow of air through the column. Kozeny (2) and Green and Ampt (8) also studied the flow of fluids through soils and developed equations for the fluid flow.

The exact relationship between soil porosity and soil permeability is not yet known. Numerous factors influence the permeability, including size, mode of packing, hydration and shape of the soil particles. Recent work by Baver (1) indicates that soil permeability is related to the shape of the pF - moisture curve. Donat (2) has used the tension - moisture curve to calculate the size distribution of pores. He considered the shape of the pores and used tensions up to 160 centimeters of water. Numerous workers (7, 12, 14, 17) have studied the relation between pore size distribution and permeability. Most workers have used water as the fluid for the determination of the permeability. A few (12, 9, 7) have used air for the fluid. In no case has the correlation between the permeability as expressed by a permeability constant, and the pore size distribution, as expressed by a porosity factor, been exact. Baver (1) obtained perhaps the best correlation in his work. He plotted the percolation rate against a porosity factor and obtained an exponential curve. The porosity factor was obtained by dividing the non-capillary porosity by the pF of the flex point of the tension - moisture curve.

EXPERIMENTAL PROCEDURE

A. Preparation Of Samples.

Artificial samples of various soils and separates were prepared. The pore size distribution of these samples was measured and their permeability to air determined.

Soil separates were prepared from Berrien loamy sand. Thesand fraction was treated with hydrogen peroxide to remove organic matter and then washed, dried and screened. The objective of using the various separates was to secure a variation in the pore size distribution of the samples. The attainment of an extremely uniform size separate was not important. Samples were also prepared from Brookston clay loam, Conover loam, Wisner loam, Miami loam, Arenac sand and Plainfield loamy sand. The soils were passed through a 2 millimeter screen and thoroughly mixed. Conover loam was dry sieved to obtain aggregates between two and four millimeters.

The air dry samples were placed in metal cylinders which were 7 centimeters in diameter and 5 centimeters high. A double layer of cheesecloth was stretched across one end of the cylinder and held in place with a heavy rubber band. A sheet of Whatman #1 filter paper, 7 centimeters in diameter, was placed on the cheesecloth. The separate or soil was poured into the cylinder and tamped by dropping the cylinder and its contents on the table twenty times from a height of eight to ten centimeters. The separate was leveled even with the top of the cylinder using a spatula.

The samples were then saturated with water by placing them in a layer of water 2-3 centimeters deep for twenty four hours. At the end of this time the level of the water was raised until it was nearly even with the top of the cylinder. Care was taken not to wet the top of the sample and to allow the sample to wet entirely from below.

B. Pore Size Distribution Apparatus.

For the determination of the pore size distribution of the samples an apparatus similar to that of Leamer and Shaw (11) was used. However, Plaster of Paris plates were used as a porous membrane instead of desk blotters. This method is based on the fact that a capillary tube will support a column of liquid whose height is a function of the radius of the capillary tube. The pore size corresponding to a given tension can be calculated. By subjecting a saturated soil sample to increasing increments of tension, the volume of pores between the size limits corresponding to the tensions used can be evaluated from the volume of water lost or from the loss in weight.

The apparatus which was used is shown in fig. 1. A porous plate, P, whose pores are all of smaller diameter than the range of pore sizes to be determined, is connected by a tubing, B, to a leveling bottle, C. The tubing and the pores of the plate are filled with water. A tension equivalent to the length of the water column, h, is exerted upon any water present on the porous plate at the level, h, above the water level in the bottle. A saturated sample placed upon the porous plate will then drain to such a moisture level that the tension of the soil moisture is at equilibrium with the tension exerted by the apparatus. An automatic siphon, S, serves to keep the level of the water in the bottle constant and a carboy of water arranged with a drip siphon supplies any loss of water from the system due to evaporation from the surface of the plates.

The porous plates were made in the following manner. A hole was cut in the bottom of an ordinary pie tin and a tube, A, soldered to the bottom of the tin. A wire screen with a filter paper over it was laid in the bottom of the tin and enough Plaster of Paris poured into the pan

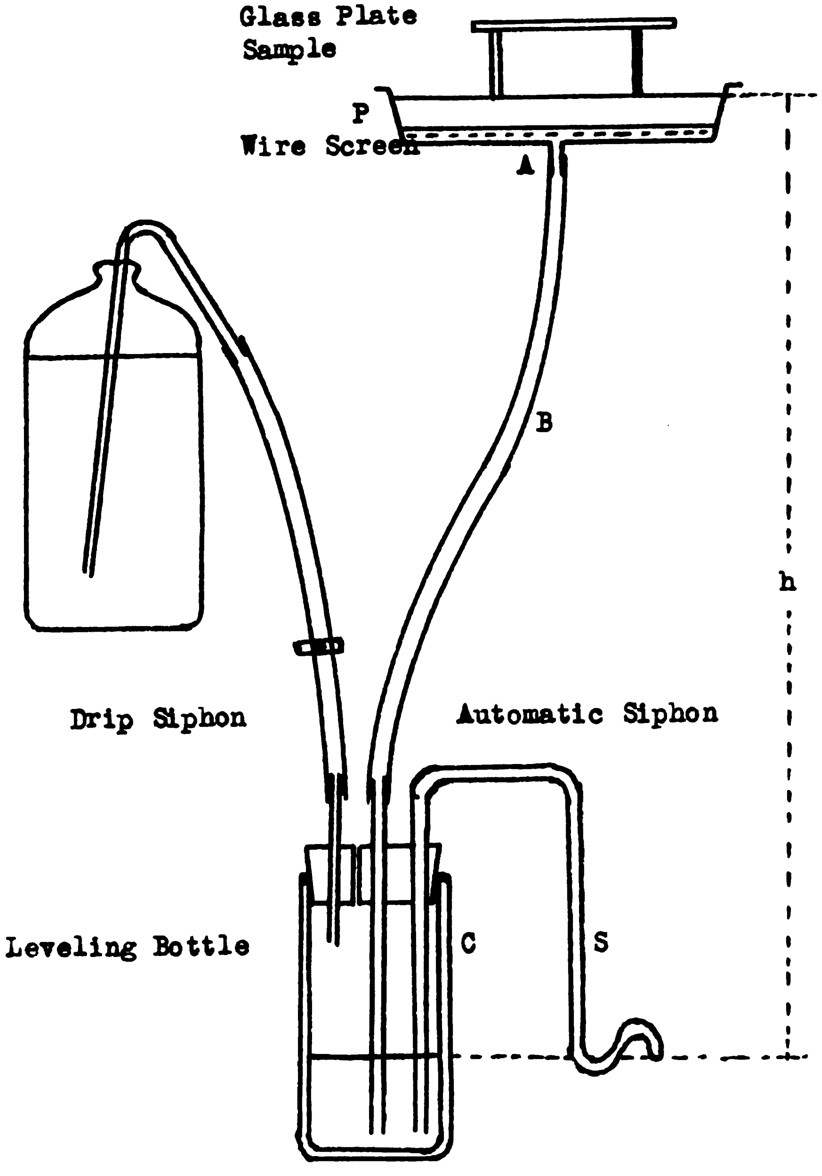


Fig. 1

Apparatus For The Detemmination Of

Pore Size Distribution

to make a plate two to three centimeters thick. In order to free the Plaster of Paris from air bubbles the plate was tapped for about a minute while the Plaster of Paris was still soft.

To set up the apparatus a plate was placed under water in a large dessicator and placed under reduced pressure for five to ten minutes. The tubing, B, which was previously filled with water was then connect- to the plate while it was still under water. It is important that all air bubbles be eliminated from the porous plate and associated tubing in order to obtain the desired tension.

Tensions corresponding to 10, 20, 40, 80, and 160 centimeters of water were used. Not all samples were run at each of these tensions. The saturated samples were weighed and placed on the porous plates at the lowest tension to be used. The sample was covered with a glass plate to prevent evaporation from the surface of the sample. After a twelve hour drainage period the sample was removed and weighed. The loss in weight corresponds to the volume of pores larger than the pore size equivalent to the tension used. The sample was replaced on the porous plate and the tension was increased to the next highest tension to be used. After a twelve hour drainage period the sample was weighed again. The loss in weight between the two tensionsused corresponds to the volume of pores of sizes between the limits equivalent to the two tensions used. The above process was repeated until the weight at the highest desired tension was obtained. Then the sample was placed in an oven at 110° C. and the oven dry weight was obtained. Since the volume of the sample was known, the percent non-capillary porosity at any one of the tensions used and the total porosity could be calculated.

In practice, a number of porous plates were connected together with tubing leading to a common leveling bottle. Four samples could be placed on each of the plates. As many as eight or ten plates were connected together allowing 32 to 40 samples to be worked on at one time. The reason for using several small plates connected together rather than one large plate of equivalent area was merely one of expediency. The smaller plates were easier to handle and if one of them leaked the connecting tube could be closed with a clamp and hence prevent the loss of the determinations on the other plates. Plaster of Paris plates were found to be more reliable at tensions above sixty centimeters of water than membranes made of desk blotters. A shorter drainage time could have been used, perhaps as short as several hours, but convenience determined the twelve hour drainage period.

C. Gas Permeability Apparatus.

An apparatus similar to that used by Kirkham (9) was employed for the determination of the permeability of the samples. The apparatus is shown in fig. 2. An air tank with a water manometer, a tire pump, a timer to read in tenths of a second, a holder for the soil sample and the necessary tubing comprise the equipment.

To use the apparatus the sample was clamped in place and the tank was pumped to a pressure y_0 as read by the water manometer. The pump was then clamped off and the air permitted to pass through the sample. As the tank pressure dropped, the time necessary for the manometer to drop from y_0 to another value, y, was recorded. The permeability was then calculated by equation (2) given below.

DISCUSSION AND RESULTS

The size distribution curve of soil pores has been calculated from the tension moisture curve by Donat (6), Childs (5), Lutz and

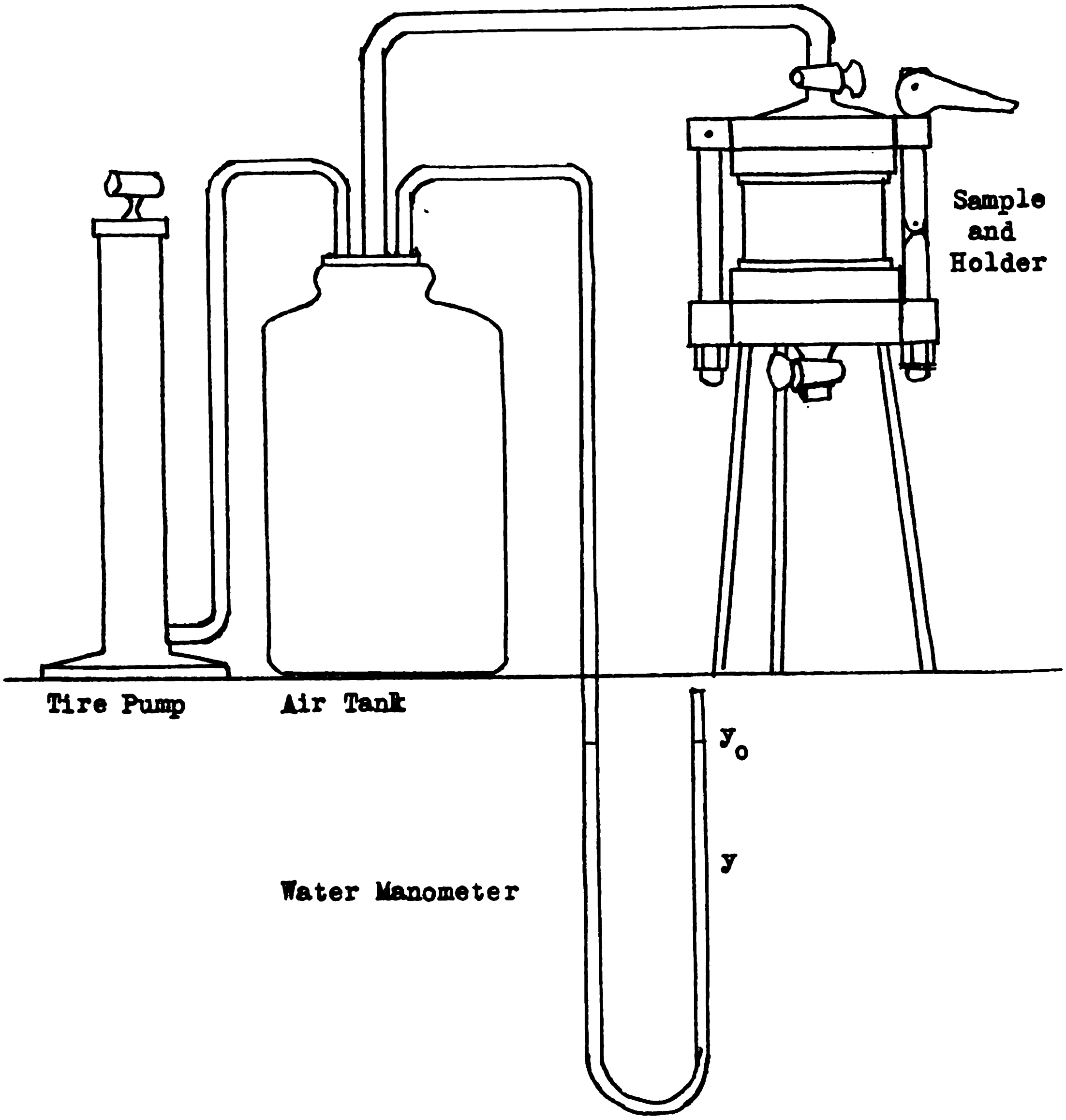


Fig. 2

Air Permeability Apparatus

Leamer (10), and others (15, 16, 17). The method is based on the relationship of the height of rise of water in a capillary tube to the radius of that tube. In a circular tube, where the liquid wets the tube, the height of rise, h, is given by:

$$h = \frac{2T}{dgr} \qquad (1)$$

where T is the surface tension in dynes per centimeter, d is the density of the liquid, r the radius in centimeters of the capillary, g the gravitational constant and h is given in centimeters. However, it is known that soil pores are not circular, nor are they of uniform diameter. Consequently, the above formula will give an equivalent diameter of a pore, just as Stoke's law gives an equivalent diameter of a particle in mechanical analysis. The varying cross section of the soil pores produces a hysteresis effect in the drainage and filling of the pores as has been pointed out by Haines (2). The volume of pores filled with water under a given tension depends upon whether the sample is being wetted or drained. In this work all the tension moisture curves were obtained by drainage, so that the pore size distribution obtained represents an equivalent pore size distribution by gravity drainage. As Russell (15) points out, pore size distribution curves obtained by this method actually represent the volume of portions of the void labyrinth through which air-water interfades are caused to retreat by unit increases in tension.

Typical tension-moisture curves are shown in fig. 3. These curves show that a large part of the moisture is removed from a .5 to 1.0 mm sand separate below a tension of 20 cms of water. The extend-

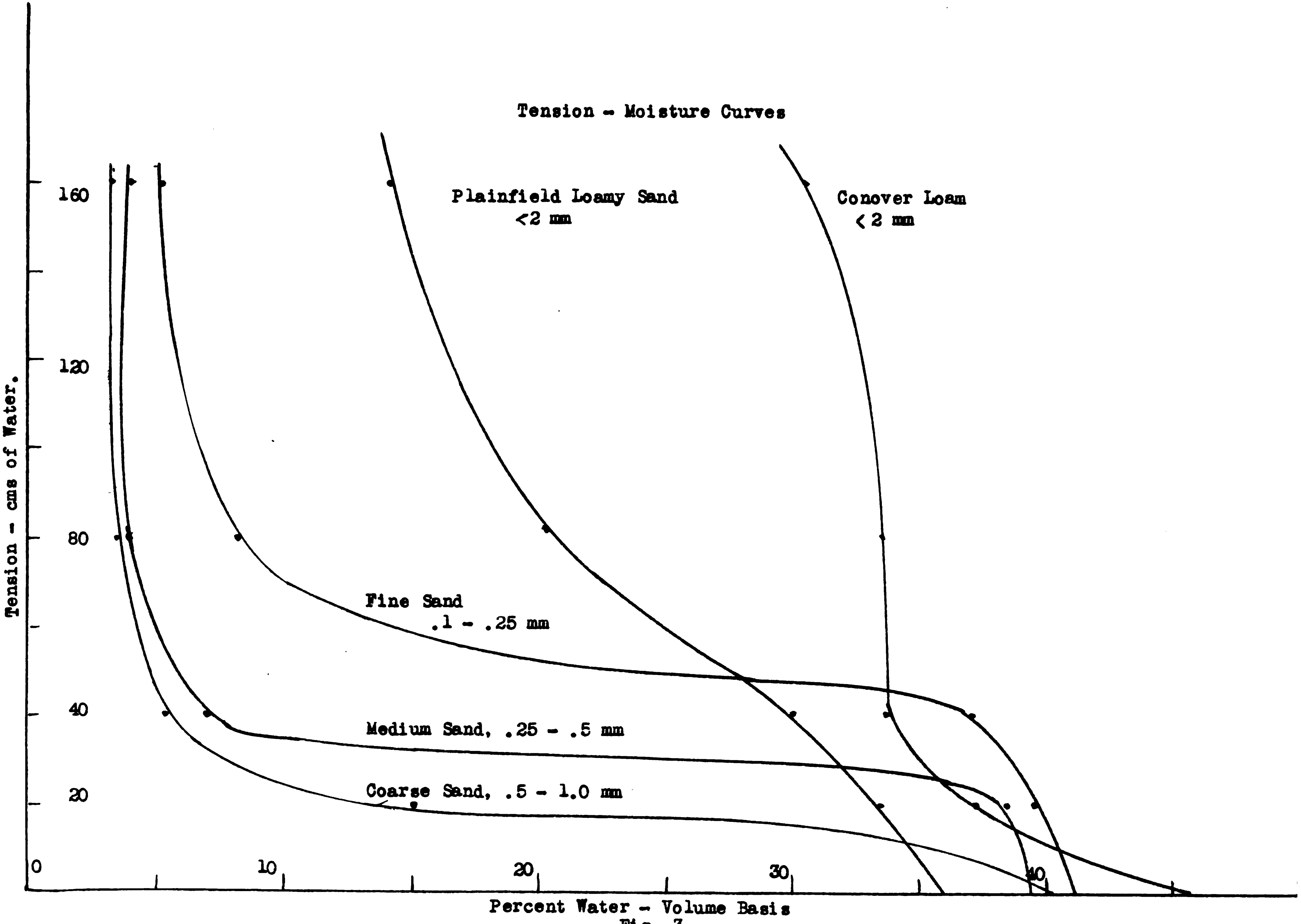

Tension - Moisture Curves
Plainfield Loamy Sand
<2 mm
Conover Loam
< 2 mm
Fine Sand
.1 - .25 mm
Medium Sand, .25 - .5 mm
Coarse Sand, .5 - 1.0 mm
Tension - cms of Water.
160
120
80
40
20
0
10
20
30
40
Percent Water - Volume Basis

Fig. 3

Pore Size Distribution Graphs

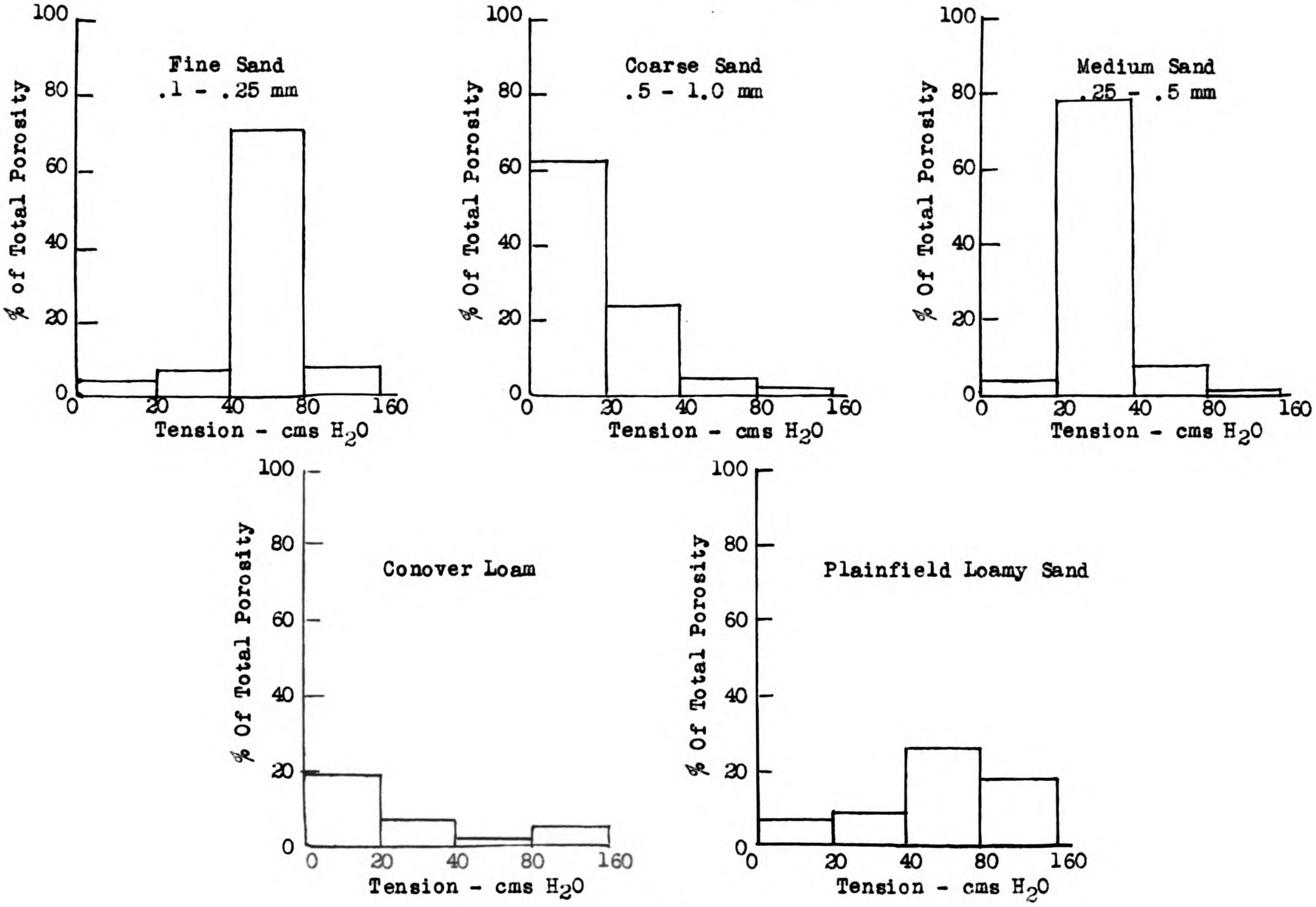


Fig. 4

ed flat portions of the curves show that the pores are nearly all of one size, i.e., most of the pores in such a sample are of a size to drain at or near 20 cms tension. The curve for the Plainfield loamy sand shows that the pore sizes are more uniformly distributed over the range measured, as evidenced by the more constant and steeper slope of the curve. The sample of Conover silt loam was quite well aggregated. The water held in the large pores between the aggregates drained at a low tension (less than 20 cms) as shown by the initial flat portion of the curve. The steeper portion of the curve shows the gradual removal of water from the finer pores of the sample at higher tensions. If the tension had been increased to a high enough value, the moisture content of the sample would be expected to decrease. This would require a rather high tension due to the heavy texture of the sample.

Pore size distribution curves may be obtained from the tension moisture curves. Childs (5) has shown that the volume of pores of a given radius, r, is proportional to the reciprocal of the slope of the desorption curve at a point where the tension equals h as given by equation (1). Alternatively, the volume of pores between any two tensions, h and $h + dh$, can be calculated from the volume of the water lost when the tension is increased by dh. By dividing the range of tension to be covered into sufficiently small increments and measuring the volume of water lost at each increase of tension, a pore size distribution curve can be plotted. Pore size distribution curves obtained by the latter method for the samples in fig. 3 are shown in fig. 4.

The permeability of the samples was calculated by means of a formula derived by Kirkham (9). It is:

$$k = \frac{2.30\ u\ L\ V}{A\ P_a} S \qquad (2)$$

where u is the viscosity of air in centipoise, L is the length in centimeters of the sample, V is the volume of the air tank in the apparatus in cubic centimeters, A is the cross section area of the sample in square centimeters, P_a is atmospheric pressure, and k is the permeability or permeability coefficient in darcys. The time in seconds required for the manometer of the apparatus to drop from y_0 to y divided into the ratio $\log_{10} y_0/y$ yields a value for S which is the slope of the plot of log y vs. time. Kirkham has shown that this curve is a straight line under proper experimental conditions so that only two readings of y and the corresponding times need be noted.

Air permeability measurements on soil samples will disturb the sample less than water permeability measurements especially if a low pressure differential is used. Translocation of the colloidal fraction by percolating water is avoided. Temperature, pressure and humidity are the main variables affecting the use of air as a fluid in the permeability determination, and these can either be controlled or corrections made for them. For these reasons the permeability measurements were made with air. Preliminary work, in which the permeability measurements were made on the air dry samples immediately after the samples were prepared, was not satisfactory. There was an extremely wide variation in the permeability values obtained. Thus, the practice of measuring the permeability of the samples after the pore size distribution data had been taken was followed. During the process of saturating and subsequent drainage under tension, the samples became more compact and permeability measurements made on the samples were not as variable. The permeability was measured after the samples were drained at a tension of 80 cms of water while they were still moist. A tension of 80 cms probably drains all or nearly all pores which are most effective in contributing to the permeability. On the other hand, the sample is still moist at this tension and the soil colloids are still considerably swelled. Thus, the permeability measured at this tension considers the effect of the swelling of soil colloids on permeability.

Values of the permeability constant obtained from similar samples varied considerably, often by a factor of two or three. The permeability of a sample to air can be greatly changed by the introduction of a very small wormhole, roothole, or other direct passage through the sample. A small change in the arrangement of the particles of the sample will produce a large change in the permeability. The permeability measurement is thus extremely sensitive to the condition of the sample. In the practical use of the permeability constant as a measure of a particular soil's permeability to air, it would seem best to run as many samples as possible and to avoid samples with obvious channels and root holes. While it is somewhat difficult to obtain an absolute value of the permeability with any degree of consistency, the permeability determination could be used in a comparative or relative manner. For example, the permeability of a soil known to the unsuitable for the growth of crops might be compared with the permeability of a soil of the same texture which was supporting the satisfactory growth of crops. In this technique a number of samples would have to be run and care would have to be exercised in the selection of the samples.

In contrast to the variability of the permeability measurements, the pore size distribution determinations were quite consistent for similar samples. It would seem that measurements of this type are fairly satisfactory for evaluating soil structure. In particular, the method used in this work seems suitable for use with a large number of samples. Nearly all the apparatus described in the literature for pore size distribution determinations is limited in capacity, i.e., only a single sample or at most a few samples can be run at one time. Because it is desirable to run as many samples as possible, this is a serious handicap. Therefore, considerable preliminary work was expended upon developing a suitable and reliable method for pore size distribution determinations. As pointed out previously, desk blotters were not satisfactory at tensions above 60 or 80 cms and were not reliable at tensions below this. A search was made for a material which could be used for the porous membrane which would be easy to work with and inexpensive. The Plaster of Paris porous plates each holding a few samples were found to be quite satisfactory. When one or only a few samples are to be run it probably would be better to use a method similar to that of Haines which has been modified by Russell (15). The advantage of this latter method lies in the fact that the sample need not be removed from the porous plate between each increase in tension and the volume of water drained from the sample can be read directly.

Data showing pore size distribution as expressed in a porosity factor, and the permeability are presented in tableII. One would expect a sample with a large proportion of large pores to be more permeable than a sample which had a large proportion of small pores. Such was found to be true. For example, a sample of .1 - .25 mm sand had a permeability of 4.09 darcys and a porosity factor of 10.4. A sample of .5 - 1.0 mm sand had a permeability of 22.9 darcys and a porosity factor of 28.4. The latter sample had a larger proportion of large pores as evidenced by its greater porosity factor.

The choice of a porosity factor involves considerable difficulty. Total porosity bears little relation to the permeability. This is shown by the data given in table I.

Table I

TOTAL POROSITY AND PERMEABILITY

Nature of Sample	Percent Total Porosity	Permeability Darcys
.1 - .25 mm sand	40.4	2.86
"	40.7	4.09
.25 - .5 mm sand	40.2	20.1
"	41.3	23.1
Plainfield loamy sand	38.2	9.00
Conover loam	48.0	9.20

The above data are typical of the variation obtained in the permeability factor with only a minute change in the percent total porosity.

Nelson and Baver (14) state that there is a better correlation between the non-capillary porosity at pF 1.6 (tension of 40 cms) and soil

Table II

PERMEABILITY AND POROSITY OF SOILS AND SAND SEPARATES

Porosity Factor*		Permeability
b	p	Darcys
	Fine Sand, .1 - .25 mm	
3.00	10.1	2.86
3.20	9.9	4.09
4.00	10.2	2.99
2.10	9.8	4.94
3.93	10.1	6.85
4.08	10.4	4.09
2.54	9.3	4.31
3.33	9.5	10.5
2.96	10.2	4.81
3.73	8.5	0.65
2.23	9.2	1.65
2.11	9.2	2.52
	Medium Sand, .25 - .5 mm	
32.7	17.9	16.3
32.8	18.0	20.1
32.5	17.6	12.6
34.0	19.1	23.1
33.0	18.0	13.6
34.1	18.3	11.8
32.6	17.3	16.9
32.8	17.7	30.4
33.9	18.6	23.2
29.0	15.2	26.3
34.0	17.0	2.33
33.1	17.5	1.09
	Coarse Sand, .5 - 1.0 mm	
29.9	26.4	39.7
33.8	28.4	22.9
32.9	30.7	16.6
34.8	33.6	5.75
34.2	32.2	27.2
35.3	34.7	19.2

---

* b - Percent non-capillary porosity at a tension of 40 cms H_2O.

p - Porosity factor as given by equation (4).

Table II (Cont.)

Porosity Factor b	p	Permeability Darcys
	Fine Gravel, 1.0 - 2.0 mm	
34.4	33.9	14.8
34.0	33.3	18.0
34.2	33.7	18.7
34.0	33.3	22.4
37.3	36.8	55.5
	Plainfield Loamy Sand	
8.40	8.50	3.87
7.30	8.10	1.55
6.10	7.40	1.51
11.2	10.0	4.58
8.60	8.90	4.31
6.73	7.10	1.37
11.8	10.7	1.86
	Conover Loam	
11.3	7.2	3.36
11.8	7.5	.98
9.1	8.5	4.27
14.8	13.9	5.66
12.2	11.3	3.79
10.8	9.6	2.43
8.08	7.5	2.92
17.6	16.5	10.1
13.4	12.8	2.67
13.8	12.7	.70
34.2	32.1	27.8
35.1	33.1	27.0
16.5	15.5	16.2
15.2	14.6	23.4
11.7	11.5	4.89
12.4	12.1	8.52
11.7	11.9	15.4
12.7	12.6	12.7
11.9	11.5	15.6
12.4	12.2	11.9
	Miami Loam	
10.8	10.0	2.75
10.3	9.6	4.08
15.5	13.3	11.8
15.7	13.6	5.11

Table II (Cont.)

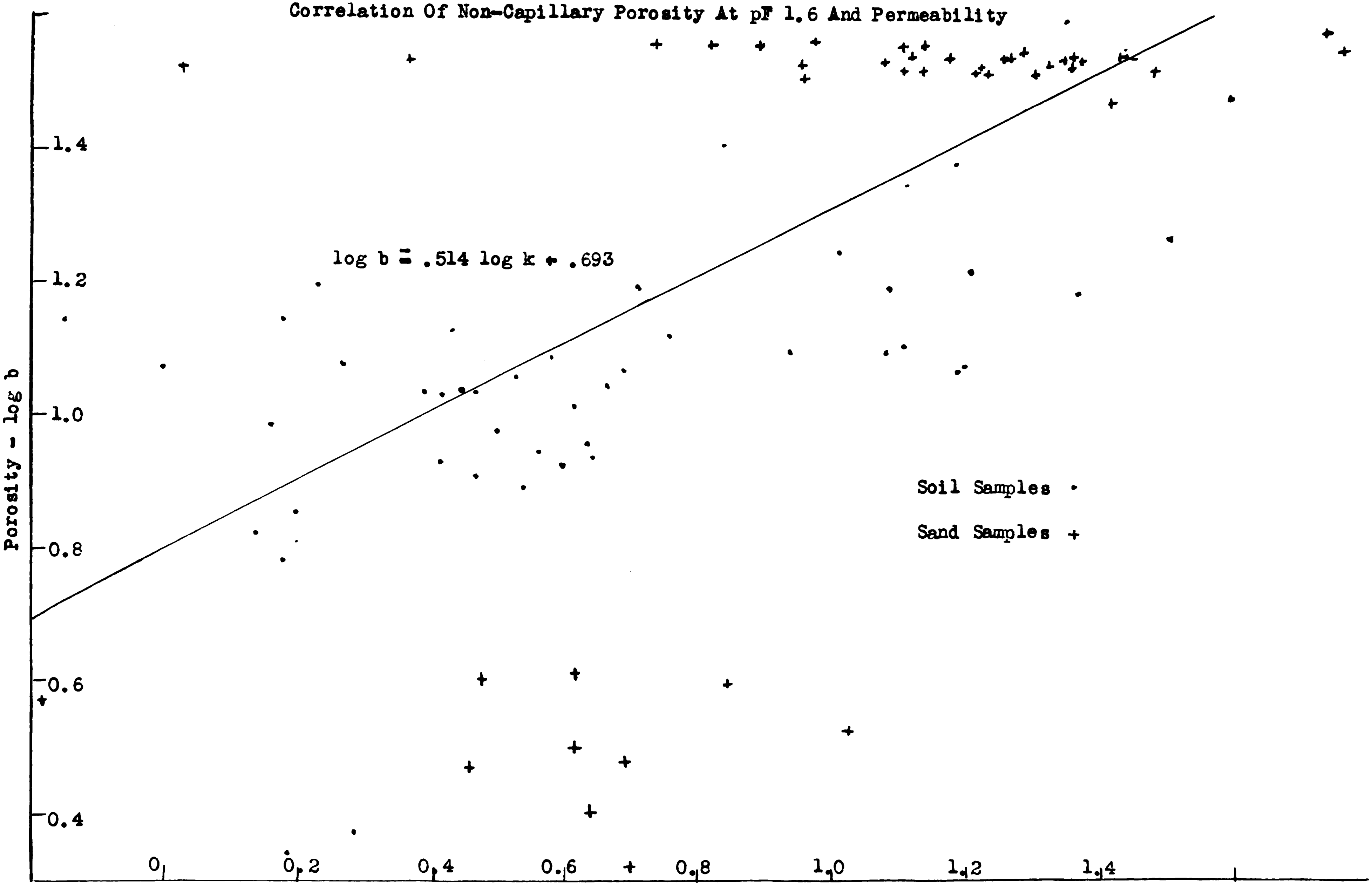
Porosity Factor b	p	Permeability Darcys
	Wisner Loam	
25.6	21.1	6.87
23.9	20.3	15.2
22.3	20.2	12.7
	Arenac Sand	
8.70	9.60	3.63
7.80	10.4	3.45

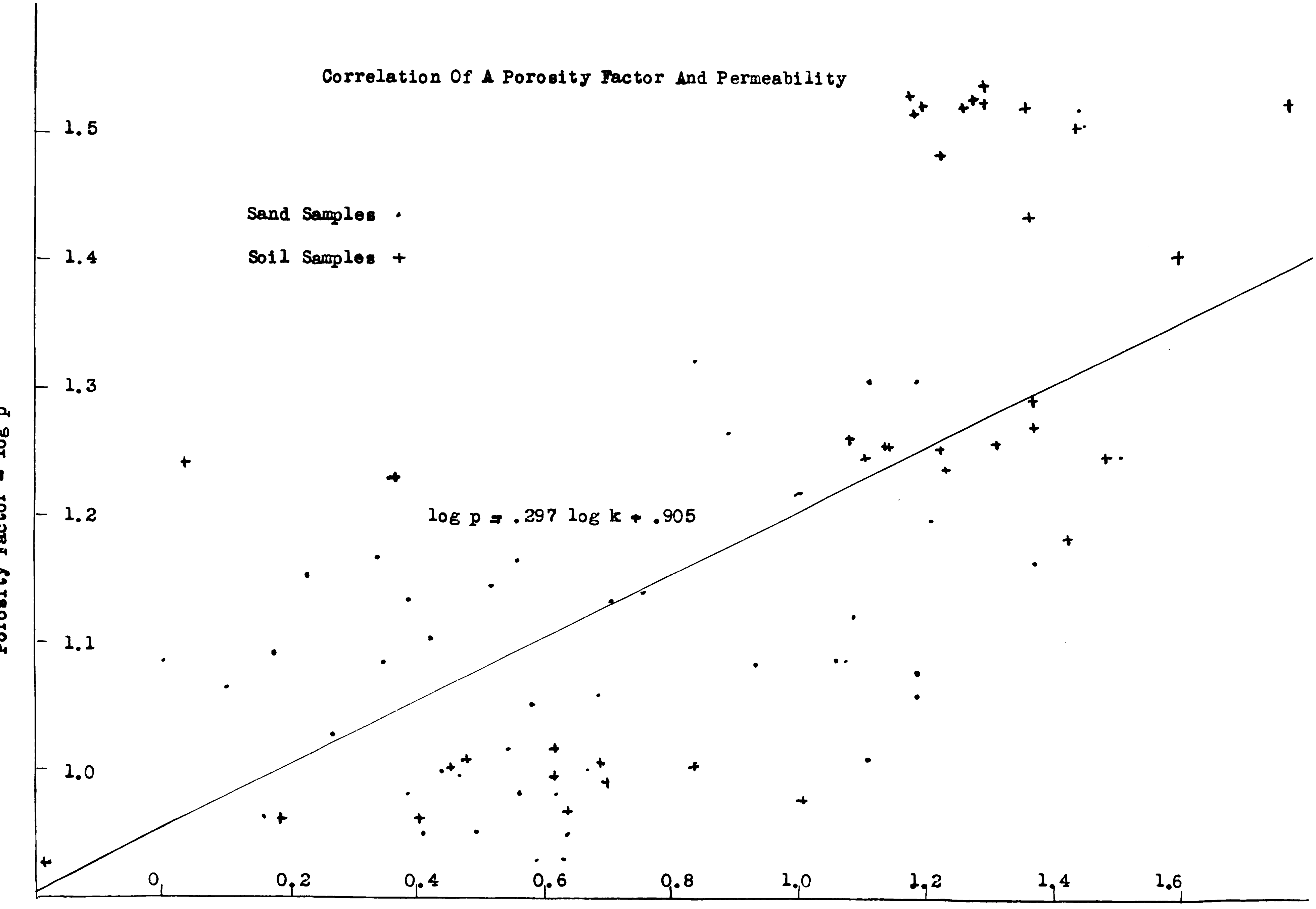
structure and permeability than at any other tension. They suggest that a single determination of the non-capillary porosity is sufficient to characterize a soil with regard to its structure and permeability. Accordingly, the percent non-capillary porosity was compared with the permeability. The results are presented in table II and the scatter diagram is given in fig. 5. The log of the values of the permeability and porosity were plotted in order to obtain a linear relationship. A linear correlation coefficient of .629 was obtained for the soil samples and .697 for the sand separates. The overall correlation coefficient of the two groups was .639. This value of the correlation coefficient is significantly different from zero, showing that there is considerable dependence of the permeability upon the percent non-capillary porosity at a tension of 40 cms. The sand separates samples fell into two groups, those drained at 40 cms constituting one group and those not drained at 40 cms another group. The permeability of each of these groups varied over quite a wide range. The variability of the permeability bactor at a given percent non-capillary porosity shows that permeability does not depend upon this porosity factor alone.

Smith, Browning and Pohlman (17) proposed a porosity factor of the following nature:

$$P = A + B/4 + C/10 \qquad (3)$$

where A is the percent porosity drained at 10 cms, B is the percent porosity drained between 10 and 40 cms and C is the percent porosity drained between 40 and 100 cms of tension. They also used the porosity factor proposed by Nelson and Baver described above and obtained fair results in correlating permeability with pore size distribut-





Correlation Of A Porosity Factor And Permeability

Fig. 6 Permeability - log k

ion. In the porosity factor presented above, the largest pores are given the greatest weight and the smaller pores less weight. The large pores are believed to be more effective in contributing to the permeability of the sample. In this work a porosity factor expressed by the following was used:

$$p = A + \frac{B}{2} + \frac{C}{4} + \frac{D}{10} \qquad (4)$$

where A is the percent porosity drained at 20 cms, B is the percent porosity drained between 20 and 40 cms, C is the percent porosity drained between 40 and 80 cms, and D is the perdent porosity drained between 80 and 160 cms of tension. The values of the porosity factor were compared with the permeability factor. The results are presented in table II and the scatter diagram is given in fig. 6. The correlation coefficient of the whole group of samples was .699. The sand separate samples gave a higher correlation coefficient of .736 and the soil samples a coefficient of .686. These values are significantly different from zero. It was thought that this type of porosity factor would give better correlation than the percent non-capillary porosity at 40 cms. On the basis of the data presented here, such was not the case. There is no significant difference between the correlation coefficients obtained for either porosity factor.

It seems likely that no porosity factor based on volume distribution of pore space alone will give perfect or nearly perfect correlation with permeability. There are other factors which influence permeability considerably which are not considered in a porosity factor of this type. One of the most important of these, when working with unconsolidated samples, is the arrangement of the particles. It is conceivable that samples with greatly different arrangements of particles would yield about the same results in a pore size distribution determination. The samples would have greatly varying permeability factors since the presence or absence of a comparatively small number of particles in such a position as to block the pore channels would influence the permeability a great deal.

SUMMARY AND CONCLUSIONS

1. The permeability to air and the pore size distribution of samples prepared from sand separates and soils were measured.

2. The technique of measuring pore size distribution using Plaster of Paris plates gave consistent results.

3. Permeability measurements made with an apparatus similar to that used by Kirkham (9) were quite variable. Measurements of this type are very sensitive to small modifications in the arrangement and mode of packing of the particles of the sample.

4. A comparison of the percent non-capillary porosity at 40 cms and permeability yielded a significant correlation.

5. A comparison of a porosity factor of the type proposed by Smith, Browning and Pohlman (17) and permeability also gave significant results.

6. There was no significant difference between the correlation coefficients obtained with either factor showing that one factor was as good as the other for evaluating the permeability.

LITERATURE

1. Baver, L. D., Soil permeability in relation to non-capillary porosity. Soil Sci. Soc. Am. Proc., 3:52-58, 1938.
2. Baver, L. D., Soil Physics, John Wiley & Sons, 1940.
3. Bendixen, G. L., and Slater, F. S., Effect of the time of drainage on the measurement of soil pore space and its relation to permeability. Soil Sci. Soc. Am. Proc., 11:35-39, 1946.
4. Buehrer, T. F., The movement of gases through a soil as a criterion of soil structure. Ariz. Agr. Expt. Sta. Tech. Bul. 39:39- , 1932.
5. Childs, E. C., The use of soil moisture characteristics in soil studies. Soil Sci., 50:239-252, 1940.
6. Donat, J., Das Gefuge des Bodens and dessen Kennzeichnung. Trans. Sixth Comm. Int. Soc. Soil Sci. B:423-439, 1937.
7. Free, G. R., and Palmer, V. J., Interrelationship of infiltration, air movement and pore size in graded silica sand. Soil Sci. Soc. Am. Proc., 5:399-417, 1940.
8. Green, H. and Ampt, G. W., The flow of water and air through soils. J. Agr. Sci. 4:1-24, 1911.
9. Kirkham, D., Field method for the determination of air permeability in its undisturbed state. Soil Sci. Soc. Am. Proc., 11:93-104, 1946.
10. Leamer, R. W. and Lutz, J. F., Determination of pore size distribution in soils. Soil Sci. 49:347-360, 1940.

11. Leamer, R. W. and Shaw, N., A simple apparatus for measuring non-capillary porosity. J. Am. Soc. Agron., 33:1003 - 1008, 1941.

12. Lutz, J. F. and Leamer, R. W., Pore size distribution as related to permeability. Soil Sci. Soc. Am. Proc., 4:28-43, 1939.

13. Muskat, M,, The Flow Of Homogeneous Fluids Through Porous Media. McGraw Hill Book Co., 1937.

14. Nelson, W. L. and Baver, L. D., Movement of water through soils in relation to the nature of the pores. Soil Sci. Soc. Am. Proc., 5:69-76, 1940.

15. Russell, M. B., Pore size distribution as a measure of soil structure. Soil Sci. Soc. Am. Proc. 6:108-112, 1942.

16. Schofield, R. K., Pore size distribution as revealed by the dependence of suction on moisture content. Trans. First Comm. Int. Soc. Soil Sci., A:38-44, 1938.

17. Smith, B. M., Browning, G. M., and Pohlman, E. R., Laboratory percolation through undisturbed soil samples in relation to pore size distribution. Soil Sci. 57:197-213, 1944.