LABORATORY TESTS ON PHYSICAL PROPERTIES OF WATER-BEARING MATERIALS

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INTRODUCTION

The need of more definite quantitative data in regard to the hydrologic properties of water-bearing materials has long been recognized by geologists and engineers engaged in investigations of ground water. With the increase in importance of quantitative field studies, has come a demand for definite and accurate methods of testing samples of water-bearing sands and rocks. Until recently the classic researches of Hazen,[1] King,[2] and Slichter[3] have been the chief basis of any quantitative estimates in this field in this country.

In 1923 an intensive investigation of the ground-water supplies in New Jersey was undertaken by David G. Thompson, of the United States Geological Survey, in cooperation with the New Jersey Department of Conservation and Development. The need for laboratory tests in connection with this investigation afforded the opportunity for establishing a small hydrologic laboratory in the Geological Survey. This paper describes briefly the apparatus and methods used in making tests of mechanical composition, porosity, moisture equivalent, and permeability, gives the data obtained from the first 97 samples that were tested, and discusses to some extent the interpretation and use of these data.

The samples for which results are given in this paper were obtained in 1923 by geologists who were making ground-water studies. The samples from New Jersey are all unconsolidated sand and gravel and range in age from Cretaceous to Recent. Those from Montana comprise unconsolidated sand, silt, and gravel and consolidated rocks,

[1] Hazen, Allen, Experiments upon the purification of sewage and water at the Lawrence Experiment Station, Mass.: Massachusetts State Board of Health Twenty-third Ann. Rept., pp. 425–434, 1891. Some physical properties of sands and gravels, with special reference to their use in filtration: Massachusetts State Board of Health Twenty-fourth Ann. Rept., pp. 541–556, 1892.

[2] King, F. H., Principles and conditions of the movements of ground water: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, pp. 59–294, 1899.

[3] Slichter, C. S., Field measurements of the rate of movement of underground water: U. S. Geol. Survey Water-Supply Paper 140, 1905.

chiefly sandstone and shale, ranging in age from Lower Cretaceous to Recent. The samples from Idaho are chiefly surface silt and loess that mantle certain reservoir sites.

The primary object of the laboratory tests is to obtain quantitative data on permeability and on specific yield as defined on page 144. The results of mechanical analysis and tests of porosity together give a nearly complete definition of the texture of unconsolidated materials, which chiefly controls both their permeability and specific yield. The porosity test supplies an essential factor in certain indirect methods of obtaining both permeability and specific yield. The moisture equivalent gives an approximation of the specific retention (p. 137) and hence of the specific yield. The permeability test gives a direct measurement of permeability to water. The four tests give at least fairly reliable comparative data on the water-bearing characteristics of the materials investigated, but much work is yet to be done before the results can be confidently applied in quantitative field problems.

ACKNOWLEDGMENTS

The hydrologic laboratory of the United States Geological Survey was started by O. E. Meinzer, geologist in charge of the division of ground water, and the laboratory work has been organized and carried on under his supervision. Mr. Meinzer devised the methods and apparatus for taking volumetric samples and for determining permeability as described in this report. Throughout the work his counsel and the results of his long experience in the study of ground-water problems were available. Acknowledgments are due to C. E. Van Orstrand and D. G. Thompson for advice and criticism; to A. F. Melcher and C. S. Howard for aid in the laboratory procedure; and to Prof. J. H. Griffith, of Iowa State College, and Dean C. S. Slichter, of the University of Wisconsin, for criticism of the manuscript.

METHODS OF TAKING SAMPLES

Samples of unconsolidated material are taken volumetrically if possible. The apparatus devised by Mr. Meinzer for taking volumetric samples consists of a sampler and a gage rod. (Fig. 18.) The sampler is a heavy brass cylinder, 3 inches in diameter and about 1 foot long, closed at one end and having a cutting edge at the other. The gage rod is a steel rod about 2 feet long, sharpened at the front end and having a definite reference mark near the rear end. In taking a sample with this apparatus a smooth surface is first made on the exposed face of the material to be sampled. Then the gage rod is driven far into the bank at right angles to the smoothed surface, and the cylinder is pushed or driven in parallel to the rod, generally not more than 6 inches. By means of the gage rod the distance that the cylinder is inserted and hence the volume of the sample are readily determined. The material around the cylinder is carefully excavated, and the sample is cut off flush with the front of the cylinder with a knife or trowel. The sample is then dumped into a tin can about 4 inches in diameter and 6 inches high. A strip of soft adhesive tape is wrapped around the junction of cover and can to prevent any loss of material. The cans are shipped to the laboratory in wooden cases that hold eight cans each. Under some conditions it is practicable to obtain volumetric samples from auger holes of known diameter, care being taken to save all the material within certain limits of depth and to keep out all other material. If the deposit to be sampled has a tendency to

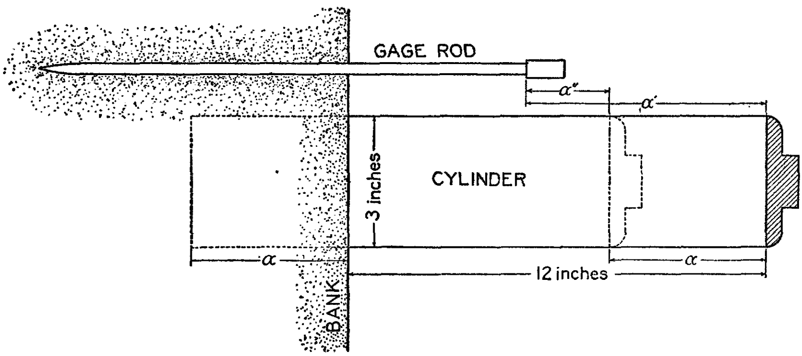


FIGURE 18.—Apparatus used for obtaining volumetric samples in the field. The length of the cylindrical sample is $a=a'-a''$. The diameter is 3 inches. Hence the volume, in cubic inches, is $\frac{9\pi a}{4}$ or $7.07a$

cave the auger method can obviously not be used; if it contains very coarse material, neither of these volumetric methods can be used. Volumetric samples can rarely be obtained from drilled wells.

APPARENT SPECIFIC GRAVITY

When a sample of unconsolidated material is received in the laboratory it is placed in a tray and left to dry in air from one to several days, according to the wetness of the sample, until it reaches a nearly constant weight. Small samples for the several tests are obtained by quartering. If the sample is lumpy, it is first put on a glass plate and rolled with a wooden rolling pin, care being taken not to crush the grains.

Throughout this paper the term "apparent specific gravity" is used to designate the weight per unit volume of the material tested, including the pore space, in distinction from the specific gravity of the mineral matter that composes the material. From the volume and weight the apparent specific gravity of the air-dry sample is obtained and recorded in grams per cubic centimeter. If the sample is unconsolidated and its volume was not determined in the field, a laboratory method is used to approximate the true volume. (See pp. 131–132.) The method of determining the volume and apparent specific gravity of consolidated samples is explained on page 132. In connection with the mechanical analysis (see below) the weight of an oven-dried sample is obtained and is used in computing the apparent specific gravity as given in the table on pages 164–169.

In general gravel and shale are heavier per unit volume than sand, and silt and loess are lighter. The materials from Rosebud County, Mont., have apparent specific gravities ranging from 1.33 to 2.50 and averaging 1.75. The gravel and the shales, which contain considerable clay, are heavy per unit volume; the sandstones of about average weight; and the alluvial silts, which contain a little clay, are light, ranging from only about 1.33 to 1.37. The materials from Fergus County, Mont., have apparent specific gravities ranging from 1.89 to 2.09. The shales and sandstones that include considerable clay and silt have apparent specific gravities of 2.06, 2.07, and 2.09; the sandstones that are massive and fairly tight, 1.93, 1.96, and 1.98; and the gravel 1.89. The Idaho samples, which are all soils, have apparent specific gravities ranging from only 0.80 to 1.52. The loess sample has the lowest of the group. Silty loess soils that look light and fluffy have an apparent specific gravity of 1.01; a loam soil, 1.27; and a fine red uniform clay, 1.52. The New Jersey samples, which consist largely of assorted sands, have apparent specific gravities that average about 1.50. The gravels, however, range from 1.68 to 1.81, and a few silts are relatively light and fluffy and have apparent specific gravities of only 1.01 to 1.15.

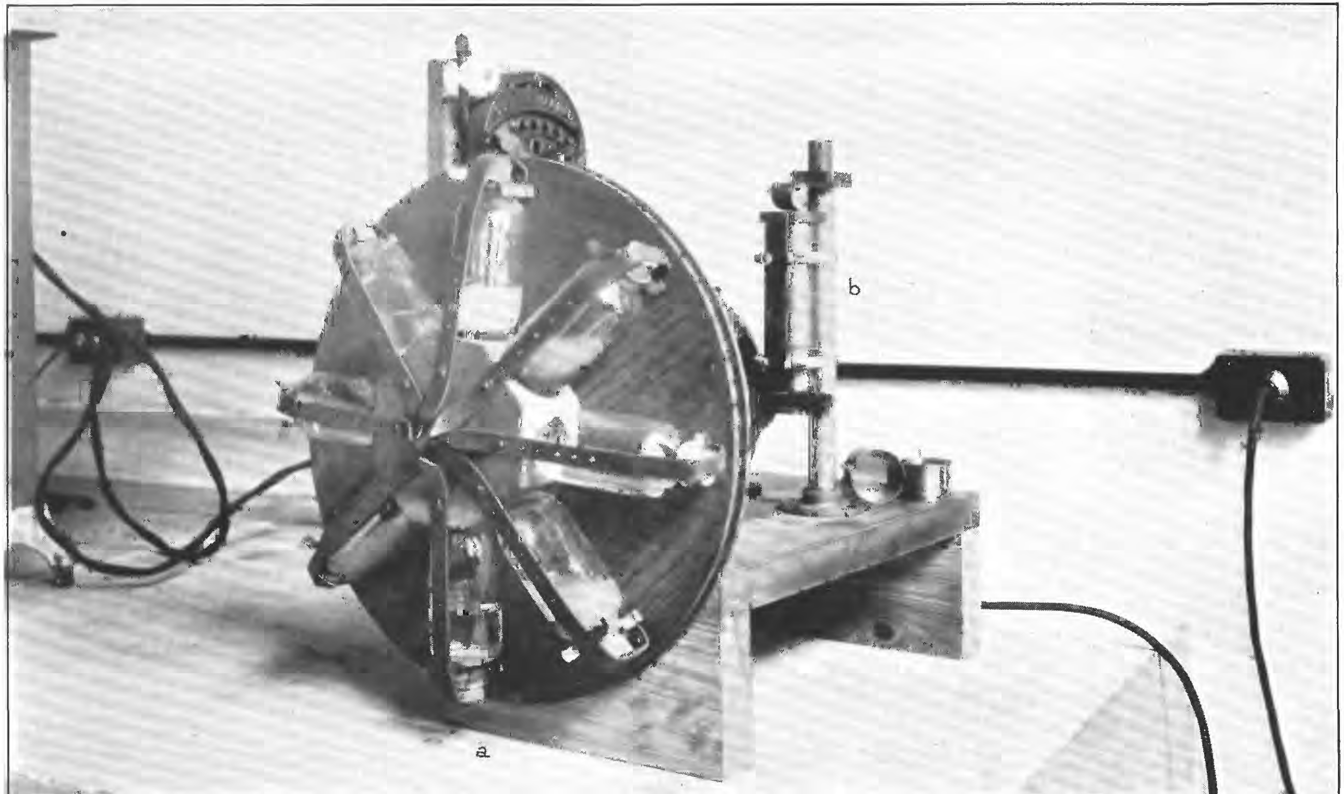
MECHANICAL ANALYSIS

METHOD OF ANALYSIS

The mechanical analysis consists of sorting the particles of a sample by sizes. The procedure followed is in general that of the United States Bureau of Soils,[4] because it is applicable to water-bearing materials, and its use makes all the mechanical analyses of the Bureau of Soils available for comparison. As much water-bearing material is coarser than the common soils, however, it is desirable to have a few sieves with larger openings than 2 millimeters.

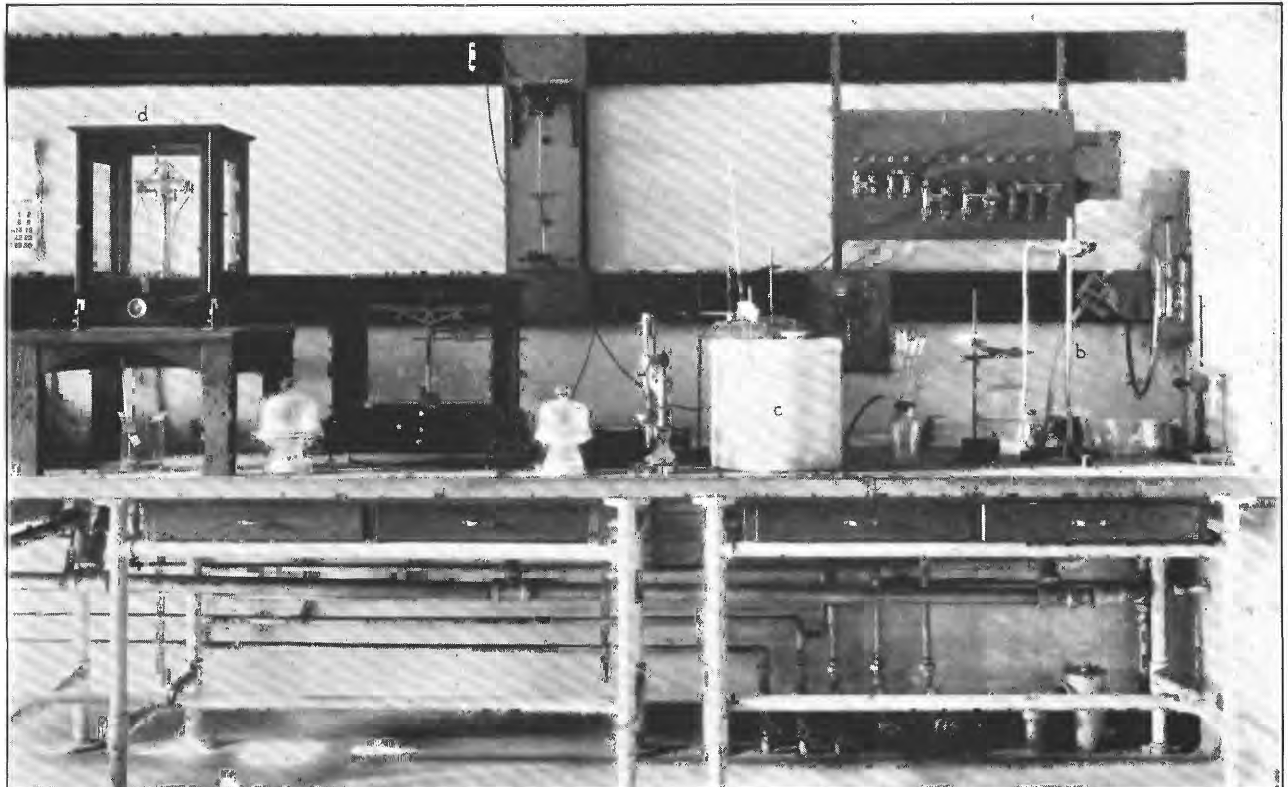
About 5 grams of the air-dry sample is put into a small dish and weighed and is then dried in an electric oven at about 110° C. for at

[4] Fletcher, C. C., and Bryan, H., Modification of the method of mechanical soil analysis: U. S. Dept. Agr. Bur. Soils Bull. 84, 1912.



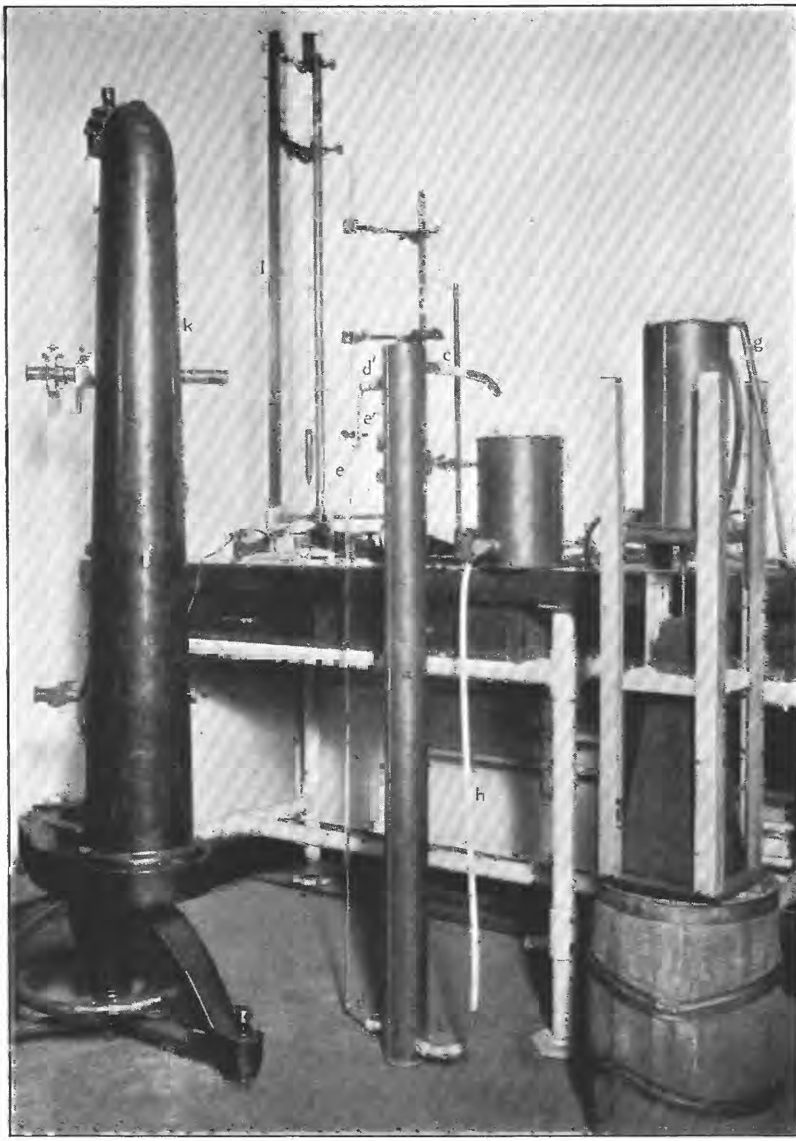
SHAKERS USED IN MAKING MECHANICAL ANALYSIS

a, Shaker for bottles containing sample with water and ammonia to deflocculate the particles; b, shaker for sieves used to separate the sand by sizes



APPARATUS USED IN DETERMINING POROSITY BY THE PYCNOMETER METHOD

a, Pycnometers; b, aspirator used to fill pycnometers under vacuum; c, constant-temperature bath; d, balance used for weighing paraffined sample in water



PERMEABILITY APPARATUS, INCLUDING THE LONG CYLINDER USED IN THE EXPERIMENT WITH SAND FROM FORT CASWELL, N. C.

a, Percolation cylinder; b, inflow opening; c, discharge opening; d, d', pressure-gage openings; e, e', pressure gages; f, supply tank; g, inflow to supply tank; h, tube leading from supply tank to percolation cylinder; i, screw jack; k, cathetometer with telescope; l, meter rod

least two hours. It is then cooled in a desiccator and again weighed. The sample is then put into an 8-ounce sterilizer bottle with 4 ounces of water and about 5 cubic centimeters of ammonia, one-third strength, to deflocculate the particles. It is said that 5 drops of ammonia has been shown to be sufficient. However, in the process of analysis the soil is washed again and again, and each time the amount of ammonia left in the bottle is reduced. Hence it has been found advisable to put in several cubic centimeters at first, and thus enough is successively left to keep the particles deflocculated until all the silt and clay is washed from the sand.

The bottles containing the soil, water, and ammonia are put on the shaking machine (pl. 11, *A*) and shaken for at least seven hours. More time usually does no harm to the soil, but if left too long the rubber stoppers may be eroded to an appreciable extent.

Eight samples are usually tested at one time.

The bottles containing the samples are removed from the shaking machine and placed upright in a rack. The rubber stoppers are removed and examined for erosion. If the stoppers are badly eroded it may be necessary to repeat the analysis, as the eroded rubber may cause considerable error in the result. Any material adhering to the stopper is washed back into the bottle with the jet from a wash bottle. Each of the eight samples is in turn brought into suspension by the use of the compressed water jet, and then sufficient time is allowed for all the sand to settle. This time is determined by inspection and can be checked by an examination under the microscope. Usually, if the contents of the eight bottles are stirred up in order, by the time the last bottle is reached the first is ready to decant.

The liquid in each of the bottles is decanted into a separate dish. The residue is again washed and the liquid is again decanted, and this process is repeated until the liquid is clear. The sands remaining in the bottles are washed into porcelain dishes and dried on the steam bath. They are then transferred to small dishes and dried in the electric oven at about 110° C. After being cooled in a desiccator they are weighed, then allowed to take moisture from the atmosphere, and again weighed. The sands are then ready for sieving.

The decanted liquids are placed in centrifuge tubes, and the centrifuge is run until there are no silt particles left in suspension. This is determined by inspection and by use of the microscope. The liquid, which is the clay suspension, is decanted. The silt at the bottom of the tubes is brought into suspension by the water jet. After centrifuging again another examination is made to determine the absence of silt particles in suspension and the liquid is decanted as before. This procedure is continued until the separation is virtually complete. As a rule, in the earlier processes of separation the larger particles are held up by smaller ones, and, consequently, as the separation nears completion it is possible to reduce the time of centrifuging.

The length of time for centrifuging will differ with the soil and with the speed of the centrifuge. Thus clayey samples are almost invariably more difficult to separate than sandy samples.. They require a longer period of centrifuging and must be centrifuged more times before the separation is complete. The centrifuge used is run at a speed of 500 revolutions a minute, the time run ranges from 5 minutes or less to about 10 minutes, and the number of times from about 5 to 15 or more.

The silts in the bottom of the tubes are washed into dishes and dried on a steam bath. They are then transferred to small dishes and dried in an electric oven at about 110° C., cooled in a desiccator, and weighed.

The clay content may be determined directly by drying and weighing or by difference. In the first method the clay water is evaporated and the residue weighed. Because of the large amount of clayey water to be reduced by evaporation and hence the large container that is required, a heavy balance must be used in weighing, with corresponding loss in accuracy, or else the dry clay must be transferred to a smaller dish. A transfer of the dried clay, however, requires much time and involves great possibilities of loss of material. In the second method the total initial weight minus the weight of the sand and silt gives the weight of the clay. The error thus introduced is believed to be no greater than that involved in the separation of the clay and silt, and all errors due to loss by transfer and change in the state of hydration of the clay are eliminated.

There is usually little or no organic matter in the water-bearing materials, and hence organic matter is disregarded in the mechanical analysis made in the hydrologic laboratory. If the sample contains material that is much larger than 2 millimeters, a larger sample is taken and is put through the coarser sieves in the air-dry condition. The 5-gram sample is then taken from the material that passed through the 2-millimeter sieve.

The air-dry sand is placed in the top of a nest of sieves 2 inches in diameter and the sieves are agitated on a shaker (pl. 11, *B*) for about three minutes. The portions of sand remaining on each of the sieves and that which went through all the sieves to the bottom pan are weighed. Two of the sieves consist of brass plates with perforations about 1 and 0.5 millimeter in diameter. The other two are made of bolting cloth, the meshes of which give openings of about 0.25 and 0.1 millimeter. If the sample is very coarse sieves with perforations 2 and 5 millimeters in diameter are also used. The silt particles are regarded as 0.05 to 0.005 millimeter in diameter and the clay as less than 0.005 millimeter. Thus the separations ordinarily made are as follows, expressed in millimeters:

Gravel, greater than 5.
Gravel, 5 to 2.
Fine gravel, 2 to 1.
Coarse sand, 1 to 0.5.
Medium sand, 0.5 to 0.25.
Fine sand, 0.25 to 0.1.
Very fine sand, 0.1 to 0.05.
Silt, 0.05 to 0.005.
Clay, less than 0.005.

A calibration by the United States Bureau of Standards of the sieves used indicates that the exact sizes of the openings are slightly different from the sizes stated above. The 0.5 is 0.59, the 0.25 is 0.26, the 0.1 is 0.09. These exact sizes are used in the graphs and table. A summary of the classifications of materials according to size of grain used in different countries is given in a brief paper by Von Greyerz.[5]

METHODS OF EXPRESSING RESULTS

The weights of the materials of the several sizes are computed into percentages of the total weight. These percentages are given in the table on pages 164–169. They show that whereas some of the water-bearing materials investigated are more nearly uniform than others, each comprises several sizes. Some have large percentages of one or two sizes and small percentages of others; some have small percentages of all the sizes. The materials are, in general, coarser and more heterogeneous than the soils analyzed by the Bureau of Soils and not so well assorted as the sands used for filters. In Figures 19 and 20 are shown two methods of representing the mechanical composition graphically. As the terms are ordinarily used, No. 60 shows a clay, No. 47 a silt, No. 33 a fine sand, No. 72 a medium sand, No. 73 a coarse sand, and No. 65 a gravel.

The effective size of grain of a soil or rock is defined as the diameter of the grains in an assumed material that has the same transmission constant, or permeability, as the soil or rock under consideration and is composed of spherical grains of equal size arranged in a specified manner as indicated by the porosity. This is the general definition given by Meinzer[6] and is substantially the meaning of the term as used by Slichter (p. 171). In correspondence Slichter has explained that in his use of the term the assumed soil or rock has the same porosity as the actual sample, except in materials to which this definition can not be applied. He states: "This definition can not be applied to a sandstone or to a mass of crystalline or angular particles. For such material I define effective size, but at stated porosity,

[5] Von Greyerz, Walo (captain, Royal Swedish Engineers), Nomenklatur för lösa jordarter; Teknisk Tidskrift, Häft 52, 1925.
[6] Meinzer, O. E., Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water-Supply Paper 494, p. 45, 1923.

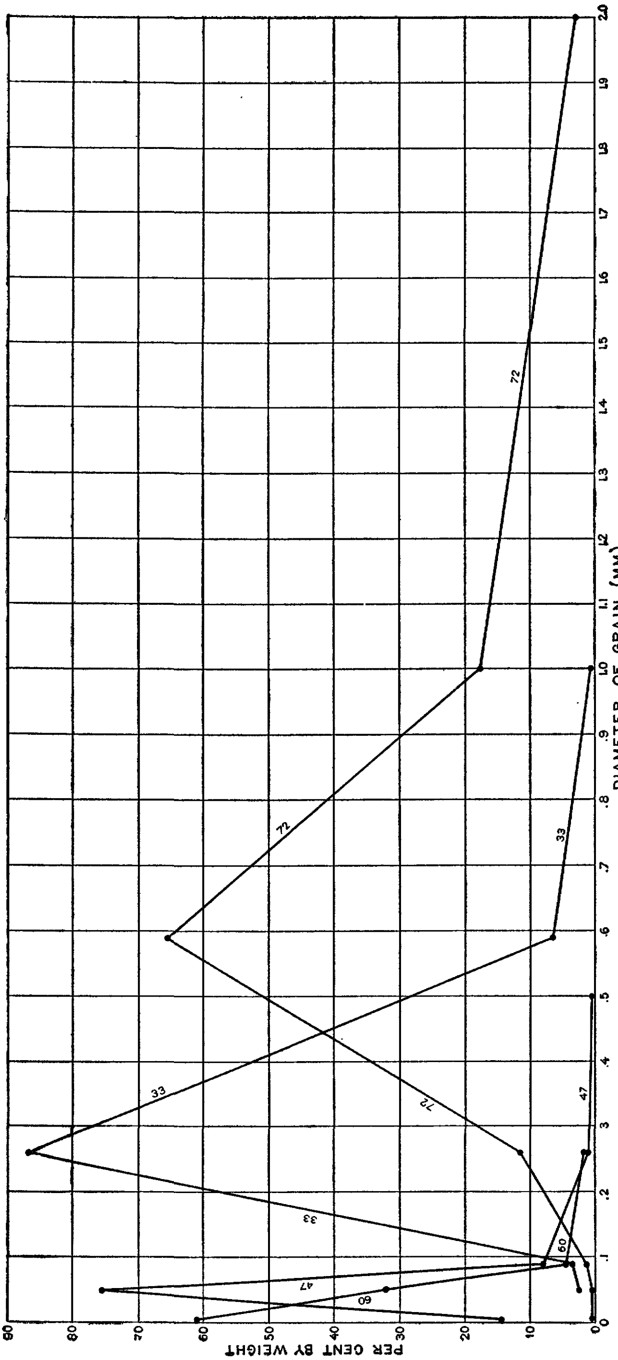


FIGURE 19.—Diagram showing distribution curves of mechanical composition of typical materials. The numbers are those used to designate the samples in the table and text

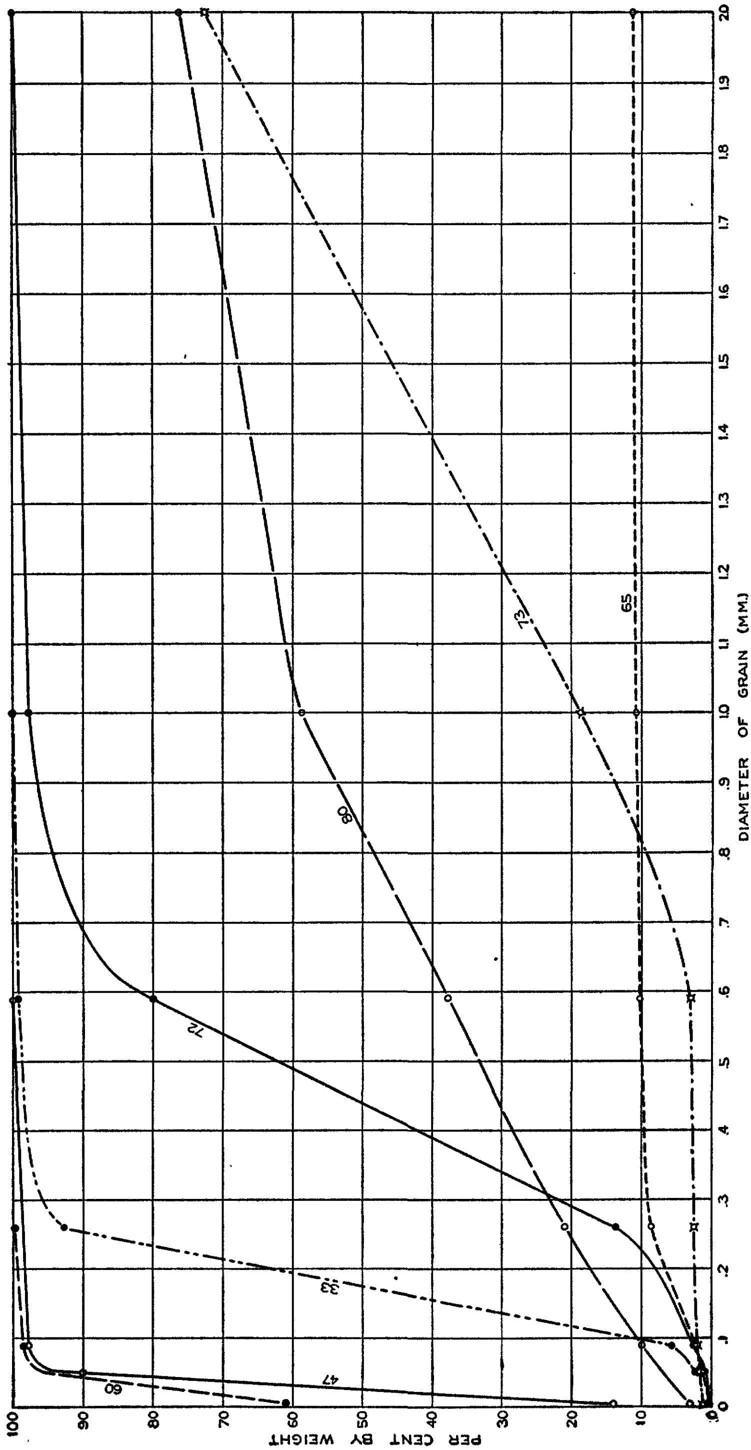


FIGURE 20.—Diagram showing accumulative curves of mechanical composition of typical materials. The numbers are those used to designate the samples in the table and text

26 per cent. The definition needs must be very artificial, as sandstone of 15 per cent porosity can not be replaced by a uniform sand of that porosity." King, however, used the term "effective size" with the meaning of size of grain having average surface (p. 171), and Hazen used it in the sense of the size of grain that is larger than 10 per cent of the material and smaller than 90 per cent of the material (p. 170). The 10 per cent sizes of the samples tested, as obtained from accumulative curves of the mechanical analyses, are given in the table on pages 164–169.

The uniformity coefficient was used by Hazen [7] to compare granular materials with respect to their degree of assortment. It is an expression of the variety of the sizes of the grains that constitute the material. As the term has been used, it is defined as the quotient of the diameter of the grain that is just too large to pass through a sieve that allows 60 per cent of the material by weight to pass through, divided by the diameter of a grain that is just too large to pass through a sieve that allows 10 per cent to pass through. The 60 per cent size, as well as the 10 per cent size, can be taken from the accumulative curves of the mechanical analyses. The more nearly uniform the grains of a material the steeper will be the curve and the smaller will be the uniformity coefficient. The uniformity coefficient of a material whose grains are all of the same size is 1.

The computed uniformity coefficients of the samples tested are given in the table on pages 164–169. This coefficient is obviously only a rough expression of the degree of uniformity of a material, and in some samples it is rather misleading. Thus in sample 19 the 60 per cent line cuts the 0.155 millimeter size, and the 10 per cent line cuts the 0.005 millimeter size, giving a uniformity coefficient of 31. Nevertheless, the material is relatively uniform, as is shown by the fact that 63 per cent is between 0.10 and 0.25 millimeter and 15 per cent between 0.05 and 0.10 millimeter, which gives 78 per cent of the size about 0.10 millimeter. In contrast, the coefficient of uniformity of No. 80, a typically heterogeneous material, is only 12, the 10 per cent line being at 0.09 millimeter and the 60 per cent line at 1.07.

Van Orstrand [8] has suggested a method by which three essential quantities computed from a mechanical analysis define the material in a comparative scale. The computation of these quantities involves higher mathematics and is laborious, but on the basis of his work it may be possible to devise a more simple formula which will give approximate results and can be more widely used. Such quantities

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[7] Hazen, Allen, Experiments upon the purification of sewage and water at the Lawrence Experiment Station, Nov. 1, 1889, to Dec. 31, 1891: Massachusetts State Board of Health, Twenty-third Ann. Rept., p. 431, 1892. See also Meinzer, O. E., op. cit., p. 45.

[8] Van Orstrand, C. E., On the empirical representation of certain production curves: Washington Acad. Sci. Jour., vol. 15, pp. 19–39, 1925.

would express briefly the important features now shown in a mechanical analysis. Attempts have also been made to express the mechanical analyses by means of a "fineness modulus" or a "surface modulus."[9]

POROSITY

GENERAL METHOD

The porosity of a sample is the percentage of pore space in the total volume of the sample—that is, the space not occupied by solid mineral matter. This percentage expresses practically the volume that can be occupied by water. The method used in the hydrologic laboratory for determining the porosity is that used by Melcher,[10] with modifications for unconsolidated and coarse materials. There are two parts to the test—one to obtain the volume of the sample and the other to obtain the aggregate volume of the grains. The total volume of the sample minus the aggregate volume of the grains gives the volume of the pore space. The porosity is computed by the formula $P=100\,\frac{V-v}{V}$, in which P is the porosity in percentage, V is the volume of the sample, and v is the aggregate volume of the grains.

METHOD OF DETERMINING THE VOLUME OF THE SAMPLE

If the sample is unconsolidated and its volume was determined in the field, the volume of the small sample used for the porosity test is computed from its air-dry weight as compared with the air-dry weight of the entire sample.

If the sample is unconsolidated and its volume was not determined in the field (see pp. 123–124), some of the air-dry material of the sample is put into a beaker or small-mouthed bottle of known capacity and weight and is jarred and tamped to make it as compact as possible. After a certain amount of compacting any further jarring and tamping does not appreciably decrease the volume. The vessel filled with the material is then weighed, and the apparent specific gravity of the air-dry material is computed in grams per cubic centimeter.

The compacting in the laboratory may be either greater or less than that in nature. The compacting of fine, well-assorted materials is likely to be greater. For instance, a very tight packing in the laboratory of sample 78, a light fluffy loess, gave an apparent specific

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[9] Tyler, R. G., A fineness modulus for filter sands: New England Waterworks Ass. Jour., vol. 39, pp. 239–253, 1925; vol. 40, pp. 24–28, 1926. See also reference to the work of A. N. Talbot, on page 253 of Tyler's paper.

[10] Melcher, A. F., Determination of pore space of oil and gas sands: Mining and Metallurgy, No. 160, sec. 5, April, 1920.

gravity of 1.00, but the apparent specific gravity computed from the volume of the sample as determined in the field is only 0.80, showing that the compacting was much greater in the laboratory than in nature. On the other hand, it is difficult to pack gravel tightly. The rather heterogeneous sample of sand No. 102 had an apparent specific gravity of 1.85 in nature but only 1.66 in a laboratory test.

If the material is consolidated, the volume is obtained by coating it with paraffin and weighing it in air and in water. The fragment is cleaned of foreign material and loose particles are brushed off. It is weighed and then dipped in paraffin heated to a temperature a little above the melting point. The layer of paraffin is examined for air bubbles and pin holes, and these are removed by remelting the paraffin around them with the end of a hot wire. In dipping the fragments it is best to hold them with the fingers, first dipping one half of the fragment and then the other half. The samples are immersed for very short periods, two to three seconds or less, as the paraffin should not enter the pores. If there is any doubt about the paraffin entering the pores, the specimen is broken and examined after the test has been made. When the paraffin cools the sample with its coating is weighed to determine the weight of the paraffin.

The sample with the coating of paraffin is suspended in distilled water by a fine wire and weighed. (See d in pl. 12.) A fine wire is used so that the error due to surface tension will be as small as possible. The temperature of the water is taken at the time of the weighing. The sample is then removed from the water, dried by pressing the surface against bibulous paper or a small towel, and weighed in air. The purpose of this weighing is to see whether the sample absorbed any water. If an appreciable quantity of water was absorbed, its weight, determined from the difference between the last weighing and the former weighing of the sample plus the paraffin in air, is added to the weight of the water displaced.

From the weight of the water displaced, its temperature, and its density the volume of the sample plus the paraffin is obtained. From a previous determination of the density of paraffin and the weight of the paraffin covering the sample the volume of the paraffin is computed. This volume subtracted from the total volume gives the volume of the fragment of rock used.

METHOD OF DETERMINING THE VOLUME OF THE GRAINS

A sample weighing about 5 grams is dried in an electric oven at 110° C. for 30 minutes to 1 hour, cooled in a desiccator, and weighed. It is then exposed to the air and allowed to take up moisture. After the sample has reached a nearly constant weight, it is transferred to a pycnometer of known weight by means of glazed paper. The pycnometer containing the sample is then weighed to correct for any loss in transfer.

The pycnometer used is of the type designed by Johnston and Adams,[11] of the Carnegie Institution. The essential feature of this type is the plane-ground joint between the stopper and the bottle. The neck is made fairly thick, partly for strength and partly to minimize heat transfer when the bottle is held by the neck between the fingers. It is made in such a manner that there is no recess on the outside from which water can not readily be wiped away.

The pycnometer is attached to an aspirator (b in pl. 12), the air is evacuated from the sample, and distilled water is added under a vacuum. The pycnometer is placed in a constant-temperature thermostat (c in pl. 12) regulated to 0.1° C. Filling of the pycnometer is completed with distilled water taken from another vessel in the thermostat. After half an hour the pycnometer is removed from the thermostat, the outside surface is carefully dried with a towel, and the pycnometer is weighed. From a previous calibration of the pycnometer, which gives the weight of water necessary to fill it, the weight of water that the sample displaced is found. The volume of the particles of the sample in the pycnometer is computed from the weight of the water displaced and the table of densities of water at the temperature of the thermostat.

Although this method was used in determining the porosities given in this report, a study of the subject shows that the refinements of the method are not essential, because the experimental errors involved in determining the volume of unconsolidated samples are unavoidably great.

The pycnometer described is not adapted for use with coarse material. If the sample is a clean gravel a larger sample is taken, and a larger wide-mouthed bottle of known capacity and weight is used instead of the pycnometer. The aspirator is not used. If the sample contains both fine and coarse material the material larger than 2 millimeters is separated from the rest of the sample and is tested by the method used for gravel. The rest of the sample is then tested by the ordinary method.

POROSITY DATA

The porosity of a granular material depends largely upon the degree of assortment and the manner of packing of the grains. As

[11] Johnston, John, and Adams, L. H., On the density of solid substances with especial reference to permanent changes produced by high pressures: Am. Chem. Soc. Jour., vol. 34, p. 566, 1912.

is explained by Slichter,[12] spheres of the same size can be packed so as to give porosities ranging from 25.95 to 47.64 per cent. In fact, even less compact arrangements are possible and occur, especially in soils. Angular grains of various sizes can be packed either more closely or more loosely than spherical grains, and hence they have an even wider range of possible porosities. The size of the grains is not important with respect to porosity. If other conditions are the same a material will have the same porosity whether it consists of large or small grains. On the whole, silt and clay are about as porous as sand and gravel. A sample composed of large grains of uniform size has a high porosity, and a sample composed of small grains of uniform size has an equally high porosity, but a sample composed of a mixture of grains of these two sizes has a much lower porosity.

Of the materials tested (see table on pp. 164–169), the heterogeneous gravels have low porosities; the consolidated samples have the next lowest; the medium-grained, fairly well assorted sands have rather high porosities, usually between 30 and 50 per cent; and the fine-grained, well-assorted materials, such as the loess and silt from Idaho, the shales and silt from Montana, and the fine silty materials from New Jersey, have the highest porosities—between 50 and 60 per cent.

Figure 21 shows that in a very general way the porosity of the samples tested increases with the uniformity coefficient, but that in many of the samples there are wide digressions from this rule. These digressions may be due partly to the fact that the so-called uniformity coefficient does not always express the actual degree of uniformity and partly to the fact that heterogeneous materials may be arranged in nature in a manner that gives high porosity, as is the case in many soils.

MOISTURE EQUIVALENT

METHOD OF DETERMINING MOISTURE EQUIVALENT

The term "moisture equivalent" was introduced by Briggs and McLane[13] to denote the quantity of water retained by a sample of soil or other material when it is saturated and then subjected to a constant centrifugal force.[14] As originally defined it is the ratio of the weight of water retained to the weight of the dry sample.

[12] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, pp. 306 et seq., 1899.

[13] Briggs, L. J., and McLane, J. W., The moisture equivalents of soils: U. S. Dept. Agr. Bur. Soils Bull. 45, 1907.

[14] For a summary of the work done by Briggs, McLane, Israelsen, and others on moisture equivalents see Meinzer, O. E., The occurrence of ground water in the United States, with a discussion of principles: U. S. Geol. Survey Water-Supply Paper 489, pp. 50–76, 1923.

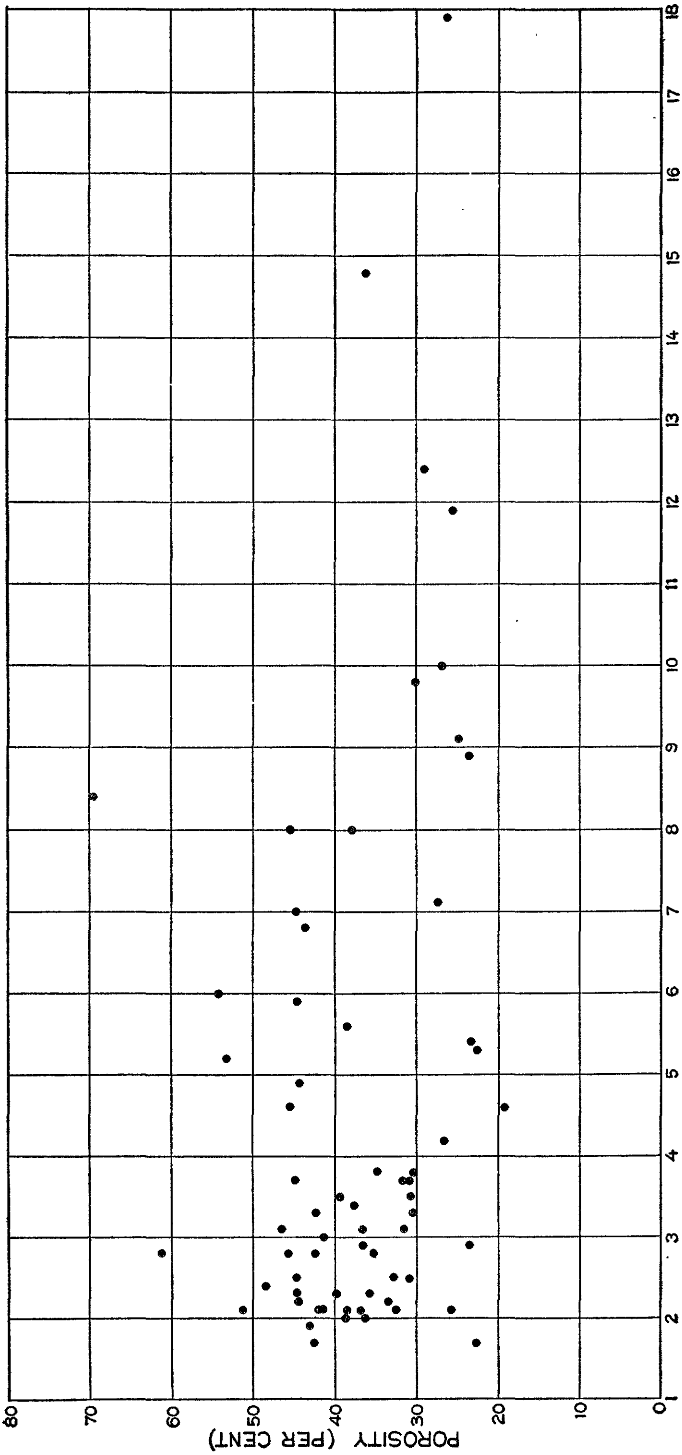

FIGURE 21.—Diagram showing relation between the uniformity coefficients and the porosities in the materials tested

The moisture equivalent is computed by the formula

$$M_w = 100\frac{w}{W}$$

in which M_w is the moisture equivalent in percentage by weight, w is the weight of the moisture, and W is the weight of the dry sample. The formula for the moisture equivalent by volume is

$$M_v = 100\frac{w}{W}S,$$

in which M_v is the moisture equivalent in percentage by volume and S is the apparent specific gravity of the dry sample.

The test for moisture equivalent is made practically according to the method used by Boyd[15] in the laboratory of the United States Bureau of Public Roads and is not essentially different from the method used by the Bureau of Soils. A small piece of filter paper is placed in the bottom of a Gooch crucible to prevent the material to be tested from sifting through. A 5-gram sample is placed in the crucible and the crucible is set in a pan of water to allow the sample to take up water by capillarity until it is saturated. The crucible with the saturated sample is placed in a moist chamber overnight to insure an even distribution of moisture throughout the sample. It is then placed in a Babcock cup with a perforated rubber stopper at the bottom, which serves as a cushion. This stopper is provided with a hole sufficiently large to hold the water that is thrown out during the centrifuging, without allowing any moisture to be drawn back into the crucible by capillarity after centrifuging. The Babcock cup is provided with a brass cover to prevent evaporation. The sample is centrifuged for an hour at a speed which for the diameter of head used will exert a centrifugal force approximately 1,000 times the force of gravity.

As a check on the results duplicate samples are placed opposite each other in the centrifuge. The centrifuge may vibrate badly if the cups do not exactly balance, but as about the same quantity of water is thrown out from equal weights of the same material the cups opposite each other generally continue to balance throughout the centrifuging. If the cups do not balance, fine shot is put in the bottom of one until it balances the other exactly.

After centrifuging the samples are weighed at once, before appreciable evaporation can take place. They are then dried in an electric oven at 110° C., cooled in a desiccator, and weighed. The weight of the moist soil minus the weight of the dry soil gives the weight of the moisture which was retained after centrifuging. The moisture

[15] Boyd, J. R., Physical properties of subgrade materials: Am. Soc. Testing Materials Proc., vol. 22, pt. 2, Technical papers, pp. 337 et seq., 1922.

equivalent, by weight, is this moisture expressed as a percentage of the weight of the dry soil. The moisture equivalent by volume is computed by multiplying the percentage by weight of the apparent specific gravity. (See formulas, p. 136.)

In some samples, especially in those consisting of clayey material, the moisture equivalent by volume is greater than the porosity. When the samples are saturated they usually show an excess of moisture on the top. In clayey samples the centrifuging often allows this excess to remain or to accumulate on top because the material is too impervious to allow it to pass through and be thrown out. It is possible that the centrifuging compacts the clay particles and squeezes out moisture, which accumulates on top. This excess moisture gives the sample a high apparent moisture content. Briggs and McLane[16] state that they encountered this difficulty in some of the more retentive materials when large quantities of soil were used, and they therefore used samples with a depth of only 5 millimeters. Some samples of clay that contain considerable colloidal material may absorb large amounts of water, and the moisture equivalent may be greater than the porosity. Such absorbed water is actually retained in the material against the pull of the centrifugal force and can properly be considered a part of the moisture equivalent.

Tests of moisture equivalent can not be made by this method on coarse materials. The conditions of the test require a sample weighing not more than about 5 grams, in order not to have too great a thickness of material, and only material with particles less than 2 millimeters in diameter is used. It is found that fine uniform materials give close checks in results, and that coarse, heterogeneous materials differ rather widely. In heterogeneous materials the proportions of coarse and fine in the small samples used may not be the same. The method of quartering is evidently not sufficiently refined for a 5-gram sample, and it is probably impossible by any feasible method to obtain two 5-gram samples of heterogeneous material that do not differ considerably in their proportions of large and small grains.

RELATION OF MOISTURE EQUIVALENT TO SPECIFIC RETENTION

The moisture-equivalent test is made to obtain a value for the specific retention. The term "specific retention"[17] is used to express the quantity of water which a soil or rock will retain against the pull of gravity if it is drained after having been saturated. The ratio

[16] Op. cit., p. 15.

[17] Meinzer, O. E., The occurrence of ground water in the United States, with a discussion of principles: U. S. Geol. Survey Water-Supply Paper 489, pp. 50 et seq., 1923; Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water-Supply Paper 494, p. 28, 1923.

of the volume of this retained water to the total volume of the material, expressed as a percentage, is the specific retention. The specific retention of the formation is invariably less than the percentage of water retained by small isolated samples of the same material that are saturated and then allowed to drain. The communicating interstices of a soil or rock commonly form irregular capillary tubes. In a small sample these tubes may be short enough to hold all of their water, but in nature many of the tubes are indefinitely long and hence are drained down to a certain level above the water table determined by their diameters. Obviously, in any direct test, whether made in the laboratory or in the field, the true specific retention of the material can be ascertained only by using a high column of the material and disregarding the lower part that lies within the capillary fringe. A good summary of the measurements of the water-retaining capacity of soils, made chiefly in the field and beginning with King in 1889, is given by Israelsen and West.[18]

The moisture-equivalent method of determining the specific retention is based on the theory of applying a centrifugal force great enough to reduce the capillary fringe so much that this fringe can be ignored without introducing much error, even in small samples, and yet not great enough to withdraw a large proportion of the water that is held more securely above the capillary fringe. Thus, if a material will lift water 100 inches by capillarity acting against gravity, it will theoretically be able to hold it only 0.1 inch against a centrifugal force that is 1,000 times as great as the force of gravity.

Experimental work indicates that for at least some materials the moisture equivalent approximates the specific retention. Israelsen,[19] who has made extensive field experiments on water-retaining capacities, states:

> Correlations between the moisture equivalent and the maximum amounts of water found after irrigation show a gratifying agreement and suggest that the moisture equivalent might be made a basis of judging maximum capillary capacities [essentially specific retentions].

F. H. Veihmeyer, of the University of California, who has done much work on this subject, wrote on February 8, 1924: "All of the results we have obtained so far indicate that the moisture equivalent is a fairly accurate measure of the moisture-holding capacity of our agricultural soils." Veihmeyer's method is similar to that used by Israelsen. He determines the moisture content of samples of a soil 24 hours after an irrigation sufficient to wet the soil 6 feet in

[18] Israelsen, O. W., and West, F. L., Water-holding capacity of irrigated soils: Utah Agr. Coll. Exper. Sta. Bull. 183, p. 18, 1922.

[19] Israelsen, O. W., Studies on capacities of soils for irrigation water, and on a new method of determining volume weight: Jour. Agr. Research, vol. 13, p. 34, 1918.

depth and also the moisture equivalents of the same samples. Veihmeyer [20] found that the percentage of moisture retained by a sample that is centrifuged at 1,000 times the force of gravity varies inversely with the size of the sample. Thus a 60-gram sample of a certain sandy loam gave a moisture equivalent of 21 per cent, whereas a 10-gram sample of the same soil gave a result of 32 per cent. Similarly a 60-gram sample of a certain clay loam gave a moisture equivalent of 22 per cent and a 10-gram sample 38 per cent. He says that with samples in excess of 60 grams in standard centrifuge cups the moisture equivalent is fairly constant. These experimental data obtained by Veihmeyer seem to verify the theoretical conclusions reached by Meinzer [21] that each centrifuged sample retains at the bottom a capillary fringe the height of which is inversely proportional to the centrifugal force. As the height of the capillary fringe is independent of the height of the sample, it follows that the shallower the sample the larger the proportion of it that remains in the capillary fringe and hence the higher the percentage of moisture it retains against the centrifugal force. By using large samples this error becomes negligible. It seems desirable, therefore, that a test should be devised in which a relatively large sample can be used.

Bates [22] attempted to make moisture-equivalent tests on coarse heterogeneous forest soils and suggested centrifuging large samples of soil under a force of only one hundred times gravity. The large sample is obviously an advantage, but the reduction of the force exerted seems of doubtful value, because it will result in higher capillary fringes in the samples while they are being centrifuged. If the moisture-equivalent test is to be used to determine the specific retention of water-bearing materials, there is urgent need of adapting the test to materials that are coarse and heterogeneous.

RELATION OF MECHANICAL ANALYSIS TO MOISTURE EQUIVALENT AND SPECIFIC RETENTION

The moisture equivalents of the samples tested range from 1.34 per cent to more than 100 per cent. (See table, pp. 164–169.) The samples that have extremely high moisture equivalents contain large amounts of clay or silt; those that have small moisture equivalents consist largely of coarse material. Figure 22 shows a general relation between the moisture equivalents of the samples tested and their 10 per cent sizes.

[20] Correspondence Feb. 8, 1924. See also Veihmeyer, F. J., Israelsen, O. W., and Conrad, J. P., The moisture equivalent as influenced by the amount of soil used in its determination: California Univ. Agr. Exper. Sta. Tech. Paper 16, 1924.

[21] Meinzer, O. E., op. cit. (Water-Supply Paper 489), p. 72.

[22] Bates, C. G., and Zon, Raphael, Research methods in the study of forest environment: U. S. Dept. Agr. Bull. 1059, May 19, 1922.

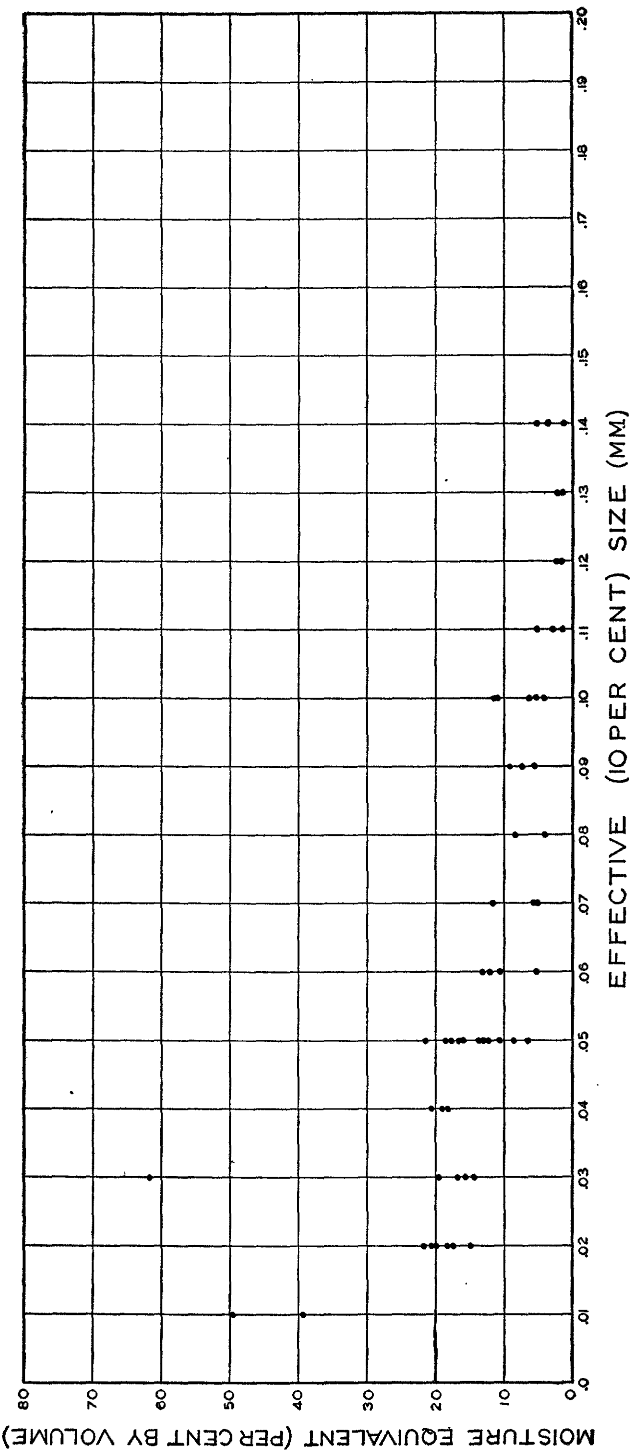

FIGURE 22.—Diagram showing relation between the moisture equivalents and the 10 per cent sizes of materials tested

Briggs, Martin, and Pearce[23] make the following statement in regard to the relation of the mechanical composition of a material to its moisture retentiveness:

Soil texture has been used for the quantitative description of soils more extensively than any other physical property, and unfortunately it has been one of the most difficult to interpret from the standpoint of moisture retentiveness. Texture is quantitatively expressed by means of the mechanical analysis, which shows the composition of the soil when the particles are separated into groups according to size. The accuracy with which the texture of the soil can be expressed by this means is dependent on the number of groups into which the particles are separated. But the difficulty of effecting a complete separation of the finer particles into the desired groups places a practical limit upon the number of groups, which is usually limited to seven.

The use of mechanical analysis as a basis for determining the moisture retentiveness of a soil is further complicated by the fact that soils having a high clay content will show great differences in the amount of colloidal material, which greatly affects the moisture retentiveness. Furthermore, the particles constituting a given group may lie much nearer one limit of the group than the other, so that a given group does not always have the same properties. Consequently, the particles constituting a given group in the mechanical analysis do not always have the same moisture retentiveness per unit mass. It is also possible that the specific retentivity of a group when measured alone is modified to some extent by admixture with particles from other groups.

Several formulas for obtaining the moisture equivalent from the mechanical analysis of a soil have been developed. The first work of this kind was done by Briggs and McLane,[24] who used a moisture equivalent based on a force three thousand times that of gravity. Later Briggs and Shantz[25] developed a number of formulas among which is the following, based on a centrifugal force of 1,000 times gravity:

$$\text{Moisture equivalent} = 0.02 \text{ sand} + 0.22 \text{ silt} + 1.05 \text{ clay}.$$

In this formula the sand, silt, and clay are expressed in percentages of the weight of the dry sample, and the moisture equivalent is, of course, also expressed by weight.

Alway and Russel[26] compiled a table in which are compared moisture equivalents (1) determined by experiment, (2) computed by the formula of Briggs and Shantz, and (3) computed by a modified formula. They make the following statement:

It will be seen that the formula of Briggs and Shantz gives values too low for the coarsest-textured members of the series and too high for the finest

[23] Briggs, L. J., Martin, O. F., and Pearce, J. R., The centrifugal method of mechanical soil analysis: U. S. Dept. Agr. Bur. Soils Bull. 24, p. 33, 1904.

[24] Briggs, L. J., and McLane, J. W., The moisture equivalents of soils: U. S. Dept. Agr. Bur. Soils Bull. 45, pp. 17 et seq., 1907.

[25] Briggs, L. J., and Shantz, H. L., The wilting coefficient for different plants and its indirect determination: U. S. Dept. Agr. Bur. Plant Industry Bull. 230, p. 72, 1912.

[26] Alway, F. J., and Russel, J. C., Use of the moisture equivalent for the indirect determination of the hygroscopic coefficient: Jour. Agr. Research, vol. 6, p. 843, 1916.

textured. In the modified formula the value assigned to the clay is lowered, that to the sands much increased, and that to the silt slightly raised.

This modified formula gave results in close concordance with the directly determined values. The authors summarize the matter thus:

For the calculation of the moisture equivalent from the mechanical analysis no general formula appears universally applicable, the formula needing modification according to the soil type to which it is to be applied.

The moisture equivalent has also been used by Middleton [27] to interpret the mechanical analyses of soils. Middleton summarizes his paper as follows:

There is a direct relationship between the moisture equivalent and the percentages of sand, silt, and clay in the soil as determined by mechanical analysis. This relationship may be expressed as

$$\text{Moisture equivalent} = 0.063 \text{ sand} + 0.291 \text{ silt} + 0.426 \text{ clay}.$$

The presence of considerable amounts of organic matter in the soils tends to increase the moisture equivalent and to disturb the relation between the moisture equivalent and the mechanical analysis.

For samples containing less than 20 per cent of silt and clay Middleton recommends the following formula:

$$\text{Moisture equivalent} = 0.02 \text{ sand} + 0.40 \text{ silt} + 0.53 \text{ clay}.$$

In the following table are given the moisture equivalents of the samples tested in the present investigation as determined in the hydrologic laboratory and as computed from the mechanical analysis by means of the formula of Briggs and Shantz and the two formulas of Middleton. In each column the moisture equivalent by volume is given. To compute this the results obtained from the formulas by Briggs and Shantz and by Middleton were multplied by the apparent specific gravity. The samples are arranged in the order of their experimental moisture equivalents.

[27] Middleton, H. E., The moisture equivalent in relation to the mechanical analysis of soils: Soil Sci., vol. 9, No. 2, pp. 159–167, February, 1920.

Experimental moisture equivalents and moisture equivalents computed from formulas of Briggs and Shantz and of Middleton [a]

[All moisture equivalents are expressed by volume]

No.	Apparent specific gravity	Moisture equivalent				No.	Apparent specific gravity	Moisture equivalent			
		Experimental	Briggs and Shantz	Middleton				Experimental	Briggs and Shantz	Middleton	
				General formula	Special formula					General formula	Special formula
14	1.37	1.3	3.7	9.1	3.4	88	2.06	14	18	21	17
13	1.42	1.8	4.2	9.5	3.7	107	1.51	14	5.6	11	6.0
12	1.46	1.8	4.3	9.7	3.8	75	1.19	15	8.9	15	--------
71	1.51	1.9	4.2	10	3.8	90	1.93	15	20	20	16
105 [b]	1.55	2.0	5.7	11	4.5	104 [b]	1.74	16	18	21	--------
73 [b]	1.54	2.1	5.1	11	4.5	51	2.19	16	21	21	16
72	1.47	2.2	4.0	10	3.7	28	1.72	16	7.6	15	10
103	1.59	2.6	6.5	11	5.9	89	2.06	16	13	18	12
11	1.44	2.7	4.9	9.9	4.0	32	1.85	17	17	20	17
10	1.48	3.0	5.3	10	--------	26	1.47	17	16	18	--------
16	1.50	3.7	5.6	11	5.0	38 [b]	1.36	18	16	17	--------
102 [b]	1.85	2.6	7.8	14	6.8	78	.75	18	7.7	9.5	--------
100 [b]	1.81	3.7	9.2	16	7.4	27	1.47	18	10	15	12
25	1.47	4.2	8.2	12	7.5	76	1.01	19	9.0	12	--------
86	1.96	4.2	6.1	14	7.1	19	1.47	19	21	18	16
23	1.51	5.0	6.5	11	5.9	87	2.07	19	14	19	14
82 [b]	1.67	5.2	11	15	10	46	1.87	20	13	19	15
101	1.65	5.3	10	15	9.9	18	1.47	20	16	16	12
15	1.48	5.4	13	13	8.6	52 [b]	2.50	20	25	24	20
24 [b]	1.56	5.4	4.7	11	4.7	59	1.79	21	17	23	--------
21	1.47	5.7	7.1	12	7.5	30	2.08	21	12	19	13
34	1.66	5.7	4.2	11	5.0	92	2.09	21	20	25	--------
80 [b]	1.77	5.7	11	16	10	57	1.84	28	34	26	--------
33	1.72	6.4	4.3	12	5.0	106	1.00	32	25	23	--------
22	1.47	6.7	9.2	13	9.0	74	1.25	33	13	16	--------
81 [b]	1.75	6.8	13	16	12	79	1.25	38	38	31	--------
69	1.73	7.6	5.9	14	8.1	40	1.54	39	22	24	--------
108 [b]	1.67	7.0	3.5	11	3.5	48	2.00	42	38	36	--------
55	1.81	8.4	6.2	13	6.7	56	1.67	42	114	59	--------
83 [b]	1.76	8.8	13	17	12	77	1.19	50	16	20	--------
17 [b]	1.52	9.2	11	13	8.1	47	2.01	52	65	58	--------
64	1.73	11	7.4	15	11	35	1.65	53	72	49	--------
62	1.80	11	6.7	15	9.5	41	1.81	49	36	33	--------
50	1.87	11	7.3	15	9.7	53	1.73	62	19	19	15
43	1.91	11	7.4	15	8.2	61	1.92	72	94	59	--------
45	1.73	11	5.1	13	6.7	58	1.27	76	40	24	--------
67	1.54	12	5.0	12	6.8	54	2.06	77	131	73	--------
31	1.71	12	7.5	14	9.4	39	1.57	85	51	40	--------
91	1.97	12	13	18	12	36	1.91	122	73	49	--------
29	1.78	13	6.4	14	7.8	60	2.07	124	148	74	--------
49	1.82	13	7.0	15	10	66	1.93	172	58	37	--------

[a] The formulas used to compute the moisture equivalents by weight are as follows: Briggs and Shantz, 0.02 sand+0.22 silt+1.05 clay; Middleton, general formula, 0.063 sand+0.291 silt+0.426 clay; Middleton, special formula for samples that contain less than 20 per cent of silt and clay, 0.02 sand+0.40 silt+0.53 clay. All results were multiplied by the apparent specific gravity to obtain moisture equivalents by volume.
[b] Some grains greater than 2 millimeters in diameter.

For the samples that contain less than 2 per cent of silt and clay all the formulas give results that are much higher than the experimental moisture equivalents. The results obtained by use of the Middleton general formula are the most erratic. For the samples that contain 2 to 10 per cent of the silt and clay the Middleton general formula is likely to give results that are much higher than the experimental; the Briggs and Shantz formula and the Middleton special formula give fairly good results for many of the samples but results that are much too high or much too low for a considerable proportion. On the average the Middleton special formula gives somewhat the best results. For the samples that contain 10 to 20 per cent of silt and clay all three of the formulas give results that agree fairly well with the experimental results for most samples but with wide departures for some. For the samples that contain 20 to 30 per cent of silt and clay both the Briggs and Shantz formula and the Middleton general formula give fairly good results for most samples but with wide departures for some. For a large part of the samples that contain more than 30 per cent of silt and clay the results computed by either formula give results that vary widely from the experimental results.

RELATION OF MOISTURE EQUIVALENT TO SPECIFIC YIELD

The term "specific yield" is used to express the quantity of water that a formation will yield under the pull of gravity if it is first saturated and then allowed to drain. The ratio, expressed in percentage, of the volume of this water to the total volume of the formation that is drained is the specific yield. It is the porosity minus the specific retention.

In the table on pages 164–169 is given the porosity minus the moisture equivalent by volume of the samples tested. The difference represents the percentage of pore space that is empty when a sample comes out of the centrifuge. For a material that has a low or moderate moisture equivalent the difference between the porosity and the moisture equivalent gives an approximation of the specific yield, but for a material that has a high moisture equivalent this computation is likely to give erratic results. The moisture equivalents computed from mechanical analyses of materials that contain less than 30 per cent of silt and clay apparently have some value in computing the specific yield. For materials with very low content of silt and clay the computed moisture equivalent is likely to have a large percentage of error, but as the moisture equivalents of these samples are low the resulting percentages of error in the computed specific yields are not correspondingly large.

PERMEABILITY

APPARATUS

The permeability test was devised by O. E. Meinzer to measure the rate of flow of water through columns of water-bearing materials under low heads, such as are found in nature. The method is to allow inflow of water at the bottom of a column of the material of known height and outflow at the top. The difference in head of water at the bottom and the top is regulated by an adjustable supply tank and is indicated by two pressure gages. Observations are made on the rate of discharge and the temperature of the water.

In view of the difficulties King [28] found in running water through samples and his subsequent use of air instead of water, it was believed that the permeability test would necessarily be one of permeability to air, the results of which would be computed into permeability to water. Therefore the air-permeability apparatus of Karr and Sager, of the Bureau of Standards, used in work on molding sands, was at first seriously considered. However, a little study into the subject showed that, although the viscosities of both air and water have been accurately determined, serious uncertainties are involved in converting permeabilities to air into permeabilities to water, chiefly because of notable effects of hygroscopic or other moisture in the sample on the air permeability, as determined by Karr and Sager. A few preliminary tests of permeability were made with water in the apparatus devised by Mr. Meinzer. The results were very satisfactory, and a more careful and extended series of tests were then made on a sand obtained from Fort Caswell, N. C. (pp. 152–159). The results of this series of tests were so good that this apparatus was used in all the work on permeability. It is, however, Mr. Meinzer's opinion that before a final decision can be reached as to the relative merits of the air and water methods further research is necessary, in which tests by the two methods shall be made on duplicate samples of the same material with the same compacting and in which tests shall also be made with the water apparatus on a series of samples of the same material and with the same compacting.

The permeability apparatus shown in Plate 13 and Figure 23 is known as the long-cylinder apparatus. It differs from the short-cylinder apparatus, which is used in most of the tests, only in the length of the cylindrical copper vessel that holds the sample and in the length of the pressure gages. The cylindrical vessel *a*, which is called the percolation cylinder, is closed at the lower end and has four openings, two at the bottom and two at the top. It is 3 inches in diameter. In the long-cylinder apparatus this vessel is 48 inches high; in the apparatus that is ordinarily used it is only 8 inches high. There is one opening, *b*, near the bottom for inflow of water; one near the top, *c*, for discharge of water that has percolated up through the sample; and two, *d* and *d'*, for pressure gages. The pressure gages consist of two glass tubes, *e* and *e'*, each about half an inch in diameter. They indicate the difference in head at the bottom and top of the column of material that is being tested. The glass tubes must be of large enough diameter to make capillarity in them negligible. Another cylindrical copper vessel, *f*, about 12 inches high and 5 inches in diameter, is used as a water-supply tank.

[28] King, F. H., Principles and conditions of the movements of ground water: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, pp. 107–206, 1899.

Water from an ordinary faucet enters the supply tank slowly through a glass tube, *g*, which extends below the water level in the tank to prevent splashing. A rubber tube, *h*, leads water from the supply tank to the percolation cylinder. The surplus water is discharged from the supply tank through an opening 1½ inches in diameter

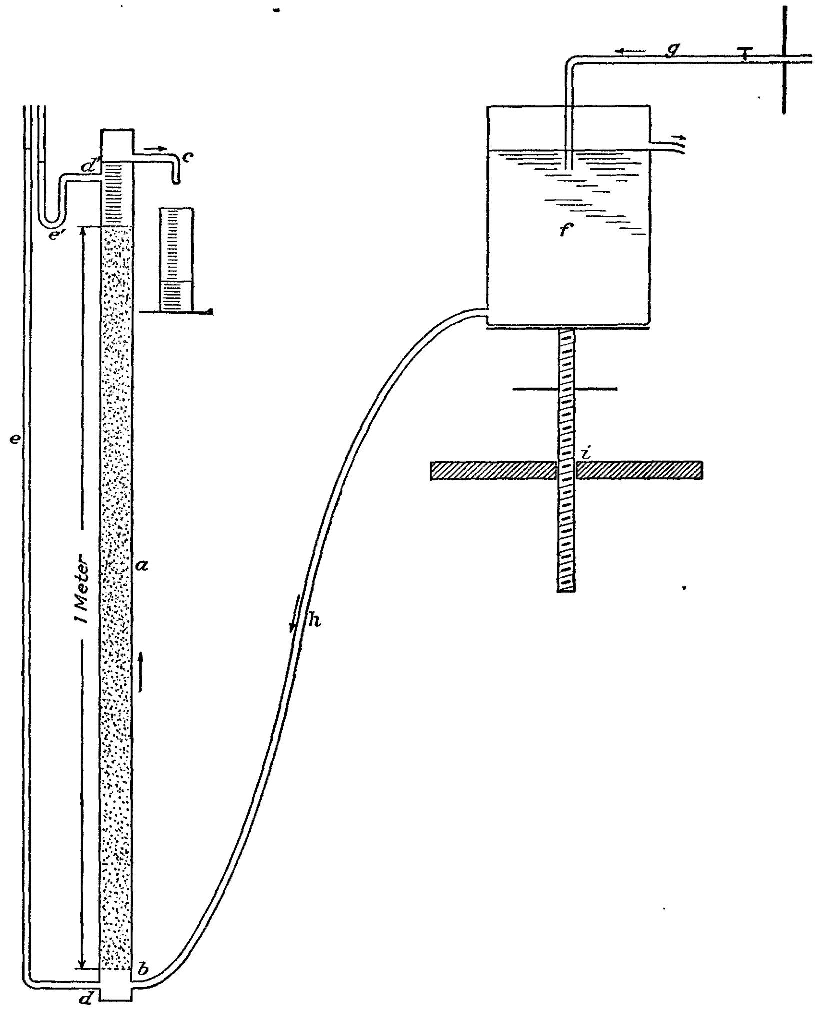

FIGURE 23.—Diagram of long-cylinder permeability apparatus

near the top, not visible in Plate 13. This overflow outlet keeps the water level in the tank nearly constant. Its accuracy as a regulator of the water level increases with the size of the outlet opening. The tank is raised or lowered by means of a screw jack, *i*, with which very fine adjustments of head are possible. Half a turn of the handle in the jack gives about 1 millimeter difference in the head.

A cathetometer, *k*, in Plate 13, is used to read the difference in level in the pressure gages when this difference is small. It consists of a telescope, mounted on a vertical rod on which it can be raised and lowered and swung in a 90° arc. The telescope has an eyepiece with movable cross hair and micrometer adjustment. The telescope is focused on a meter rod, *l*, and calibrated. It is then swung to the pressure gages, and the distances between the levels are determined by means of the micrometer adjustment. By use of this cathetometer heads can be read down to less than a hundredth of a millimeter.

METHOD OF PUTTING SAMPLE INTO THE APPARATUS

Several rubber stoppers are put in the bottom of the percolation cylinder. On these is placed a circular piece of fine copper gauze to keep the sand from sifting through. If the material to be tested is very fine, a piece of fine-mesh bolting cloth is placed on the copper gauze.

In the short-cylinder apparatus the column of material to be tested is as nearly as possible 10 centimeters high. If the sample was taken volumetrically, the requisite weight of sand to make a column 10 centimeters high, based on the air-dry apparent specific gravity, is put into the percolation cylinder. The sample is shaken, tamped, and jarred in order to make it occupy practically the volume it had in nature. A sample may occupy more space than its computed volume in nature, and further jarring and tamping may not compact it further. Another sample, however, may occupy less than the computed volume, and there is no practicable method of increasing its volume to that which it occupied in nature. If the height of the column was greater or less than 10 centimeters, this fact is recorded in the footnotes of the table (pp. 164–169). If the sample is not volumetric, the material is packed into the cylinder until a column 10 centimeters high is obtained. It is jarred and tamped so as to make it as compact as possible, and this maximum compacting is assumed to be that of the natural sample. Serious errors may be involved in applying the coefficient of permeability in field problems because of irregularities in the natural packing of the formation that was sampled and especially because of local assortment and stratification even within the material that furnished the sample, which could not be restored in the laboratory. The assortment in nature generally increases the average permeability in the direction of the stratification. On the other hand, any assortment produced by shaking and jarring the sample in the percolation cylinder is likely to decrease the permeability. It is obviously desirable that a method should be developed for obtaining undisturbed samples of unconsolidated materials for the permeability tests. Permeability tests have not yet been made in this laboratory on consolidated samples.

After the percolation cylinder has been filled with the material to be tested, water is allowed to enter very slowly at the bottom, the head being kept very low so as not to roil the material. It may require only a few minutes or as much as several hours to saturate the sample, according as the material is coarse or fine.

METHOD OF MAKING THE TEST

When the water is discharging uniformly from the outlet at the top of the cylinder the test is begun. The temperature of the water is taken in degrees Fahrenheit. The head, as shown by the difference in the water levels in the pressure gages, is measured in millimeters by means of a metric rule or the cathetometer. The rate of discharge is observed with a graduated cylinder and a stop watch, usually in cubic centimeters in a period of either 30 or 60 seconds. If the discharge is very slow, however, it has been found convenient to count drops, the weight of one drop being determined. After a test has been made at a given head, the supply tank is raised or lowered, and a new test with a different head is made. Generally three to five tests are made, covering a considerable range in head.

METHOD OF COMPUTING THE RESULTS

The results of the tests are expressed as a coefficient of permeability, which is based on Darcy's law that the rate of flow varies in direct proportion as the hydraulic gradient. The coefficient of permeability of a material is the rate of flow, in gallons a day, through a square foot of its cross section, under a hydraulic gradient of 100 per cent, at a temperature of 60° F. In field terms the coefficient of permeability may be expressed as the number of gallons of water a day, at 60° F., that is conducted laterally through each mile of the water-bearing bed under investigation (measured at right angles to the direction of flow), for each foot of thickness of the bed and for each foot per mile of hydraulic gradient.

The general formula for permeability may be written as follows:

$$P=\frac{qlt}{Tah}$$

in which P is the coefficient of permeability, q the quantity of water, l the length of column of sample, t the correction for temperature, T the time, a the cross-section area of sample, and h the head.

If the percolation cylinder has a diameter of 3 inches and the column of material is 100 millimeters high, the formula becomes

$$P=\frac{46.56ft}{h}$$

in which P is the coefficient of permeability, as above defined; f is the rate of flow $\frac{(q)}{T}$ expressed in milligrams per second; h is the head in millimeters; and t is the correction for temperature which gives the rate of flow at 60° F., based on the viscosity of water, as given in the Smithsonian Physical Tables (7th ed., p. 155) and in Water-Supply Paper 140 (p. 13).

Slichter's transmission constant[29] is defined as the quantity of water, measured in cubic feet, that is transmitted in one minute through a cylinder of the soil 1 foot in length and 1 square foot in cross section under a difference in head at the ends of 1 foot of water. He computed the transmission constants for water at 60° F. The difference between Slichter's transmission constant and Meinzer's coefficient of permeability is that the former gives the flow in cubic feet a minute and the latter gives it in gallons a day. To convert the transmission constant into a coefficient of permeability it is only necessary to multiply it by 10,770.

PERMEABILITY DATA

In the table on pages 160–163 are given the data on the permeability of the samples tested. Details regarding the samples are given in the table on pages 164–169. On the assumption that Darcy's law holds exactly, the differences between the several coefficients of permeability for a given sample, recorded in the next to the last column, represent the experimental errors. The average of the results obtained by the several tests on a given sample is recorded in the last column as the average coefficient of permeability of the material. The differences are due largely to maladjustments of the apparatus and to inaccuracies in reading the head. It was found that after a few changes in the apparatus the coefficients checked more closely. The use of the cathetometer for small heads and of the metric rule for larger heads has probably caused a few discrepancies.

The hydraulic gradients used in the tests range from 0.64 to 91.3 per cent and are usually below 50 per cent. In other words, they range from about 35 to about 4,800 feet to the mile and are usually less than 2,650 feet. The high gradients were used only on the nearly impermeable materials in order to get a measurable flow. The lower gradients were used whenever practicable both to prevent roiling and to approximate natural hydraulic gradients.

The coefficients of permeability range from 0.26 to 20,663. The fine silty samples and those with a considerable clay content yield only a few gallons a day or even less than 1 gallon. The coarse,

[29] Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, p. 11, 1905.

relatively clean gravels yield several thousand gallons a day. The medium-grained, relatively uniform sands yield about 400 to 600 gallons a day.

Slichter's work on the relation of porosity to rate of flow shows that a difference in packing may make a large difference in the permeability. For instance, in sample 22 the sand was packed in the cylinder into a space 10 per cent smaller than it had occupied in nature. Therefore its porosity was reduced from 42 to 32 per cent, and according to Slichter's table (Water-Supply Paper 67, p. 25), the observed rate of flow was 2.5 times slower than it would have been if the sample had been in its natural condition. In other words, the conclusion is reached that the true coefficient of permeability of the formation that was sampled is 68 instead of 27, as determined in the laboratory. According to Slichter's data, if two samples of the same sand are packed, one so that it has a porosity of 26 per cent and the other so that it has a porosity of 47 per cent, the flow through the latter sample will be more than seven times the flow through the former sample, showing how important it is to obtain volumetric samples.

COMPUTED AND EXPERIMENTAL COEFFICIENTS OF PERMEABILITY COMPARED

In the table on page 163 are given the coefficients of permeability as computed by Slichter's graphic scale[30] from the effective size and porosity, the 10 per cent size being taken as the effective size. Only samples having porosities that fall within the range of Slichter's graphic scale or close to it were used.

The table shows that for only a few of the samples is there a close agreement between the computed and the experimental coefficients and that for most of them the differences are large. In 26 of the 34 samples included in the table the experimental coefficient of permeability is greater than the computed coefficient. Some of the data also seem to suggest that for some kinds of material the variation of permeability with porosity is not so great as Slichter's formula indicates.

In many of the volumetric samples the material was packed more closely into the percolation cylinder than it had been in its natural state. If corrections were made on these samples, the experimental coefficients, most of which are already larger than those computed, would be larger still, and the difference between the experimental and computed coefficients would generally be greater. In the non-volumetric samples the maximum packing was used in obtaining the porosity and hence in the computed coefficients of permeability. A

[30] Slichter, C. S., op. cit. (Water-Supply Paper 140), pl. 2.

maximum packing was also used in obtaining the experimental coefficients of permeability. Hence, in these samples the experimental and computed coefficients are comparable.

A number of investigators have found that experimental rates of flow are larger as a rule than those computed from porosity and mechanical analyses. Smith[31] found this true in his study of flow of ground water in the Rillito Valley, Ariz. Melcher[32] states that actual rates of discharge of oil wells are invariably greater than those computed. King found that the observed rates of flow were usually larger than those computed. (See p. 173.)

An unsuccessful attempt was made to discover a law for effective size by using Slichter's formula to compute the effective size from the known porosity and experimental coefficient of permeability. Thus both No. 14 and No. 16 have a 10 per cent size of 0.14 millimeter; their porosities are 48 and 31 per cent, respectively; their uniformity coefficients, which do not enter into the formula, are 2.4 and 3.1; their computed coefficients of permeability 350 and 75; and their experimental coefficients 518 and 284. The effective sizes obtained by Slichter's graph are 0.16 and 0.24 millimeter, respectively, and on the accumulative curves these sizes are found to be about at 15 and 31 per cent instead of 10 per cent. Further, both No. 10 and No. 15 have a 10 per cent size of 0.11 millimeter; their porosities are 45 and 44 per cent, respectively; their uniformity coefficients are 2.3 and 4.9; their computed coefficients of permeability are 165 and 150; and their experimental coefficients are 495 and 1,095. By means of Slichter's graph an effective size of 0.17 millimeter was obtained for No. 10 and 0.26 millimeter for No. 15. The character of the grains in these two samples was entirely different. No. 15 contained numerous flakes of mica and angular grains and when wet it acted much like quicksand. No. 10 was a well-assorted quartz sand with rounded grains. The true effective size is, of course, affected by differences in texture, and the differences mentioned probably played an important part in determining the rate of flow of water through these samples. This case is cited because it shows the difficulty of expressing the characteristics of a complex natural material by the quantitative determination of a few properties such as porosity and 10 per cent size.

Further study of this subject may develop new factors which will express more adequately and completely the physical character of the materials than those hitherto used and may lead to a revised formula which will give a closer approximation to the true permeability of water-bearing materials. In the present state of knowledge the most

[31] Smith, G. E. P., Ground-water supply and irrigation in the Rillito Valley: Ariz. Agr. Exper. Sta. Bull. 64, p. 127, 1910.

[32] Melcher, A. F., personal communication.

reliable results are to be obtained from either field or laboratory tests of rate of flow through a given cross section under a known hydraulic gradient.

EXPERIMENT WITH SAND FROM FORT CASWELL TO INVESTIGATE FLOW UNDER LOW HYDRAULIC GRADIENTS

PURPOSE OF EXPERIMENT

King found that the rate of flow may increase either somewhat faster or somewhat slower than the increase in head. In a recent publication Miller-Brownlie[33] stated that with certain low gradients there is no apparent motion of ground water. He says:

> Observations made during the past few years of the subsoil of the Punjab have shown that the slopes necessary to cause water motion have varied from 1 in 260 in moderately coarse sand to 1 in 175 in fairly fine sand. In gradients flatter than this in each type of sand there is no apparent motion. Capillary attraction interferes with the true flow and investigation into the forward motion becomes greatly involved. Observations indicate that any lateral or forward motion of the water, where the hydraulic gradients are slightly less than those mentioned, is so slow that for practical purposes it may be neglected, the actual velocity probably not exceeding a few inches per day.

Miller-Brownlie's limiting gradients of 1 in 260 and 1 in 175 equal about 0.4 and 0.6 per cent or about 20 and 30 feet to the mile. The gradients found in the water-bearing sand and sandstone formations in the United States are very generally less than 20 feet to the mile, hence it appeared to be imperative to investigate the law of flow for low gradients before adopting any laboratory method based on the use of higher gradients. For if Darcy's law does not hold through a range of hydraulic gradients that includes those found in nature, the results of laboratory tests made with higher gradients can obviously not be used in computing by this law the rates of flow in nature, and either a new law that is applicable to low heads must be discovered, or else laboratory tests must be made with the low heads found in nature. Tests with such low heads are necessarily difficult and laborious. In order to find out whether the results of the tests made with relatively high gradients could be used for lower natural gradients a series of tests with low gradients was made by means of the specially devised long-cylinder apparatus. Sand of the same kind was also used with high gradients in the short-cylinder apparatus, and the results of both series of tests were compared. These results were further compared with the permeability computed by Slichter's formula and by field experiments with dye. These comparisons gave such reassuring results that the convenient short-cylinder apparatus was used in obtaining permeabilities of all the unconsolidated samples.

[33] Miller-Brownlie, T. A., Subsoil water in relation to tube wells: Indian and Eastern Engineer, December, 1919, pp. 191–193.

SOURCE AND PHYSICAL PROPERTIES OF THE SAND

The sand used was obtained in connection with a field investigation at Fort Caswell, N. C., made by C. W. Stiles and H. R. Crohurst,[34] of the United States Public Health Service, in regard to the pollution of ground water. It is a reddish-brown, fairly uniform fine-grained beach sand. The writer had spent a month studying the ground-water phase of the experiment and had made physical tests on the sand and sent a large sample to the laboratory for future study. The field experiment was made to determine the distance, rate, and conditions of movement of *Bacillus coli* through ground water from a dosed pit. Uranin dye, which is similar to fluorescein, was put into the pit with the dose of fecal material, and from a series of pipe wells surrounding the pit water samples were obtained and tested for the dye and for *Bacillus coli.* The dye and the bacteria were both carried by the ground water, but the spread of the dye was taken to indicate the movement of ground water. Data were obtained on the rate of movement of ground water under the hydraulic gradients existing in the sand underlying the experiment field.

The field data obtained related to the so-called "500 trench" area, and the sample used in the laboratory came from the "600 trench" area, a few hundred feet away. However, the physical tests on the sands from both areas show a close agreement.

The mechanical composition of the sand from the "600 trench," determined by sieving, is given below. The nest of sieves was put on a shaking machine and shaken for 15 minutes. Because the samples contained relatively small quantities of very fine materials, the samples were not washed.

Mechanical composition of sand from Fort Caswell, N. C.

Diameter of grains in millimeters	Per cent
More than 2	0.04
2 to 1	.11
1 to 0.5	4.33
0.5 to 0.25	36.75
0.25 to 0.125	56.36
0.125 to 0.074	1.35
Less than 0.074	1.06
	100.00

Effective size (10 per cent size), 0.14 millimeter.
Uniformity coefficient, 1.9.

[34] Stiles, C. W., and Crohurst, H. R., The principles underlying the movement of *Bacillus coli* in ground water with resulting pollution of wells: Public Health Repts., vol. 38, No. 24, p. 1350, June 15, 1922. Stiles, C. W., Crohurst, H. R., and Thomson, G. E., Experimental bacterial and chemical pollution of wells via ground water and the factors involved: U. S. Public Health Service Hygienic Lab. Bull. 147, 1927.

The porosity of the sand, as determined from a known volume obtained in the field, is 49 per cent.

PERMEABILITY EXPERIMENT WITH 1,000-MILLIMETER COLUMN OF SAND

For the permeability experiment with a 1,000-millimeter column of sand the long-cylinder apparatus was used. As the hydraulic gradient varies directly as the head and inversely as the length of

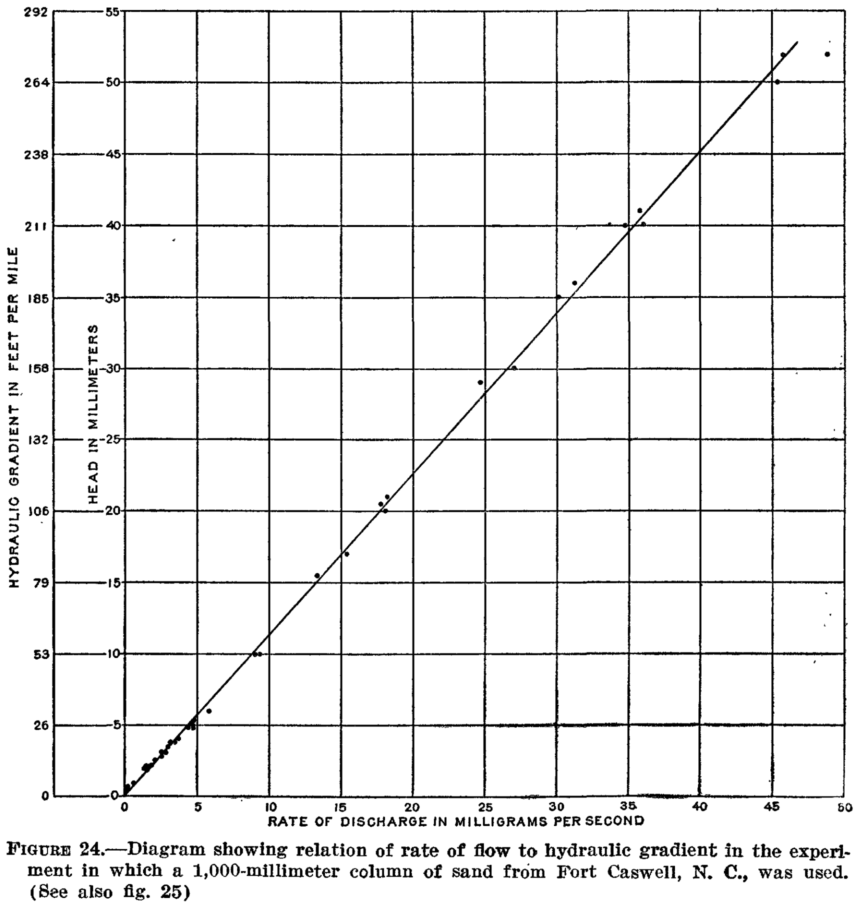

FIGURE 24.—Diagram showing relation of rate of flow to hydraulic gradient in the experiment in which a 1,000-millimeter column of sand from Fort Caswell, N. C., was used. (See also fig. 25)

column through which the water percolates, it was obviously necessary in order to obtain a low gradient to use a low head and a high column of sand. Hence the cathetometer was used to obtain the differences in head, which were read down to hundredths of a millimeter, and a column of sand 1,000 millimeters high was used instead of the 100-millimeter column used in the short-cylinder apparatus. The apparatus as used is shown in Plate 13.

A series of tests was made using heads ranging from 52 millimeters down to about 0.2 millimeter. The head of 0.2 millimeter gave a hydraulic gradient of 0.02 per cent or about 1 foot to the mile. In the following table are given the coefficients of permeability for 68 tests with heads ranging from 0.95 millimeter to 52 millimeters. A weighted average gives a coefficient of permeability of 415. To obtain this weighted average, the average coefficients of permeability

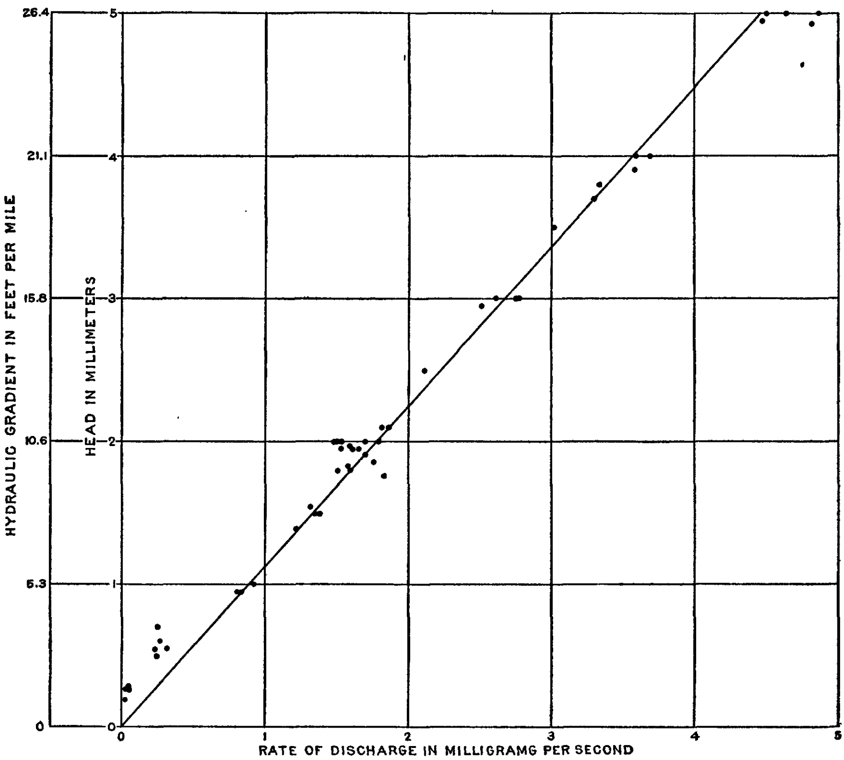

FIGURE 25.—Diagram showing on an enlarged scale a part of the data shown in Figure 24

with heads of 0.95 to 2, 2 to 4, 4 to 8, 8 to 16, 16 to 32, and 32 to 52 millimeters were successively taken, and an average of these averages was used as the weighted average.

In the diagrams in Figures 24 and 25 the coefficients of permeability are plotted against the pressure heads and hydraulic gradients. The resulting curve down to a gradient of 5 feet to the mile approximates a straight line and supports Darcy's law for this sand for hydraulic gradients ranging from about 5.20 to 0.1 per cent, or from about 270 feet to about 5 feet to the mile.

Permeability tests on a 1,000-millimeter column of sand from Fort Caswell, N. C.

[The results are given in the order in which the tests were made]

No.	Head (millimeter)	Hydraulic gradient (per cent)	Rate of flow (milligrams per second)	Temperature (°F.)	Coefficient of permeability	No.	Head (millimeter)	Hydraulic gradient (per cent)	Rate of flow (milligrams per second)	Temperature (°F.)	Coefficient of permeability
1	52.00	5.20	58.82	78.8	411	76	1.83	0.18	1.93	74.3	402
2	35.00	3.50	36.32	73.4	401	77	1.88	.19	1.95	74.3	396
3	36.00	3.60	37.65	73.4	404	78	1.95	.20	1.98	74.3	387
4	29.00	2.90	29.87	73.4	398	79	1.95	.20	2.02	74.3	396
6	21.00	2.10	22.05	73.4	406	82	2.00	.20	2.07	74.3	396
7	20.50	2.05	21.49	73.4	405	85	2.50	.25	2.59	74.3	395
8	15.50	1.55	16.16	73.4	403	86	2.95	.30	3.07	74.3	398
9	15.50	1.55	16.10	73.4	401	87	3.00	.30	3.19	74.3	407
10	5.10	.51	5.72	74.3	428	88	3.50	.35	3.69	74.3	403
11	3.80	.38	4.07	74.3	409	89	4.00	.40	4.37	74.3	417
12	3.70	.37	4.04	74.3	416	90	4.00	.40	4.49	74.3	428
16	2.10	.21	2.23	74.3	406	91	3.90	.39	4.37	74.3	427
17	2.10	.21	2.28	74.3	415	92	4.00	.40	4.49	74.3	428
19	.95	.095	1.03	74.3	412	93	5.00	.50	5.93	74.3	453
20	.95	.095	1.01	74.3	407	94	6.00	.60	7.22	74.3	459
30	4.94	.49	5.46	74.3	422	95	6.20	.62	7.22	74.3	445
31	5.00	50	5.49	74.3	419	96	6.00	.60	7.22	74.3	459
32	4.88	.49	5.88	74.3	460	97	10.00	1.00	11.45	74.3	437
53	1.00	.10	1.14	74.3	433	98	20.00	2.00	22.23	74.3	424
59	1.50	.15	1.68	74.3	428	100	30.00	3.00	33.20	74.3	422
60	1.38	.14	1.49	74.3	412	101	40.00	4.00	44.17	74.3	422
61	1.54	.15	1.61	74.3	399	103	50.00	5.00	55.31	74.3	422
62	1.50	.15	1.65	74.3	419	104	3.00	.30	3.33	72.5	430
64	2.00	.20	2.20	74.3	419	105	52.00	5.20	59.00	72.5	438
66	1.76	.18	2.24	71.6	487	107	40.00	4.00	42.11	72.5	407
67	1.87	.19	2.16	71.6	441	108	41.00	4.10	43.23	72.5	407
68	1.91	.19	2.08	71.6	417	110	30.00	3.00	32.79	72.5	422
69	1.95	.20	1.97	71.6	387	114	20.00	2.00	21.86	72.5	422
70	1.97	.20	1 96	71.6	381	115	10.00	1.00	11.03	72.5	426
71	1.95	.20	1.88	71.6	368	116	5.40	.54	5.93	72.5	424
72	2.00	.20	1.88	71.6	359	118	5.00	.50	5.59	72.5	432
73	2.00	.20	1.82	71.6	347	119	4.00	.40	4.44	72.5	430
74	2.00	.20	1.84	71.6	352	120	3.00	.30	3.33	72.5	428
75	1.80	.18	1.84	74.3	391	121	2.00	.20	2.05	72.5	396

Average coefficient of permeability, 408; weighted average, 415.

The results obtained with heads lower than 1 millimeter, or hydraulic gradients lower than 0.1 per cent, were erratic on account of losses through evaporation and differences in temperature that could not be adequately controlled with the apparatus that was used. It is planned to construct a constant-temperature apparatus that will not allow appreciable evaporation and to obtain reliable results down to a gradient of 1 foot to the mile.

In carrying on this experiment the apparatus was kept in operation for five days under a head, according to the cathetometer readings, of only about 0.2 millimeter, or an apparent hydraulic gradient of only about 1 foot to the mile. The rate of discharge under this low head was very slow, but was continuous for the entire period of five days, showing that movement continues under gradients that are much less than 5 feet to the mile.

Another experiment was performed which showed in a still more impressive manner that movement under hydrostatic pressure may be continuous even though the velocity is extremely slow. A column 50 millimeters high of fine silty material, which is nearly impervious but has a porosity of 54 per cent, was put in one side of a U-shaped glass tube 15 millimeters in diameter, and enough water was placed in the other side to give a hydraulic gradient of 100 per cent. Evaporation was prevented. The experiment was started August 13, 1924. At the end of a week the 50-millimeter column of the material to be tested was just wetted throughout, and by December 31 the column of water that had come through was only 7 millimeters high. This result indicates that water percolates through the material used at a rate of about 0.04 foot in 133 days, or about 1 foot in 10 years. At this rate it would take about 50,000 years for the water to move a mile through the sand. This experiment proves the extremely slow but continuous movement of water through dense material. It indicates that water behaves as a typical fluid.

The tests made in the course of this investigation have led to the conclusion that movement of ground water continues in water-bearing formations even under exceedingly low hydraulic gradients and that Darcy's law is probably reliable, even in fine sands, for gradients down to 5 feet to the mile or less, and certainly for gradients of much less than 30 feet to the mile.

PERMEABILITY EXPERIMENT WITH 100-MILLIMETER COLUMN OF SAND

Next a series of 31 tests was made on the sand from Fort Caswell in the short cylinder, using a column of sand 100 millimeters in height, in order to determine whether the results with this apparatus checked with those of the 1,000-millimeter column. In the following table are given the results of these tests. The heads used ranged from 5 millimeters to 0.5 millimeter, giving hydraulic gradients that ranged from 5 to 0.5 per cent, or from about 265 feet down to about 25 feet to the mile. The average coefficient of permeability is 389. A weighted average similar to that obtained with the 1,000-millimeter column (p. 155) is 379. The coefficients of permeability were plotted against the pressure heads as shown in Figure 26, and a straight-line curve was obtained, which also supports Darcy's law.

Permeability tests on the sand from Fort Caswell, N. C., with 100-millimeter column

[The results are given in the order in which the tests were made]

No.	Head (millimeter)	Hydraulic gradient (per cent)	Rate of flow (milligrams per second)	Temperature (°F.)	Coefficient of permeability	No.	Head (millimeter)	Hydraulic gradient (per cent)	Rate of flow (milligrams per second)	Temperature (°F.)	Coefficient of permeability
1	1.54	1.54	17.24	73.8	428	19	1.50	1.50	15.10	73.4	388
2	1.50	1.50	16.67	73.8	424	20	1.00	1.00	11.10	73.4	428
4	1.50	1.50	16.67	73.8	424	21	1.00	1.00	8.90	73.4	345
5	5.00	5.00	53.60	73.4	414	22	.88	.88	8.90	73.4	392
6	4.50	4.50	49.00	73.4	421	23	1.00	1.00	8.90	73.4	345
7	4.00	4.00	39.20	73.4	378	24	.50	.50	4.50	73.4	345
9	4.00	4.00	39.20	73.4	378	26	1.10	1.10	10.40	71.6	372
10	3.50	3.50	32.70	73.4	361	27	1.20	1.20	11.50	71.6	380
11	3.00	3.00	26.60	73.4	343	31	2.50	2.50	30.00	71.6	475
12	2.50	2.50	24.50	73.4	378	32	3.00	3.00	34.40	71.6	453
13	2.10	2.10	20.60	73.4	379	33	3.50	3.50	34.40	71.6	388
14	2.10	2.10	19.40	73.4	357	34	3.50	3.50	33.70	71.6	380
15	2.00	2.00	18.70	73.4	361	35	4.00	4.00	40.40	71.6	399
16	1.50	1.50	14.00	73.4	360	36	4.50	4.50	45.50	71.6	400
17	1.30	1.30	13.10	73.4	390	37	5.00	5.00	52.00	71.6	412
18	1.50	1.50	14.00	73.4	360						

Average coefficient, 389; weighted average, 379.

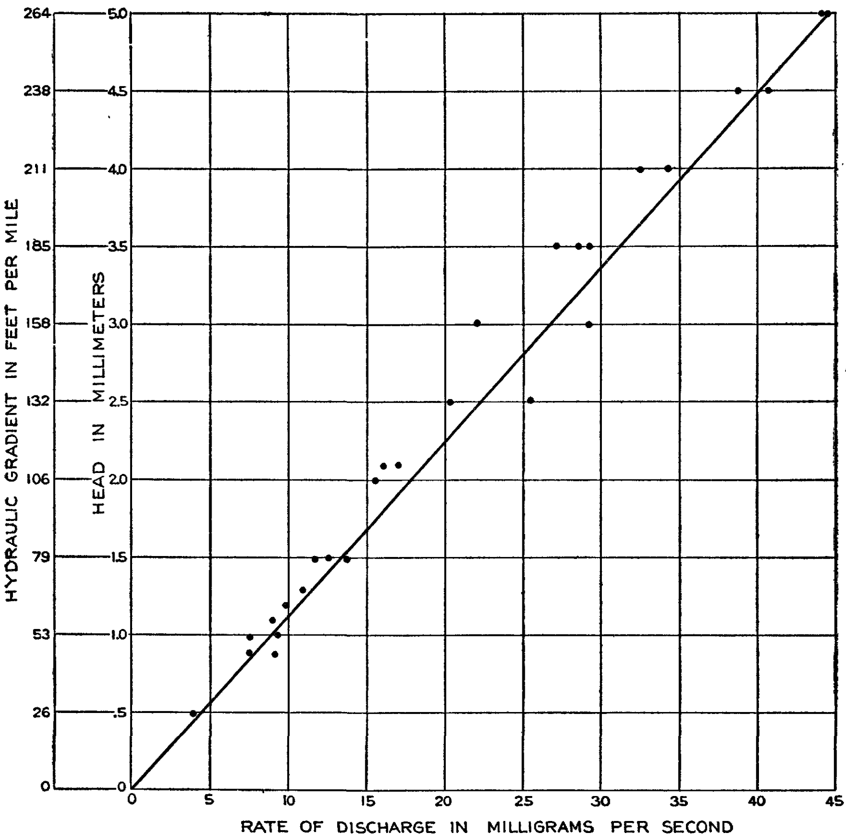

FIGURE 26.—Diagram showing relation of rate of flow to hydraulic gradient in the experiment in which a 100-millimeter column of sand from Fort Caswell, N. C., was used

PERMEABILITY OF SAND AS CALCULATED BY SLICHTER'S FORMULA

The effective size (that is, the 10 per cent size) of the sand from Fort Caswell is 0.14 millimeter, and the porosity is 49 per cent. From field data[35] the hydraulic gradient during the month of May, 1922, was found to be about 0.9 per cent. By using these figures in Slichter's formula, or graphic scale, the discharge is computed to be 0.468 cubic foot in 24 hours. Computing this at 100 per cent gradient and 60° F. into gallons a day gives a coefficient of permeability of 389. This figure compares very well with the coefficients 415 and 379 obtained by the two permeability tests (pp. 155, 157). The close agreement is believed to be partly accidental and partly due to the fact that this sand is somewhat similar in size of grain and assortment to the sand studied by Hazen.

PERMEABILITY OF SAND AS DETERMINED IN THE FIELD WITH DYE

The uranin dye used in the experiment reached a known distance of 23 feet in 30 days at trench 500. It is possible that the dye had gone farther, but for the distance of 23 feet there is positive evidence. Using the 0.9 per cent hydraulic gradient and the rate of 23 feet in 30 days gives a coefficient of permeability of 306.

SUMMARY OF EXPERIMENTS WITH SAND FROM FORT CASWELL

The experiments made on the sand from Fort Caswell gave consistent results and support Darcy's law for hydraulic gradients ranging from 270 feet down to 5 feet to the mile. The tests made with the long column checked closely with those made with the short column and indicated that tests with the more convenient short-column apparatus are trustworthy. The field determination of rate of movement by means of dye showed a permeability that agreed substantially with that obtained in the laboratory tests. Moreover, the permeability as computed by Slichter's formula agreed closely with the permeability derived by the laboratory and field tests. After these preliminary determinations and checks, the short-cylinder apparatus was adopted for making permeability tests on the regular samples.

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[35] Stearns, N. D., Report on the geology and ground-water hydrology of the experimental area of the United States Public Health Service at Fort Caswell, N. C.: U. S. Pub. Health Service Hygienic Lab. Bull. 147, pp. 137–168, 1927.

TABLES

Permeability tests

No. of test	Height of column (millimeters)	Head (millimeters)	Hydraulic gradient (per cent)	Rate of low (milligrams per second)	Temperature (° F.)	Coefficient of permeability, individual test	Average
10	100	4.86	4.86	60.61	73	482	495
		5.8	5.8	69.93		466	
		3.0	3.0	41.67		537	
		.96	.96	13.51		544	
		6.15	6.15	71.43		449	
11	70	4.0	5.71	59.95	71	420	413
		6.0	8.57	87.72		410	
		7.5	10.71	114.15		427	
		5.0	7.14	71.84		403	
		3.0	4.29	43.40		405	
12	40	2.66	6.65	85.03	62	577	562
		4.0	10.00	124.37		562	
		5.0	12.50	148.80		538	
		3.5	8.75	101.62		525	
		1.75	4.38	58.27		602	
		.5	1.25	15.69		567	
13	100	5.0	5.00	65.10	70	527	545
		6.5	6.50	88.65		552	
		8.0	8.00	114.15		578	
		5.0	5.00	63.10		511	
		3.5	3.50	48.17		558	
14	100	9.0	9.00	112.61	68	514	518
		13.0	13.00	166.66		531	
		10.0	10.00	130.20		540	
		9.0	9.00	105.48		486	
		3.0	3.00	36.23		500	
		5.5	5.50	70.02		528	
		8.0	8.00	101.62		526	
15	55	5.0	9.09	284.94		947	1,095
		4.0	7.27	163.57		1,047	
		2.0	3.65	95.37		1,221	
		3.5	6.36	150.58		1,102	
		.5	.91	22.53		1,154	
16	93	10.0	10.75	66.66	62	280	287
		12.0	12.90	80.90		283	
		15.0	16.13	102.88		288	
		19.0	20.43	128.20		283	
		13.0	14.00	88.65		286	
		7.0	7.53	50.50		303	
18	110	41.0	37.27	12.27	70	13	13
		28.0	25.56	8.26		13	
		15.0	13.64	3.82		11	
		19.0	17.27	5.05		12	
		27.0	24.56	8.27		14	
		38.0	34.56	11.79		14	
		4.72	4.29	1.26	69	12	
22	90	17.0	18.89	11.90	68	26	28
		22.0	24.44	15.84		27	
		29.0	32.22	20.88		27	
		34.0	37.78	25.02		27	
		39.0	43.33	28.44		27	
		32.0	35.56	25.02		29	
		26.0	28.89	20.42		29	
23	95	11.0	11.58	61.84	68	221	246
		15.5	16.32	95.78		243	
		17.5	18.42	122.54		276	
		13.0	13.68	80.13		243	
		10.0	10.53	62.19		245	
24	95	6.0	6.32	52.41	70	336	317
		8.0	8.42	66.66		321	
		11.0	11.58	87.72		307	
		12.0	12.63	99.20		318	
		14.0	14.74	117.37		323	
		10.0	10.53	80.13		308	
		5.0	5.26	39.49		304	
26	108	29.0	26.85	8.04	62	14	14
		34.0	31.48	9.67		14	
		39.0	36.11	11.26		14	
		49.0	45.37	13.98		14	
		44.0	40.74	12.47		14	
		34.0	31.48	9.66		14	
27	100	29.0	29.00	6.80	68	10	10
		33.0	33.00	8.09		10	
		38.0	38.00	9.29		10	
		43.0	43.00	10.29		10	
		40.0	40.00	9.88		10	
		30.0	30.00	7.44		10	

Permeability tests—Continued

No. of test	Height of column (millimeters)	Head (millimeters)	Hydraulic gradient (per cent)	Rate of low (milligrams per second)	Temperature (° F.)	Coefficient of permeability, individual test	Average
28	105	14.0	13.33	12.68	87	31	31
		19.0	18.10	17.22		31	
		29.0	27.62	26.12		31	
34	100	12.0	12.00	83.33	84	236	236
		16.5	16.50	114.94		237	
		21.0	21.00	144.93		235	
37	100	22.0	22.00	32.26	80	53	53
		25.0	25.00	37.04		53	
		30.0	30.00	44.05		53	
		35.0	35.00	51.28		53	
38	92	64.0	69.57	1.05	85	.51	.55
		68.0	73.91	1.21		.55	
		78.0	84.78	1.43		.56	
		84.0	91.30	1.64		.60	
42	120	35.0	29.17	53.19	77	67	68
		30.0	25.00	48.78		72	
		40.0	33.33	62.11		69	
		45.0	37.50	67.57		66	
43	50	10.0	20.00	70.92	78	13	13
		7.0	14.00	51.28		13	
		5.0	10.00	36.10		13	
45	100	4.0	4.00	35.71	84	303	314
		8.5	8.50	80.00		320	
		13.0	13.00	121.95		319	
55	100	12.0	12.00	47.62	85	133	132
		17.0	17.00	66.67		131	
		22.0	22.00	86.96		133	
59	100	43.0	43.00	13.89	73	12	13
		53.0	53.00	18.77		14	
		58.0	58.00	21.37		14	
		39.0	39.00	13.08		13	
63	100	5.0	5.00	119.05	79	865	856
		8.0	8.00	185.19		841	
		3.0	3.00	74.07		863	
64	100	47.0	47.00	100.40	80	77	77
		50.0	50.00	105.48		76	
		40.0	40.00	85.91		77	
		35.0	35.00	75.75		78	
65	85	15.0	17.64	57.80	78	120	120
		20.0	23.53	77.52		121	
		25.0	29.41	95.24		119	
67	115	54.0	46.96	17.48	80	13	14
		59.0	51.30	19.61		14	
		64.0	55.65	20.96		13	
68	80	7.0	8.75	344.83	80	1,413	1,233
		4.0	5.00	161.29		1,156	
		2.0	2.50	95.24		1,466	
		5.0	6.25	196.08		1,125	
		4.0	5.00	153.85		1,103	
69	107	22.0	20.56	74.07	76	134	134
		25.0	23.36	84.03		134	
		30.0	28.04	99.01		131	
		20.0	18.69	68.03		136	
70	102	4.0	3.92	100.00	81	902	827
		2.0	1.96	43.48		785	
		2.0	1.96	43.48		785	
		5.0	4.90	129.87		937	
		3.0	2.94	60.24		725	
71	100	4.0	4.00	41.05	67	435	412
		7.0	7.00	61.75		374	
		9.0	9.00	89.60		422	
		6.0	6.00	54.82		387	
		12.0	12.00	122.54		433	
		17.0	17.00	160.25		399	
		23.0	23.00	213.67		394	
		35.0	35.00	373.13		452	
72	93	1.5	1.61	25.48	72	625	589
		4.0	4.30	66.66		614	
		8.5	9.14	138.88		601	
		11.0	11.83	157.23		526	
		13.0	13.98	200.00		566	
		5.0	5.38	81.70		601	
73	100	2.5	2.50	193.79	59	3,681	3,588
		1.66	1.66	134.40		3,845	
		3.0	3.00	252.52		3,997	
		3.0	3.00	203.24		3,217	
		2.5	2.50	166.66	58	3,197	
74	110	26.0	23.64	4.27	72	7.15	7.3
		31.0	28.18	5.18		7.27	
		36.0	32.73	6.08		7.36	
		41.0	37.27	7.12		7.46	
		45.0	40.91	7.57		7.32	

Permeability tests—Continued

No. of test	Height of column (millimeters)	Head (millimeters)	Hydraulic gradient (per cent)	Rate of low (milligrams per second)	Temperature (° F.)	Coefficient of permeability, individual test	Average
75	85	36.0	42.35	17.65	65	18	18
		41.5	48.82	20.27		18	
		35.5	41.76	17.01		18	
		10.5	12.35	5.60	72	18	
		14.5	17.06	7.97		18	
		19.5	22.94	10.71		18	
76	90	23.0	25.56	7.02	68	11	11
		28.0	31.11	8.11		11	
		33.0	36.67	9.61		11	
		37.0	41.11	10.92		11	
		41.0	45.56	11.96		11	
77	111	50.0	45.05	.27	67	.26	.26
78	70	31.0	44.29	9.26	71	8.37	8.4
		35.0	50.00	10.47		8.38	
		40.0	57.86	12.08		8.36	
		44.5	63.57	13.29		8.37	
		50.0	71.43	14.52		8.35	
79	104	55.0	52.88	2.04	71	1.54	1.6
		60.0	57.69	2.27		1.57	
		65.0	62.50	2.50		1.60	
		70.0	67.31	2.71		1.61	
		75.0	72.12	2.91		1.61	
80	100	3.0	3.00	10.27	67	[a] 113	123
		6.0	6.00	21.93		[a] 121	
		11.0	11.00	43.40		[a] 130	
		15.0	15.00	57.08		[a] 126	
81	100	14.0	14.00	38.94	64	122	121
		20.0	20.00	52.41		115	
		23.0	23.00	64.60		123	
		18.0	18.00	49.02		119	
		13.0	13.00	36.23		122	
		7.5	7.50	21.64		126	
82	97	7.0	7.22	10.89	66	65	71
		11.5	11.86	19.56		71	
		16.0	16.49	28.44		74	
		21.0	21.65	37.54		74	
		26.0	26.80	46.55		74	
		17.0	17.53	28.93		71	
		12.0	12.37	20.08		70	
83	104	10.0	9.62	37.37	68	161	154
		13.0	12.50	48.45		161	
		20.0	19.23	68.30		147	
		25.0	24.04	84.17		145	
		15.0	14.42	51.12		147	
		5.0	4.81	18.81		162	
99	116	5.0	4.31	2,500.00	80	20,794	20,663
		4.0	3.45	2,000.00		20,794	
		3.0	2.59	1,428.57		20,061	
		2.0	1.72	1,000.00		21,004	
100	100	3.0	3.00	30.52	65	440	504
		4.0	4.00	43.40		470	
		5.0	5.00	63.61		551	
		7.0	7.00	83.83		515	
		4.0	4.00	54.46		590	
		2.0	2.00	23.34		505	
		1.0	1.00	10.52		455	
101	100	7.0	7.00	8.13	70	47	54
		12.0	12.00	14.49		59	
		16.0	16.00	21.10		53	
		23.0	23.00	29.45		52	
		27.0	27.00	36.23		54	
		23.0	23.00	29.76		52	
		20.0	20.00	27.23		55	
		8.0	8.00	10.51		53	
102	100	3.0	3.00	88.65	73	1,142	1,063
		5.5	5.50	143.67		1,010	
		4.5	4.50	120.77		1,037	
		7.0	7.00	132.27	70	765	735
		6.0	6.00	108.22		734	
		3.0	3.00	59.10		798	
		6.5	6.50	119.04		742	
		11.0	11.00	173.60		639	
103	96	9.0	9.38	56.30	68	249	250
		7.0	7.22	43.63		248	
		4.0	4.12	22.40		223	
		7.0	7.22	45.79		260	
		11.0	11.34	73.10		264	
		15.0	15.46	96.90		257	

[a] Corrected for 22 per cent large sand discarded.

Permeability tests—Continued

No. of test	Height of column (millimeters)	Head (millimeters)	Hydraulic gradient (per cent)	Rate of low (milligrams per second)	Temperature (° F.)	Coefficient of permeability, individual test	Average
104	100	30.0	30.00	4.70	71	6.27	7.1
		33.0	33.00	5.66		6.87	
		38.0	38.00	6.65		7.01	
		43.0	43.00	8.07		7.51	
		48.0	48.00	8.65		7.22	
		42.0	42.00	7.72		7.36	
		38.0	38.00	6.77		7.13	
		32.0	32.00	6.08		7.58	
105	100	8.0	8.00	72.46	69	371	359
		10.0	10.00	91.57		375	
		12.0	12.00	111.11		379	
		15.0	15.00	126.26		345	
		10.0	10.00	87.72		359	
		7.0	7.00	55.19		323	
106	110	41.0	37.27	.46	68	.52	.59
		50.0	45.45	.61		.52	
		55.0	50.00	.85		.70	
107	110	30 0	27.27	12.63	68	19	20
		35 0	31.82	15.15		20	
		40.0	36.36	17.84		20	
		50.0	45.45	21.93		20	
		45.0	40.91	19.84		20	
		35.0	31.82	15.15		20	
108	105	.67	.64	102.88	65	6,981	6,200
		1.0	.95	126.26		5,740	
		1.33	1.27	177.30		6,061	
		.67	.64	88.65		6,015	
109	100	1.5	1.50	119.05	88	2,587	2,561
		3.0	3.00	208.33		2,263	
		1.0	1.00	86.96		2,834	
110	50	6.25	12.50	213.67	74	654	661
		4.0	8.00	130.20		621	
		2.0	4.00	73.74		704	
		4.5	9.00	157.23		667	
111	50	.6	1.20	400.00	84	11,329	10,464
		4.0	8.00	2,500.00		10,621	
		3.0	6.00	1,666.67		9,441	
112	50	2.0	4.00	303.03	85	2,540	2,554
		1.0	2.00	166.67		2,794	
		3.0	6.00	416.67		2,328	
113	50	3.5	7.00	526.32	84	2,556	2,609
		6.0	12.00	909.09		2,575	
		7.0	14.00	1,111.11		2,698	

Computed and experimental coefficients of permeability of some of the samples that were tested

No. of sample	Effective size (10 per cent size) (millimeter)	Uniformity coefficient	Porosity (per cent)	Coefficient of permeability		No. of sample	Effective size (10 per cent size) (millimeter)	Uniformity coefficient	Porosity (per cent)	Coefficient of permeability	
				Computed	Experimental					Computed	Experimental
59	0.02	3.8	35	2.3	13	15	0.11	4.9	44	150	1,095
18	.02	5.9	44	5.2	[a] 13	71	.11	2.3	40	105	[a] 412
104	.03	20	31	3.5	[b] 7.1	110	.11	2.2	44	150	661
83	.05	18	26	5.3	[c] 154	12	.12	2.5	45	210	562
81	.05	12	29	7.5	[a] 121	103	.12	3.4	38	110	[b] 250
28	.05	2.1	37	17	31	11	.13	2.8	46	270	413
22	.05	4.6	45	32	[b] 27	13	.13	3.1	46	270	545
107	.05	1.6	42	29	20	24	.14	3.5	39	160	[b] 297
101	.06	8.0	38	28	[b] 54	14	.14	2.4	48	350	518
67	.07	1.8	43	58	[c] 14	16	.14	3.1	31	75	[b] 284
82	.07	9.8	30	17	[b] 71	42	.20	25	29	130	68
55	.08	2.5	33	30	[a] 132	72	.23	2.1	42	530	[b] 589
69	.09	2.2	33	39	134	105	.25	8.2	40	530	[a] 359
34	.09	2.1	38	58	236	109	.45	3.0	41	2,000	2,561
45	.10	2.8	35	61	314	65	.55	9.1	25	560	120
23	.10	2.8	43	120	[b] 243	108	.82	2.5	32	2,700	6,200
10	.11	2.3	45	165	495	73	.83	2.1	41	7,500	[a] 3,788

[a] Volumetric sample packed into correct volume; hence, coefficient of permeability probably correct.
[b] Volumetric sample more compacted than in nature; hence, coefficient of permeability probably too small.
[c] Volumetric sample less compacted than in nature; hence, coefficient of permeability probably too large.

Physical properties of materials from Idaho

[Samples are listed in order of geologic age]

Laboratory No.	Apparent specific gravity of oven-dry sample	Mechanical composition (per cent)									10 per cent size (millimeter)	Uniformity coefficient	Porosity (per cent)	Moisture equivalent (per cent by volume)	Porosity minus moisture equivalent by volume	Coefficient of permeability
		>5 millimeters	5-2 millimeters	2-1 millimeters	1-0.5 millimeter	0.5-0.25 millimeter	0.25-0.10 millimeter	0.10-0.05 millimeter	Silt 0.05-0.005 millimeter	Clay >0.005 millimeter						
74	1.25				0.27	0.91	36.63	37.00	20.75	4.44	0.02	5.2	53.2	32.8	20.4	7.3
75	1.19			7.37	7.16	11.75	25.76	20.53	27.43		<.005	<30	53.7	15.2	38.5	[a]18
76	1.01				1.54	3.41	48.79	21.42	22.49	2.37	.04	2.8	61.1	18.7	42.4	[a]11
77	1.19					1.25	24.50	30.83	40.30	3.12	.01	6.0	54.1	49.8	4.3	[a].26
78	.75				.29	5.84	57.25	10.71	22.19	3.72	.02	8.4	69.4	18.1	51.3	[a]8.4
106	1.00					6.58	21.90	6.42	52.69	12.41	<.005	<8	62.9	32.3	30.6	.59
107	1.51			.95	1.33	2.65	30.67	59.52	4.02	.86	.05	1.7	42.4	13.5	28.9	20

[a] Volumetric sample apparently compacted more in percolation cylinder than in nature.

74. Jerome County. Soil from Jerome Reservoir; typical of loess covering of Snake River Plains.

75. Fremont County, southeast corner lot 1, sec. 30, T. 12 N., R. 43 E. Gravelly loam soil from floor of proposed Island Park Reservoir.

76. Fremont County, sec. 34, T. 12 N., R. 43 E. (probably). Loess soil, covering basalt, from floor of proposed Island Park Reservoir.

77. Caribou County, sec. 13, T. 8 S., R. 41 E. Black gumbo soil from marsh. Taken 2 feet above Soda Creek from site proposed for upper reservoir of the Empire Irrigation District.

78. Caribou County, southwest corner SW. ¼ SE. ¼ sec. 24, T. 8 S., R. 41 E. Loess soil from cover of basalt at site of proposed dam for lower reservoir of the Empire Irrigation District on Soda Creek.

106. Jefferson County, southeast corner NE. ¼ sec. 30, T. 6 N., R. 34 E. Clay 2¼ feet below surface on J. J. Tierney's ranch.

107. Clark County. Red clay 56½ feet below surface in city well of Dubois, Idaho. Clay is 10 feet thick and holds water perched at this level. It lies between the upper and lower flows of lava.

Physical properties of materials from Fergus County, Mont.

[Samples are listed in order of geologic age]

Laboratory No.	Apparent specific gravity of oven-dry sample	Mechanical composition (per cent)									10 per cent size (millimeters)	Uniformity coefficient	Porosity (per cent)	Moisture equivalent (per cent by volume)	Porosity minus moisture equivalent by volume	Coefficient of permeability
		>5 millimeter	5-2 millimeter	2-1 millimeter	1-0.5 millimeter	0.5-0.25 millimeter	0.25-0.10 millimeter	0.10-0.05 millimeter	Silt 0.05-0.005 millimeter	Clay <0.005 millimeter						
99	1.89	73.98	5.84	1.11	2.16	4.93	4.51	2.74	3.58	1.15	1.85	>27	25.1	----------	----------	20,663
92	2.09	----------	----------	----------	----------	----------	46.88	31.31	17.80	4.01	.02	5.3	22.6	20.6	2.0	----------
91	1.97	----------	----------	1.17	4.53	11.97	64.25	8.72	6.05	3.30	.05	4.2	26.8	12.4	14.4	----------
90	1.93	----------	----------	1.35	5.71	10.02	60.26	7.78	8.37	6.50	.02	7.1	27.1	15.0	12.1	----------
89	2.06	----------	----------	1.88	3.73	4.18	64.48	16.49	6.33	2.91	.05	2.9	23.6	16.5	7.1	----------
87	2.07	----------	----------	----------	2.90	4.35	14.56	67.15	7.92	3.12	.05	1.7	22.6	18.6	4.0	----------
88	2.06	----------	----------	1.66	7.81	7.63	56.57	11.98	9.66	4.69	.03	5.4	23.2	14.3	8.9	----------
86	1.96	----------	----------	----------	----------	16.82	76.84	3.23	2.54	.57	.10	2.1	25.8	4.2	21.6	----------

99. SE. ¼ sec. 30, T. 16 N., R. 18 E. Quaternary. Pleistocene (?) gravel of Judith Basin.
92. SW. ¼ sec. 27, T. 6 N., R. 26 E., north of Buckey. Tertiary. Typical sandstone of Fort Union formation, 400 feet above base of upper part of formation.
91. SE. ¼ sec. 3, T. 3 N., R. 26 E. Tertiary (?). Typical sandstone of Lance formation, 75 feet above base of formation.
90. SE. ¼ sec. 36, T. 18 N., R. 19 E., northeast of Hilger. Upper Cretaceous. Eagle sandstone, Virgelle sandstone member, about 25 feet above its base.
89. SW. ¼ sec. 27, T. 1 N., R. 26 E., north of Billings. Upper Cretaceous. Eagle sandstone, Virgelle sandstone member; typical of Virgelle member of the vicinity.
87. NE ¼ sec. 17, T. 15 N., R. 21 E., cut on Great Northern Ry. just west of Novary post office (abandoned). Upper Cretaceous. Colorado shale, First Cat Creek sand, about 20 feet below top. Thin bedded.
88. NE ¼ sec. 15, T. 15 N., R. 20 E. Lower Cretaceous. Kootenai formation, Second Cat Creek sand, a porous sandstone about 150 feet below top of the Kootenai.
86. NW. ¼ sec. 17, T. 15 N., R. 17 E., 1½ miles east of east entrance to the Eastern tunnel of Great Northern Ry. Lower Cretaceous. Kootenai formation, Third Cat Creek sand. Thin bedded.

Physical properties of materials from New Jersey

[Samples are listed in order of geologic age]

Laboratory No.	Apparent specific gravity of oven-dry sample	Mechanical composition (per cent)									10 per cent size (millimeter)	Uniformity coefficient	Porosity (per cent)	Moisture equivalent (per cent by volume)	Porosity minus moisture equivalent by volume	Coefficient of permeability
		>5 millimeters	5-2 millimeters	2-1 millimeters	1-0.5 millimeter	0.5-0.25 millimeter	0.25-0.10 millimeter	0.10-0.05 millimeter	Silt 0.05-0.005 millimeter	Clay <0.005 millimeter						
79	1.25					0.14	6.48	22.93	53.09	17.36	<0.005	<8.4	53.2	37.8	15.4	1.6
18	1.47				0.26	.45	61.62	22.22	8.62	6.81	.02	5.9	44.5	20.0	24.5	13
19	1.47		0.66	0.75	.56	.92	62.50	15.45	9.27	9.89	.005	31	46.6	19.1	27.5	
26	1.47				.17	1.35	73.95	3.50	15.29	5.74	.02	8.0	45.3	17.4	27.9	14
27	1.47			.22	1.03	41.67	39.68	2.36	12.72	2.31	.04	6.8	43.6	18.1	25.5	10
10	1.48			.66	2.71	33.61	60.43	.67	.44	1.48	.11	2.3	44.7	3.0	41.7	495
16	1.50		.65	4.10	14.85	45.13	31.72	.86	1.32	1.45	.14	3.1	31.4	3.7	27.7	[a] 284
17	1.52		3.10	2.79	6.54	33.54	44.51	2.39	2.92	4.21	.09	3.3	42.1	9.2	32.9	
21	1.47		.63	2.86	6.10	27.87	49.17	5.75	6.01	1.60	.07	3.7	30.8	5.7	25.1	
22	1.47		.75	1.43	5.70	26.78	49.32	6.33	6.93	2.78	.05	4.6	45.3	6.7	38.6	[a] 27
23	1.51		.96	2.92	8.91	31.68	48.16	3.07	2.54	1.74	.10	2.8	42.6	5.0	37.2	[a] 243
24	1.56		6.35	8.57	14.83	39.76	27.21	.54	1.71	.64	.14	3.5	39.4	5.4	34.3	[a] 297
25	1.47		.56	1.76	9.76	34.35	42.52	3.82	4.64	2.59	.08	3.7	44.9	4.2	40.7	
80	1.77		23.73	17.41	20.97	16.70	10.98	1.25	5.90	3.06	.09	12	25.5	5.7	19.8	122
81	1.75		17.97	5.75	18.77	27.40	17.47	1.43	7.76	3.46	.05	12	29.0	6.8	22.2	121
82	1.67		20.00	5.41	17.78	24.51	21.12	1.69	6.57	2.92	.07	9.8	30.0	5.2	24.8	[a] 71
83	1.76		21.60	13.19	20.65	21.93	9.95	.87	8.26	3.56	.05	18	26.2	8.8	17.4	[b] 154
100	1.81		33.25	28.85	1.57	10.26	5.91	.64	2.94	2.41	.20	8.9	23.4	3.7	19.7	504
101	1.65		.47	4.67	23.00	34.82	25.69	1.73	6.83	2.79	.06	8	37.9	5.3	32.6	[a] 54
102	1.85		50.78	26.96	7.15	7.91	3.03	.36	2.06	1.74	.38	>5.3	27.4	2.6	24.8	{1,063 735
103	1.59			4.17	18.61	37.66	33.85	1.83	2.28	1.60	.12	3.4	37.7	2.6	35.1	[a] 250
104	1.74		2.62	10.12	21.57	23.30	20.18	2.70	14.42	5.08	.03	20	30.8	15.8	15.0	[a] 7.1
105	1.55					40.29	57.24	.39	.92	1.16	.25	>8.2	39.9	2.0	37.9	359
110	1.47			1.66	5.55	30.25	61.10	1.44			.11	2.2	44.3			[d] 662
109	1.56		10.18	45.09	29.87	11.65	3.13	.08			.45	3.0	41.2			[d] 2,561
111	1.66		22.99	35.11	16.05	16.64	6.43	.23	.66	1.89	.27	5.6	38.5			10,464
112	1.81		8.35	22.44	35.75	19.66	11.54	.68	.56	1.02	.23	3.8	30.2			2,554
113	1.67			16.13	60.42	17.21	4.27	.25	.58	1.14	.37	2.3	35.8			2,609
108	1.67	30.67	40.99	13.69	10.22	3.11	.89	.08	.35		.82	>2.5	31.9	7.1	24.8	[c] 6,200
73	1.54		27.30	54.26	15.67	.40	.34	.09	.74	1.21	.83	2.1	41.5	2.1	39.4	3,788
84	1.75		49.29	26.27	9.12	3.31	3.80	1.30	4.96	1.96	.21	>9.5	35.7	4.2	31.5	
12	1.46			.80	5.89	42.79	48.31	.93	.48	.79	.12	2.5	44.8	1.8	43.0	562
13	1.42			1.17	12.83	52.31	32.02	.43	.40	.84	.13	3.1	46.5	1.8	44.7	545
14	1.37			.82	3.66	50.09	43.74	.67	.43	.59	.14	2.4	48.4	1.3	47.1	518
71	1.51			.58	6.60	33.41	56.63	1.65	.51	.63	.11	2.3	39.9	1.9	38.0	412
72	1.47			2.44	17.83	65.92	11.37	1.36	.49	.59	.23	2.1	41.7	2.2	39.5	[a] 589
11	1.44			1.20	10.50	48.70	37.16	.79	.34	1.30	.13	2.8	45.8	2.7	43.7	413
15	1.48			2.69	30.59	47.10	11.18	.60	1.56	6.29	.11	4.9	44.4	5.4	39.0	1,095

[a] Volumetric sample apparently compacted more in percolation cylinder than in nature.
[b] Volumetric sample apparently less compacted in percolation cylinder than in nature.
[c] Large pebbles discarded in field.
[d] Sand artificially washed in field.

79. Princeton, from depth of 1 foot in trench near No. 6 well at pumping plant of Princeton Water Co. Quaternary. Recent.
18. Old Bridge, at Joseph Morrell's place, at depth of 2 feet in test hole. Quaternary. Recent or Pleistocene.
19. Old Bridge, from test hole at Joseph Morrell's place. Quaternary. Recent or Pleistocene.
26. Old Bridge, at Joseph Morrell's place, from depth of 4 feet, just above seepage of water in gage well. Quaternary. Recent or Pleistocene.
27. Old Bridge, from Morrell observation well; black sand at depth of 6 feet at bottom of hole. Quaternary. Recent or Pleistocene.
10. Runyon, from depth of 4 feet from ditch at new well and large receiving well. Characteristic of surface material of spreading basins. Quaternary. Cape May formation (Pleistocene).
16. Runyon, from depth of 4 feet in deepest hole at tank plot. Quaternary. Cape May formation (Pleistocene).
17. Runyon, from depth of 18 inches in deepest hole at tank plot. Quaternary. Cape May formation (Pleistocene).
21. Runyon, from small sand pit about 200 yards west of soil tanks, 15 inches below surface at cut. Quaternary. Cape May formation (Pleistocene).
22. Runyon, from small sand pit about 200 yards west of soil tanks, 21 inches below surface of cut. Quaternary. Cape May formation (Pleistocene).
23. Runyon, from small sand pit about 200 yards west of soil tanks, 33 inches below surface of cut. Quaternary. Cape May formation (Pleistocene).
24. Runyon, from small sand pit about 200 yards west of soil tanks, 48 inches below surface of cut. Quaternary. Cape May formation (Pleistocene).
25. Runyon, same as Nos. 21 and 22. Quaternary. Cape May formation (Pleistocene).
80. Pleasantville, from depth of 1 foot in field west of Atlantic City pumping plant. Quaternary. Cape May formation (Pleistocene).
81. Pleasantville, from depth of 1 foot, 25 feet north of No. 80. Quaternary. Cape May formation (Pleistocene).
82. Pleasantville, about 5 feet from No. 81. Quaternary. Cape May formation (Pleistocene).
83. Pleasantville, about 2 feet from No. 82. Quaternary. Cape May formation (Pleistocene).
100. Absecon, from same pit as No. 105, depth 2 feet. Quaternary. Cape May formation (Pleistocene).
101. Absecon, on west side of embayment of pond, about 50 feet northeast of No. 104, about 30 inches above water. Quaternary. Cape May formation (Pleistocene).
102. Absecon, south side of pond, about 75 feet south of old dam, 10 feet above water. Quaternary. Cape May formation (Pleistocene).
103. Absecon, north side of Absecon Pond, near derrick at lagoon, 3 feet below general land surface. Quaternary. Cape May formation (Pleistocene).
104. Absecon, at southwest corner of lower Absecon Pond, 100 feet north of dam and 50 feet northeast of observation well No. 2. Quaternary. Cape May formation (Pleistocene).
105. Absecon, from pit about 300 feet west of No. 104, at depth of $3\frac{1}{2}$ feet. Quaternary. Cape May formation (Pleistocene).
110. Atlantic City, from one of upper horizons in new well of the Atlantic City Electric Co. Sample was washed. Tertiary. Kirkwood formation (Miocene).
109. Margate City, from depth between 745 and 795 feet in well of Margate City Water Department. Representative of so-called "800-foot" sand at Atlantic City. Washed. Tertiary. Kirkwood formation (Miocene). washed in field
111. Ocean City, from Thirty-fifth Street well of Ocean City Water Co. Coarse material from near top of so-called "800-foot" water-bearing strata. Washed. Tertiary. Kirkwood formation (Miocene).
112. Ocean City, from Thirty-fifth Street well of Ocean City Water Co. Characteristic of main part of so-called "800-foot" water-bearing sand. Washed. Tertiary. Kirkwood formation (Miocene).
113. Ocean City, from Thirty-fifth Street well of Ocean City Water Co. Fine sand at lower part of so-called "800-foot" horizon. Washed. Tertiary. Kirkwood formation (Miocene).
108. Delair, from depth of 185 feet, test well No. 2, Puchack Run field of Camden Water Department. Upper Cretaceous. Raritan formation.
73. Milltown, one-half mile south of, from pit of Marcus Wright. Coarse. Upper Cretaceous. Raritan formation (?).
84. Milltown, one-half mile south of, from pit of Marcus Wright. Very coarse. Upper Cretaceous. Raritan formation (?).
12. South River, east of, from pit of Marcus Wright, southwest side, 35 feet from top. White sand with few pieces of clay mixed in like pebbles. Upper Cretaceous. Raritan formation.
13. South River, from pit about 150 feet east of No. 12 and 5 feet higher. Yellow, with iron yellow bands. Upper Cretaceous. Raritan formation.
14. South River, from pit about 300 feet north, a little east, and 5 feet lower than No. 12. Upper Cretaceous. Raritan formation.
71. Old Bridge, 1 mile north of, from pit of Marcus Wright, southwest side. Fine. From sand between the Woodbridge and South Amboy fire clays of the Raritan formation. Upper Cretaceous. Raritan formation.
72. Old Bridge, from east side of same pit as No. 71. Medium sand. From sand between the Woodbridge and South Amboy fire clays of the Raritan formation. Upper Cretaceous. Raritan formation.
X 11. Runyon, loose white sand from dump of new well near large receiving cistern. Said to be characteristic water-bearing stratum. Sand between the South Amboy fire clay and the Amboy stone ware clay of the Raritan formation. Upper Cretaceous. Raritan formation.
X 15. Imlaystown, from test hole, 20 feet below stream bed, at dam site. Upper Cretaceous. Mount Laurel or underlying Wenonah sand.

Physical properties of materials from Rosebud County, Mont.

Laboratory No.	Apparent specific gravity of oven-dry sample	Mechanical composition (per cent)									10 per cent size (millimeter)	Uniformity coefficient	Porosity (per cent)	Moisture equivalent (per cent by volume)	Porosity minus moisture equivalent by volume	Coefficient of permeability
		>5 millimeters	5–2 millimeters	2–1 millimeters	1–0.5 millimeter	0.5–0.25 millimeter	0.25–0.10 millimeter	0.10–0.05 millimeter	Silt 0.05–0.005 millimeter	Clay <0.005 millimeter						
38	1.36		3.92	0.43	0.66	2.31	18.57	49.61	18.58	5.93	0.02	4.0	49.9	17.6	32.3	[a] 0.55
42	1.36	76.33	8.03	1.99	1.44	1.57	5.14	3.03	2.18	.28	.20	>25	29.3			68
70	2.19	62.94	11.85	2.86	.86	5.07	13.32	2.22	.45	.42			20.2			827
37	1.99	73.27	7.07	.62	.20	4.36	10.57	2.68	.86	.37	.19	>26	24.1			53
63	2.02	66.02	6.79	12.76	2.58	1.93	2.98	.86	3.41	2.67			27.1			856
65	2.04	82.90	5.77	.58	.49	1.92	5.35	1.17	1.52	.31	.55	>9	25.1			120
68	2.05	78.22	2.17	2.07	6.56	8.62	1.25	.22	.76	.13	.55	>9	23.6			1,233
31	1.71				.44	1.72	78.27	10.68	8.13	.76	.06	3.1	36.6	12.1	24.5	
32	1.85					.23	50.97	31.82	12.61	4.36	.03	3.7	31.6	16.8	14.8	
49	1.82				1.51	7.86	75.67	5.70	9.26		.06	3.5	30.7	13.1	17.6	
50	1.87				5.34	9.60	52.82	23.99	7.97	.29	.06	3.3	30.6	10.8	19.8	
51	2.19			9.02	9.69	16.29	32.54	20.79	5.49	6.18	.05	4.6	19.1	16.1	3.0	
52	2.50		3.40	9.87	15.97	12.64	24.33	20.29	7.15	6.36	.04	8.6	9.4	20.5		
54	2.06					.30	.17	1.76	46.99	50.79	<.005	>2.6	23.5	76.7		
55	1.81			.22	.67	8.51	76.78	9.53	3.58	.71	.08	2.5	32.9	8.4	24.5	132
56	1.67				.49	.58	.82	4.80	36.09	57.21	<.005	<1.0	36.9	41.8		
57	1.84				.36	1.45	6.04	64.99	14.04	13.13	<.005	>14	31.4	27.7	3.7	
58	1.27						1.01	58.23	15.07	25.69	<.005	>12	53.6	76.4		Imperm.
59	1.79					.42	7.62	64.37	24.96	2.64	.02	3.8	34.9	21.5	13.4	13
36	1.91						2.23	28.03	42.97	26.77	<.005	>7.8	26.2	122		
60	2.07						1.70	4.96	32.16	61.17	<.005	<1.0	21.2	124		
66	1.93				.52	.84	44.34	13.14	17.30	23.85	<.005	>22	27.7	172		
35	1.65					.38	6.13	8.86	54.57	30.07	<.005	>6	40.1	52.5		
48	2.00				.75	1.66	8.69	42.17	37.75	8.98	.006	10.0	26.7	41.7		
53	1.73				.21	1.41	35.17	47.55	8.45	7.21	.03	2.9	36.6	61.9		
61	1.92						3.51	9.92	51.17	35.40	<.005	>5.6	29.8	72.0		
64	1.73					44.84	42.62	1.33	11.21		<.05	>5.7	34.0	10.7	23.3	77
30	2.08			13.74	24.77	14.08	21.74	15.02	8.73	1.92	.05	9.1	24.8	21	3.3	
33	1.72				.42	6.48	87.40	3.28	2.42		.10	2.0	36.1	6.4	29.7	
34	1.66				3.05	8.39	80.25	5.69	2.62		.09	2.1	38.3	5.7	32.6	236
45	1.73				1.52	40.69	50.46	2.61	4.71		.10	2.8	35.2	11.4	23.8	314
62	1.80				.65	2.14	59.50	29.00	8.70		.05	2.5	32.8	10.8	22.0	
28	1.72				1.34	4.86	42.04	41.60	9.68	.48	.05	2.1	36.7	16.3	20.4	31
44	1.72					.51	53.24	38.02	8.23		.05	2.0	38.4	17.9	20.5	
46	1.87				.77	3.52	19.91	60.74	12.85	2.20	.03	2.5	30.8	19.5	11.3	
47	2.01					.54	1.03	8.02	75.84	14.57	<.005	>6.4	27.4	52.5		
67	1.54					.94	54.90	37.96	6.19		.07	1.9	43.0	11.7	31.3	[b] 14
39	1.57				.25	1.57	13.50	11.37	53.94	19.37	<.005	>7.8	41.1	85.2		
40	1.54				.50	1.45	12.50	49.79	29.60	6.16	.01	7.0	44.8	39.2	12.1	
29	1.78				.38	2.60	44.30	46.69	5.57	.46	.05	2.1	32.3	13.0	19.3	
69	1.73				.45	14.94	75.75	1.78	7.08		.09	2.2	33.2	7.6	25.6	134
43	1.91				1.12	9.09	82.57	1.44	4.94	.84	.10	2.1	51.2	11	40.1	13
41	1.81			8.00	9.73	7.57	10.64	17.08	36.93	10.04	.005	15	36.3	48.6		

[a] Volumetric sample, compacted too much; coefficient probably too small. [b] Volumetric sample, compacted too little; coefficient probably too large.

38. Center of sec. 22, T. 2 S., R. 44 E. Alluvium silt from Tongue River. Quaternary. Recent.

42. Center of sec. 22, T. 2 S., R. 44 E. Alluvium gravel from Tongue River. Consists mostly of clinkered shale and sandstone in matrix of sand and silt Gravel lenses in silt. Quaternary. Recent.

70. NW. ¼ NW. ¼ sec. 23, T. 6 N., R. 40 E. Alluvium from gravel bar in Yellowstone River. Quaternary. Recent.

37. SW. ¼ sec. 21, T. 6 N., R. 42 E. Terrace gravel. Quaternary. Pleistocene (?).

63. Center of sec. 4, T. 6 N., R. 44 E. Terrace gravel. Quaternary. Pleistocene (?).

65. SE. ¼ sec. 14, T. 6 N., R. 42 E. Terrace gravel which covers top of terrace between Sweeney and Rosebud Creeks. Quaternary. Pleistocene (?).

68. NE. ¼ sec. 19, T. 6 N., R. 41 E. Terrace gravel from top bench. Quaternary. Pleistocene (?).

31. NW. ¼ sec. 24, T. 3 N., R. 41 E. On Burleigh ranch. Lenticular, grading into shale at places. Gives rise to a never-failing spring. Tertiary. Fort Union formation (Eocene), Tongue River member.

32. NW. ¼ SW. ¼ sec. 4, T. 2 N., R. 39 E. Sandstone from Fort Union formation below first clinker and above Lebo shale member. These sandstone beds yield good water in this locality. Tertiary. Fort Union formation (Eocene), Tongue River member.

49. NE. ¼ sec. 6, T. 2 S., R. 41 E. Sandstone about 75 feet below the Rosebud coal. Tertiary. Fort Union formation (Eocene), Tongue River member.

50. NW. ¼ sec. 33, T. 2 N., R. 43 E. Within lower 75 feet of formation. Grades from coherent massive sandstone with concretionary beds to slightly cemented sand. Tertiary. Fort Union formation (Eocene), Tongue River member.

51. SW. ¼ sec. 29, T. 6 S., R. 43 E. Typical of massive sandstone members above the Rosebud coal. Tertiary. Fort Union formation (Eocene), Tongue River member.

52. NW. ¼ sec. 21, T. 7 S., R 44 E. Typical massive sandstone above Rosebud coal. From horizon of massive sandstone above first large lavender clinker bed and below the second large clinker bed that forms top of plateau. Tertiary. Fort Union formation (Eocene), Tongue River member.

54. NE. ¼ NE. ¼ sec. 16, T. 5 S., R. 43 E. Typical arenaceous shale above Rosebud coal. Tertiary. Fort Union formation (Eocene), Tongue River member.

55. NW. ¼ NW. ¼ sec. 32, T. 5 N., R. 43 E. Sand below the first clinker and above the Lebo shale member. Water bearing. Tertiary. Fort Union formation (Eocene), Tongue River member.

56. SW. ¼ sec. 34, T. 1 S., R. 41 E. Typical light-colored shale of Fort Union formation, about 75 feet below clinker of Rosebud coal. Interbedded with massive sandstone. Tertiary. Fort Union formation (Eocene), Tongue River member.

57. NW. ¼ sec. 29, T. 6 S., R. 43 E. Typical sandy silt of Fort Union formation of the region, above Rosebud coal. Tertiary. Fort Union formation (Eocene), Tongue River member.

58. SW. ¼ sec. 30, T. 5 S., R. 43 E. Typical sandy silt of Fort Union formation of the region, above Rosebud coal. Tertiary. Fort Union formation (Eocene), Tongue River member.

59. SW. ¼ sec. 16, T. 1 S., R. 44 E. Typical sand of Fort Union formation above Rosebud coal. Grades into cemented sand which weathers easily. Tertiary. Fort Union formation (Eocene). Tongue River member.

36. NE. ¼ sec. 28, T. 2 N., R. 43 E. From light-colored beds of Lebo member. Tertiary. Fort Union formation, Lebo shale member.

60. SW. ¼ sec. 2, T. 8 N., R. 44 E. Black shale from lower part of Lebo member. Tertiary. Fort Union formation, Lebo shale member.

66. NW. ¼ sec. 34, T. 8 N., R. 42 E. Sandstone from Lebo member. Tertiary. Fort Union formation, Lebo shale member.

35. NW. ¼ sec. 29, T. 7 N., R. 44 E. Nonwater-bearing shale of Lance formation which is identical in appearance to Lebo shale member of Fort Union formation. Tertiary (?). Lance formation, Tullock member.

48. SE. ¼ sec. 31, T. 4 N., R. 43 E. Massive sandstone at top of Tullock member. Tertiary (?). Lance formation, Tullock member.

53. SE. ¼ sec. 35, T. 7 N., R. 44 E. Typical of much of upper part of Lance formation. Tertiary (?). Lance formation, Tullock member.

61. Center of sec. 4, T. 6 N., R. 44 E. Shale. Mineralization is characteristic of much of this shale. Tertiary (?). Lance formation, Tullock member.

64. NE. ¼ sec. 6, T. 6 N., R. 44 E. Slightly indurated cross-bedded sandstone from top of Tullock member. Tertiary (?). Lance formation, Tullock member.

30. NE. ¼ sec. 7, T. 5 N., R. 41 E. On Kenealey ranch. Contributes water to spring. Lenticular. Tertiary (?). Lance formation, Hell Creek member.

33. NW. ¼ sec. 26, T. 6 N., R. 39 E. Basal sandstone. Tertiary (?). Lance formation, Hell Creek member.

34. NW. ¼ sec. 20, T. 6 N., R. 41 E. Sandstone. Tertiary (?). Lance formation, Hell Creek member.

45. SE. ¼ sec. 15, T. 6 N., R. 40 E. Sandstone. Tertiary (?). Lance formation, Hell Creek member.

62. NE. ¼ sec. 29, T. 6 N., R. 40 E. Typical sandstone. Tertiary (?). Lance formation, Hell Creek member.

28. SW. ¼ sec. 24, T. 6 N., R. 44 E. Incoherent sandstone. Good aquifer. Tertiary (?). Lance formation.

44. SW. ¼ sec. 22, T. 5 N., R. 42 E. Sandstone at base of coal series. Aquifer. Tertiary (?). Lance formation.

46. NE. ¼ sec. 12, T. 4 N., R. 42 E. Sandstone, interbedded with shale, No. 47. Tertiary (?). Lance formation.

47. NE. ¼ sec. 12, T. 4 N., R. 42 E. Shale, interbedded with sandstone, No. 46. Tertiary (?). Lance formation.

67. South end Tenth Street, Forsyth. Lance quicksand. Tertiary (?). Lance formation.

39. SW. ¼ sec. 5, T. 6 N., R. 39 E. Shale. Upper Cretaceous. Bearpaw shale.

40. SW. ¼ sec. 17, T. 7 N., R. 44 E. Sandy shale in upper 75 feet of Judith River formation. Upper Cretaceous. Judith River formation, upper sandstone.

29. SE. ¼ sec. 6, T. 8 N., R. 38 E. Basal sandstone. Loosely coherent. Upper Cretaceous. Judith River formation, lower sandstone.

69. SW. ¼ sec. 5, T. 7 N., R. 38 E. Lower sandstone. Very incoherent. Upper Cretaceous. Judith River formation, lower sandstone.

43. SW. ¼ SW. ¼ sec. 22, T. 8 N., R. 38 E. Sandstone. Upper Cretaceous. Judith River formation.

41. NW. ¼ sec. 26, T. 8 N., R. 38 E. Shale, fractured easily. Fractures filled with gypsum. Upper Cretaceous. Claggett shale.

OUTLINE OF WORK BY HAZEN, KING, AND SLICHTER ON EFFECTIVE SIZE IN RELATION TO PERMEABILITY

There has been considerable misunderstanding on the part of some geologists and engineers in regard to the significance of the term "effective size" as used by Hazen, King, and Slichter. It seems desirable, therefore, to give an outline of their work on this subject in so far as it has a bearing on methods of computing permeability.

The term "effective size" was apparently first used by Hazen[36] in connection with his study of water filters. He made mechanical analyses of the sands by sieves and plotted the results in accumulative curves based on percentages by weight of the several sizes. He says:

It has been found as a result of a careful study that the points where the curves in the diagram cut the 10 per cent line give the best idea of the total effect of the various materials. * * * This gives as good an idea of the relative effective sizes of the materials as can be condensed into a single figure for each.

In another report[37] Hazen says:

As a provisional basis which best agrees with the known facts, the size of grain where the curve cuts the 10 per cent line is considered to be the "effective size" of the material. This size is such that 10 per cent of the material is of smaller grains and 90 per cent is of larger grains than the size given. The results obtained at Lawrence indicate that the finer 10 per cent have as much influence upon the action of a material in filtration as the coarser 90 per cent. This is explained by the fact that in a mixed material containing particles of various sizes the water is forced to go around the larger particles and through the finer portions which occupy the intervening spaces, and so it is this finest portion which mainly determines the frictional resistance, the capillary attraction, and, in fact, the action of the sand in almost every way.

Hazen used the effective size in his formula for permeability, or "frictional resistance," but limited the effective sizes that could be used in this way. He says:[38]

The frictional resistance of sand to water within certain limits of size of grain and rate of flow varies directly as the rate and as the depth of sand. This is given by Piefke as Darcy's law. I have found that the friction also varies with the temperature * * * and also that with different sands the resistance varies universally as the square of the effective size of the sand grain. It probably varies also somewhat with the uniformity coefficient, but no satisfactory data are at hand upon that point.

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[36] Hazen, Allen, Experiments upon the purification of sewage and water at the Lawrence Experiment Station, Nov. 1, 1889, to Dec. 31, 1891: Massachusetts State Board of Health Twenty-third Ann. Rept., p. 431, 1892.

[37] Hazen, Allen, Some physical properties of sands and gravels with special reference to their use in filtration: Massachusetts State Board of Health Twenty-fourth Ann. Rept., p. 541, 1893.

[38] Idem, p. 552.

Putting the available data in the shape of a formula, we have

$$V = c\, d^2 \frac{h}{l} (0.70 + 0.03\, t)$$

where V is the velocity of the water in meters daily in a solid column of the same area as that of the sand,

c is the constant factor which present experiments indicate to be approximately 1,000,

d is the effective size of sand grain,

h is the loss of head,

l is the thickness of sand through which water passes, and

t is the temperature on the centigrade scale.

The data at hand only justify the application of this formula to sands having a uniformity coefficient below 5 and effective size of grain 0.10 to 3 millimeters.

Hazen[39] found that for gravel with effective sizes of about 3 millimeters the permeability varied in such a way as to make the application of a general formula very difficult. He says:

As the size increases beyond this point the velocity with a given head does not increase as rapidly as the square of the effective size; and with coarse gravels the velocity varies as the square root of the head instead of directly with the head, as in sands. The influence of temperature also becomes less marked with the coarse gravels.

He gives a table showing the rate at which water will pass through gravel of different sizes under various heads. Regarding this table he says:

The available data for materials about 3 millimeters, which are far less complete than could be desired, have been obtained entirely from screened gravels with uniformity coefficients from 1.4 to 2, and at a temperature of 10° C. or a little above. The results obtained were plotted, making a diagram from which the table has been prepared. The figures given in the table must be taken as provisional, and for use only until more extended results are obtained.

Both King and Slichter used the term "effective size"—King in the sense of mean grain with average surface, and Slichter in the sense of grain of such diameter that if all grains were of that diameter the soil would have the same transmission capacity or permeability that it actually possesses.

King[40] in 1898 described his new method for the mechanical analysis of soils, the primary object of which was to determine the effective size of soil grains, chiefly in connection with soil studies. He states:

We are greatly in need of a method of soil examination which shall give definite data regarding the effective surface of a unit volume of soil, both for the holding of soil moisture and for the solution of plant food; one which will give the effective diameter of the soil grains or grouping of soil grains which determines the water-holding power or saturation capacity of a soil, and which determines the rate of percolation and of air movement through it.

[39] Idem, p. 554.

[40] King, F. H., Wisconsin Univ. Agr. Exper. Sta. Fifteenth Ann. Rept., p. 123, 1898.

Two methods of obtaining effective sizes or mean diameters of soil grains were in use and are mentioned by King.[41] One method consisted of measuring with a micrometer the diameters of all the grains in a sample of soil; the other consisted of counting the grains in a sample of known weight and computing the diameter of the mean grain from the number of grains, the weight of the sample, and the specific gravity. In order to get results that were even approximately accurate a large number of measurements in three dimensions of the grains had to be made by the first method, and a large number of grains had to be counted by the second method. King found that the labor involved in these methods was great and, moreover, that the results obtained by the two methods did not agree very well. Hence he tried to find a less laborious method of obtaining the effective size by means of the flow of water through sands. However, he encountered such difficulties in duplicating results that he resorted to the flow of air through the sand. The use of air was found so much easier and more expeditious, and the results could be duplicated so much more closely that King and Slichter put the method on a quantitative basis. King[42] says:

After considering the subject, it appeared to him [Slichter] that in view of the accepted laws of flow of air and of water through capillary tubes and the extensive experiments which had been made to determine the viscosity of both air and water, it ought to be possible to compute the effective diameter of the soil grains from a knowledge of the observed pore space and the rate at which air would flow through the specimens under known conditions.

The result was Slichter's first formula. This formula[43] for determining the effective diameter of the grain is as follows:

$$d^2 = K \frac{h}{spt} [8.9434 - 10]$$

where d is the diameter of grain in centimeters, h the length of sand column in centimeters, s the area of cross section of sand column in square centimeters, p the pressure in centimeters of water at 20° C., t the time in seconds for 5,000 cubic centimeters of air to flow through at a temperature of 20° C, [8.9434—10] a logarithm of a constant, and K a constant taken from a table that takes account of the factor of porosity.

At this stage of King's work he undertook for the United States Geological Survey an investigation of the movement of ground water, and Slichter collaborated with him in developing certain theoretical phases of the subject.[44] In connection with this work Slichter's second formula was devised. Both formulas, and con-

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[41] King, F. H., op. cit., p. 124.

[42] Idem, p. 126.

[43] Idem, p. 133.

[44] King, F. H., Principles and conditions of the movements of ground water: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, p. 67, 1899.

sequently King's aspirator method were tested and checked by King's experimental data on the rate of flow of water through sand. King[45] says:

The most rigid test yet found for the method is that furnished by comparing the observed flows of water through a series of sands with those which would be computed on theoretical considerations from the diameters as determined by the aspirator. To make such a test as this, and in order also to test the general accuracy of his two formulas, one for determining the diameter of soil grains by means of the aspirator and the other for computing the flow of water through sands, Professor Slichter has, upon request, computed the effective sizes and flows of 10 samples of sand through which the flow of water and air were carefully measured under low pressures and uniform conditions of temperature.

However, as King noted, the observed flows, both for air and for water, were slower than the computed flows through the coarse-grained soils and faster through the fine-grained soils, indicating that the formulas did not exactly meet the demands of the test or that there was some systematic error in the observations or in the operation of the apparatus. Slichter, in recent correspondence, has stated that the small departures noted by King were due to the growth of an organism in the sand.

Regarding this formula, Slichter[46] says:

In Chapter I an attempt is made to derive from purely theoretical considerations an expression for the flow of water or other fluid through a column of soil made up of grains of nearly uniform size and of approximately spherical form. For the purpose of constructing this formula a study is made of the pores of the ideal spherical-grained soil, and the relation of porosity to the average arrangement of the grains is shown and made a factor in the resulting formula. I derive as the formula for the quantity of water per second transmitted by a column of soil the following expression:

$$q = 1.0094 \frac{p\, d^2\, s}{u\, h\, K} \text{ cubic centimeters per second;}$$

in which q is the quantity in cubic centimeters, p is the difference in pressure at the ends of the cylinder in centimeters of water at 4° C., d is the mean diameter of soil grains in centimeters, s is the area of cross section of the cylinder in square centimeters, h is the height of the column of sand in centimeters, u is the coefficient of viscosity of the fluid, K is a constant taken from Table II [table of constants for various porosities of an ideal soil], and [1.0094] is the logarithm of a factor.

Regarding the experiments, King[47] states:

The general conclusion which appears to be indicated by this series is that with the smaller sizes, where the grains give a minimum pore having diameters of 0.0117, 0.01361, 0.01619, and 0.01809 millimeter, and under pressures not

[45] Idem, p. 225.

[46] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey Nineteenth Ann. Rept., pt. 2, p. 301, 1899.

[47] King, F. H., op. cit., p. 241.

exceeding a gradient of about 3 to 5, the flow increases faster than the pressure; but when the diameters of the pores are 0.02756, 0.0248, 0.03249, 0.04094, and 0.05821 millimeter, the flow does not increase so rapidly as the pressure, even when the gradient is no steeper than 1 to 5 in the three coarsest.

Details regarding the apparatus used and the results obtained are given in King's article.[48] The material used was a series of 10 grades of quartz sand, thoroughly washed and screened. The pressures that were used ranged from 0.5 centimeter to 18 centimeters. The length of the sand column was 12 inches, or about 30.5 centimeters. Therefore, the hydraulic gradients ranged from 1.64 to 59.11 per cent, or from 87 to 3,168 feet to the mile.

The experimental basis of the work of King and Slichter, then, consists of the results obtained from observed flows of water through artificially screened and washed sands under relatively high hydraulic gradients. The observed flows did not check very closely with those computed by the formulas using the mean diameters of grain as determined with the aspirator.

Later Slichter made both field and laboratory experiments on the rates of flow of water, and the results obtained were published in water-supply papers of the United States Geological Survey.[49] In Water-Supply Paper 67, pages 18–21, he summarizes the work done on laws of flow, including his own work and that of King. In this paper he makes the following definite statement regarding the effective size (pp. 22, 23):

In order to compare one soil with another as to its capacity to transmit water, it is necessary to have some way of arriving at a mean or average-sized grain which it is appropriate to associate with each sample. This mean diameter is known as the effective size and is such that if all grains were of that diameter the soil would have the same transmission capacity that it actually has. Hazen's method of determining the effective size consists in first separating or analyzing the sand or soil into several grades by use of sieves of known mesh. The effective size is determined from the dimensions of the mesh of a sieve which will permit 10 per cent of the sample to pass through it but will retain the other 90 per cent—that is, in any soil 10 per cent of the grains are smaller than the effective size and 90 per cent are larger. * * * Hazen concludes from his experimental work that the 10 per cent of small grains in a sample of a natural sand or soil has the same influence on the rate of flow of water as the 90 per cent of large grains, provided the uniformity coefficient does not exceed 5. * * *

The most promising method of soil analysis for the purpose of determining its transmission capacity is that devised by Professor King. The analysis is accomplished without the use of sieves, by means of an apparatus known as King's aspirator. In this method the effective size is determined by measuring

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[48] King, F. H., op. cit., pp. 222 et seq.

[49] The following are of especial interest in this connection: Slichter, C. S., The motions of underground waters: U. S. Geol. Survey Water-Supply Paper 67, 1902; Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, 1905.

the time required for the flow of a known amount of air through the sample, the measurements being made under a known pressure. It seems that the results yielded by this method are much more concordant than those given by other methods, and the apparatus deserves a thorough test by engineers interested in soil analysis.

Slichter then summarizes his formula for determining flow and gives a table of velocities of water in sands of different effective sizes of grain and the maximum flow or transmission constant for each sand—that is, the flow with a hydraulic gradient of 100 per cent.

In Water-Supply Paper 140 Slichter discusses the general laws of flow, presents again his formula and tables, and gives a scale for estimating graphically the transmission constant of a sand or gravel. He also gives an account of laboratory experiments upon the flow of water through sand and gravel contained in tanks. These experiments were designed primarily to supplement his electrolytic method used in the field, but also to verify the law of flow of water through sand and gravel under hydraulic gradients similar to those found in the field. The gradients used in the horizontal-tank experiments ranged from 0.33 to 2.04 per cent, or about 17 to 108 feet to the mile. Experiments were also made in a vertical tank with hydraulic gradients of 1 to 11.91 per cent, or about 53 to 630 feet to the mile. Mechanical analyses made by screening are given for each of the materials used in the tests, but their relation to the observed permeabilities is not discussed. The conclusion was reached that "the law of direct variation of the flow of ground waters with the head under which the flow takes place are verified by the experiments in the tank."

Hazen's effective size has been used in Slichter's formula with varying results. Smith,[50] in his studies in Rillito Valley, Ariz., found a velocity computed in this manner of 3 feet a day, whereas the velocities which he obtained by field experiments with Slichter's electrolytic method ranged from 25 to 400 feet a day. He states that Hazen's effective size was perhaps applicable to deposits of sand and gravel in Massachusetts, but should not be adopted elsewhere without special investigation as to its applicability. He concludes:

It is not likely that any formula for velocity of underflow can be safely published for widespread use until the problem of analyzing the soils has been most comprehensively studied in its relation to transmission of water. The effects of the sharpness or roundness of grain, of the various crystalline constituents, as, for example, mica, and especially of the peculiar stratification of sand in situ due to its sorting by running water, seem quite incapable of mathematical expression.

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[50] Smith, G. E. P., op. cit., p. 126.

Lee,[51] in his studies of ground waters in the Gila and Salt River Valleys, Ariz., attempted estimates of the amount of underflow, using Slichter's formula with Hazen's effective size. He reached the conclusion that "an application of Slichter's formula to the underflow of Salt River Valley, using the effective size thus obtained, gives results which are obviously erroneous, since the quantity of underflow thus indicated is notably less than the quantity known to return to the surface and measured as water actually diverted for irrigation purposes." Slichter advised Lee that 10 per cent size is not applicable to the gravel in these localities and that the 50 per cent size gives a value of grain nearer the true mean.

It is obvious from the foregoing discussion that an indiscriminate use of the 10 per cent size for the effective size in Slichter's formula is not warranted. Such extensive use was doubtless not contemplated by Hazen, who merely found the 10 per cent size useful in estimating the permeability of the filter materials with which he worked. Nor did Slichter authorize the use of the 10 per cent size for the effective size in his formulas. Further methods of obtaining a correct value for the effective size need to be devised if permeability is to be estimated from the mechanical analysis. King's aspirator does not seem to have been widely used, probably because students of soil have required information as to the full range of sizes and not merely as to the effective size, and because hydrologists have commonly made field determinations of rate of flow by means of the fluorescein or the electrolytic method. The process of computing the effective size from results obtained with the aspirator and then using this effective size in Slichter's formula is, of course, only a roundabout method of converting permeability to air into permeability to water.

[51] Lee, W. T., The underground waters of Gila Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 104, p. 40, 1904; Underground waters of Salt River Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 136, p. 153, 1905.