Specific Yield--

Column Drainage and

Centrifuge Moisture Content

GEOLOGICAL SURVEY WATER SUPPLY PAPER 1662-A

Prepared in cooperation with the California Department of Water Resources

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SPECIFIC YIELD—COLUMN DRAINAGE AND CENTRIFUGE MOISTURE CONTENT

By A. I. JOHNSON, R. C. PRILL, and D. A. MORRIS

ABSTRACT

The specific yield of a rock or soil, with respect to water, is the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume. Specific retention represents the water retained against gravity drainage. The specific yield and retention when added together are equal to the total interconnected porosity of the rock or soil. Because specific retention is more easily determined than specific yield, most methods for obtaining yield first require the determination of specific retention.

Recognizing the great need for developing improved methods of determining the specific yield of water-bearing materials, the U.S. Geological Survey and the California Department of Water Resources initiated a cooperative investigation of this subject. The major objectives of this research are (1) to review pertinent literature on specific yield and related subjects, (2) to increase basic knowledge of specific yield and rate of drainage and to determine the most practical methods of obtaining them, (3) to compare and to attempt to correlate the principal laboratory and field methods now commonly used to obtain specific yield, and (4) to obtain improved estimates of specific yield of water-bearing deposits in California. An open-file report, "Specific yield of porous media, an annotated bibliography," by A. I. Johnson, D. A. Morris, and R. C. Prill, was released in 1960 in partial fulfillment of the first objective.

This report describes the second phase of the specific-yield study by the U.S. Geoligical Survey Hydrologic Laboratory at Denver, Colo. Laboratory research on column drainage and centrifuge moisture equivalent, two methods for estimating specific retention of porous media, is summarized.

In the column-drainage study, a wide variety of materials was packed into plastic columns of 1- to 8-inch diameter, wetted with Denver tap water, and drained under controlled conditions of temperature and humidity. The effects of cleaning the porous media; of different column diameters; of dye and time on drainage; and of different methods of drainage, wetting, and packing were all determined. To insure repeatability of porosity in dupliacte columns, a mechanical technique of packing was developed.

In the centrifuge moisture-content study, the centrifuge moisture-equivalent (the moisture content retained by a soil that has been first saturated and then subjected to a force equal to 1,000 times the force of gravity for 1 hour) test was first reviewed and evaluated. It was determined that for reproducible moisture-retention results the temperature and humidity should be controlled by use of a controlled-temperature centrifuge. In addition to refining this

standard test, the study determined the effect of length of period of centrifuging and of applied tension on the drainage results.

The plans for future work require the continuation of the laboratory standardization study with emphasis on investigation of soil-moisture tension and unsaturated-permeability techniques. A detailed study in the field then will be followed by correlation and evaluation of laboratory and field methods.

INTRODUCTION

The specific yield of a rock, or soil, with respect to water, is the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume (Meinzer, 1923, p. 28). Specific retention represents the water retained against gravity drainage. The specific yield and retention when added together are equal to the total interconnected porosity of a rock or soil. That is, any isolated openings that do not take part in the draining and refilling of a body of rock or soil are not counted as a part of the total porosity as used here.

Gravity ground water is available free water, or the water that will be withdrawn from a given body of rock or soil in the zone of saturation by the direct action of gravity if the water table and capillary fringe move downward to a new position that is below the top of the given body. The distinction between gravity water and retained water is not entirely definite because the amount of water that will drain out depends on the length of time it is allowed to drain, on the temperature and mineral composition of the water (which affect its surface tension, viscosity, and density), and on various physical relations of the body of rock or soil.

Because specific retention is more easily determined than is specific yield, most methods for obtaining specific yield first require the determination of specific retention. As indicated above, specific yield may then be found by subtracting the specific retention from the total porosity.

OBJECTIVES AND PROPOSED SCOPE OF RESEARCH PROGRAM

Recognizing the great need for developing improved methods of determining or estimating specific yield of water-bearing materials, the U.S. Geological Survey and the California Department of Water Resources began a cooperative investigation of this subject in July 1957.

The major objectives of this research program are as follows:

1. To review pertinent literature and to prepare an annotated bibliography on specific yield and related subjects. (See Johnson and others, 1960.)
2. To increase basic knowledge of specific yield and rate of drainage and to determine the most practical methods of obtaining them for general application.

3. To compare and attempt to correlate the principal laboratory and field methods now commonly used for estimating specific yield and to investigate or develop additional methods as advisable.
4. To obtain improved estimates of the specific yield of water-bearing deposits in California.

As a first step toward accomplishing the last three objectives, a preliminary study was made of the drainage and centrifuge moisture equivalent of porous media, so that these procedures and techniques could be evaluated and standardized.

REVIEW OF PREVIOUS WORK

Israelson (1918) made a series of field tests of water-retaining capacities of different soil types in the Sacramento Valley, Calif. His method was to determine the porosity of the different soils and their water content at successive depths, immediately before irrigation and again about 4 days after irrigation. This second determination gave approximately the specific retention after a short drainage time.

Ellis and Lee (1919) made experiments on valley fill along the major stream valleys of San Diego County, Calif. Their method involved the collection of samples immediately above the capillary fringe after a decline of the water table.

Clark (1916) in his studies of the Morgan Hill area, California, observed the lowering of the water table, and hence the volume of sediments drained by pumping a measured volume of water. The specific yield was then obtained using the ratio of the volume of water pumped to the volume of sediments drained.

The recharge method (Meinzer, 1923) also has been used to determine specific yield by observing the amount of water that percolates from streams or canals into an aquifer and the resulting rise of the water table. From the volume of sediments saturated by the measured recharge, specific yield may be computed.

In addition to the above field approaches to specific yield, several laboratory tests have been used to determine specific retention.

Hazen (1891) presented the results of tests of the water-retaining and water-yielding capacities of filter sands. These tests related specific yield and specific retention to the effective size of grain as obtained from mechanical (particle-size) analyses. King (1898) presented the results of tests of the water-yielding and water-retaining capacities of five sorted sands of different grain size; these sands were saturated and then allowed to drain over a long period of time. The results of King's tests showed some discrepancy between the porosity and total water and seemed to give lower values for specific retention than Hazen's tests, especially for the coarser samples. Eckis and Gross (1934) related particle-size analysis and porosity to specific retention in their storage-capacity studies of the South Coastal basin, California.

The centrifuge-moisture-equivalent method for testing moisture-retention capacity of a soil was introduced by Briggs and McLane (1907) by determinations on more than 100 soils. Although their original work was done under a centrifugal force of 3,000 times gravity, they suggested in a later publication (1910) that a force of 1,000 times gravity could be used. In 1912, Briggs and Shantz made moisture-equivalent tests using 1,000 times gravity; since that time this procedure has been accepted as standard by most investigators. However, even though this has been the standard, many separate investigations have been made since 1912 concerning the relation of the moisture equivalent obtained to factors such as, effect of prestorage methods, preliminary sample preparation, temperature during saturation and centrifuging, depth of sample, sealing of top of sample cups, force times gravity, length of time of centrifuging, and method of drying centrifuged samples.

The centrifuge moisture equivalent may be adjusted by a correction factor proposed by Piper (1933), based on data obtained by drainage of columns of natural materials under field conditions. This adjusted value, considered to be specific retention, is then subtracted from the porosity to obtain specific yield.

This summary of past work will serve to place the current study in perspective and account for the direction that the work has taken.

ORGANIZATION OF INVESTIGATION

The report was prepared under the general supervision of J. F. Poland, research geologist, G. F. Worts, Jr., formerly district geologist, and H. D. Wilson, district engineer for California, Ground Water Branch of the Geological Survey, and under the direct supervision of the senior author, who is chief of the Hydrologic Laboratory, Denver, Colo.

ACKNOWLEDGMENTS

Many individuals contributed to this report by giving advice and furnishing information relative to the problem. Valuable assistance was provided by Mr. L. B. James, chief geologist, and Mr. R. T. Bean, supervising engineering geologist, both of the California Department of Water Resources.

INVESTIGATION OF COLUMN DRAINAGE

TECHNIQUE

MATERIALS

Homogeneous materials were used in the investigation of column drainage. Glass beads (3M "Superbrite," Minnesota Mining and

Manufacturing Co.) and sand (DM–20–Del Monte Properties Co.) were selected as the principal testing materials because they are available in a large range of sizes and because their physical properties are controlled within narrow limits. Glass beads are nearly spherical and are manufactured in a range of sizes from 0.028 to 0.59 mm. In this study, code Nos. 107 (0.470 mm medium-sand size), 112 (0.120 mm very fine sand size), and 118 (0.036 mm upper silt size) glass beads were used. Del Monte sand, a beach or dune sand from California and Idaho, is available in several mesh sizes: 16, 20, 30, or 60 mesh. The 20-mesh size, which is classified as a coarse sand, was used in this study. In addition, carefully selected fine sands from field sites near Fresno, Calif., and Holbrook, Ariz., were used. (See table 1 for particle-size distribution of materials used.)

TABLE 1.—*Particle-size distribution of materials*

[Results in millimeters]

Sample	Clay (<0.004)	Silt (0.004–0.0625)	Sand: Very fine (0.0625–0.125)	Sand: Fine (0.125–0.25)	Sand: Medium (0.25–0.5)	Sand: Coarse (0.5–1)	Sand: Very coarse (1–2)	Gravel: Very fine (2–4)	Gravel: Fine (4–8)	Gravel: Medium (8–16)	Sorting[1] coefficient S_0
Glass beads:											
0.036 mm	3.4	96.2	0.4	------	------	------	------	------	------	------	1.2
0.120 mm	------	------	52.2	47.8	------	------	------	------	------	------	1.1
0.470 mm	------	------	1.6	.4	80.0	18.0	------	------	------	------	1.0
Del Monte sand:											
20 mesh	------	------	.1	.5	9.6	85.0	4.8	------	------	------	1.1
30 mesh	------	------	.1	10.5	86.1	3.3	------	------	------	------	1.2
60 mesh	2.9		20.1	45.1	31.9	------	------	------	------	------	1.4
Alluvial sand (Holbrook, Ariz.)	2.0		11.0	56.0	30.0	1.0	------	------	------	------	1.4
58ARK146	71.6	27.8	.6	------	------	------	------	------	------	------	------
57CAL2	52.0	37.3	5.5	2.8	1.6	.7	.1	------	------	------	------
14	71.5	19.7	4.0	2.8	2.0	------	------	------	------	------	------
66	7.2	1.6	6.0	49.2	36.0	------	------	------	------	------	.4
72	9.8	9.7	7.8	22.4	36.3	8.6	1.0	1.9	1.9	0.6	1.8
57CAL106	17.0	41.2	23.2	14.2	4.3	.1	------	------	------	------	3.0
110	7.2	8.0	6.6	31.6	46.2	.1	.1	.2	------	------	1.4
112	57.0	42.0	.2	.2	.4	.2	------	------	------	------	2.6
118	6.5	7.3	17.8	62.8	5.4	.2	------	------	------	------	1.3
122	7.0	2.6	2.4	15.6	57.5	14.2	.7	------	------	------	1.4
123	26.8	61.2	7.0	3.6	1.4	------	------	------	------	------	3.2
139	9.0	43.6	32.8	13.4	1.0	.2	------	------	------	------	2.2
152	22.2	37.8	12.2	16.2	11.4	.1	.1	------	------	------	5.1
155	16.2	37.6	30.0	15.2	.8	.2	------	------	------	------	2.7
162	26.0	35.4	14.8	17.2	6.2	.2	.2	------	------	------	5.6
173	26.2	58.8	9.6	4.0	1.2	.2	------	------	------	------	3.4
205	61.0	28.8	4.6	4.0	1.5	.1	------	------	------	------	------
59CAL130–131	30.5	54.9	6.8	5.0	2.4	.4	------	------	------	------	3.6
137–138	21.4	37.6	13.0	11.5	11.1	5.4	------	------	------	------	4.9
59CAL191–244	4.3		5.5	17.3	49.3	22.4	1.2	------	------	------	1.4
191–248	20.2	41.3	16.6	16.0	5.1	0.8	------	------	------	------	4.3
251–252	10.5	38.5	21.4	19.8	8.2	1.6	------	------	------	------	2.4
253–254	16.7	28.5	20.2	21.8	10.2	2.4	.2	------	------	------	------
258–261	7.7	26.5	20.8	28.2	11.8	4.8	.2	------	------	------	2.3
580KL15	24.8	48.2	17.0	9.8	.2	------	------	------	------	------	3.7
42	25.9	53.1	16.0	4.8	.2	------	------	------	------	------	3.9
Fuller's earth	30.0	56.4	11.6	1.4	.6	------	------	------	------	------	3.4
Kaolin (EPK)	54.0	45.6	.4	------	------	------	------	------	------	------	------
Kaolin (N.F.)	93.0	7.0	------	------	------	------	------	------	------	------	1.7
Loess:											
Bonny Dam, Colo.	18.6	69.6	4.6	2.2	3.6	1.4	------	------	------	------	------
Trenton, Nebr.	16.6	79.8	3.4	0.2	------	------	------	------	------	------	------

[1] Sorting coefficient $(S_0)=\sqrt{\frac{D_{75}}{D_{25}}}$ where

D_{75}=particle diameter for which 75 percent are smaller.

D_{25}=particle diameter for which 25 percent are smaller.

COLUMNS

The drainage columns were made by filling transparent plastic tubing, having an inside diameter of ¾ to 8 inches (and a wall thickness of 3/16 to ⅜ in.) with media. The plastic tubing was used either as manufactured or subdivided into 1- to 2-inch-long segments which were placed end to end and built into leak-proof columns by use of a filament pressure-sensitive tape (Tuck Tape type I) and hose clamps, or by a pressure brace. (See fig. 1.) The lower end of each column was fitted with a 115-mesh copper screen or bronze filter disk laid across a singly perforated rubber stopper, sealed, and held in place by use of adhesive tape.

The undisturbed alluvial sand sample from the flood plain of the Little Colorado River near Holbrook, Ariz., was taken in a 5-inch plastic cylinder, about 5 feet long, by the method of advance trimming. By this method the sampling cylinder was advanced carefully downward into a short column of material; and as the cylinder's cutting edge advanced, the material was trimmed roughly to about ½ to 1 inch ahead of the cutting edge. This process continued, an excavation being dug as the sampling cylinder advanced. When the sample protruded above the top of the cylinder, the excess sample was trimmed away and steel plate was placed on top of the cylinder. The sample cylinder with the retained sample was removed carefully from the excavation, and the sample was trimmed flush with the lower end of the cylinder. A steel base plate was then placed on the lower end of the cylinder. The sample was confined in the sampling cylinder by the use of long threaded rods tightened between the upper and lower plates of the sampling cylinder. (See fig. 2.) In the laboratory, the steel base plate was replaced by a plastic base plate containing a fritted-bronze filter disk.

PACKING

The manual method of packing was used for the initial drainage work. This method involved gently tapping the side of the column with a rubber mallet as the material was added in small increments. Vertical columns of material 6 inches in height were added successively and tapped until no change in volume occurred. This process was continued until the columns were filled. Packing techniques employing this manual method of vibration were especially difficult to control, and the porosity of glassbead media throughout segmented columns ranged from about 34 to 40 percent (porosity was used as an index of the packing effects). This range of porosity using glass-bead media was considered to be too wide for research; and considering that the range would be even greater for more natural materials, a more efficient method of packing was sought. The literature was reviewed for a solution to the problem, but very little data on me-

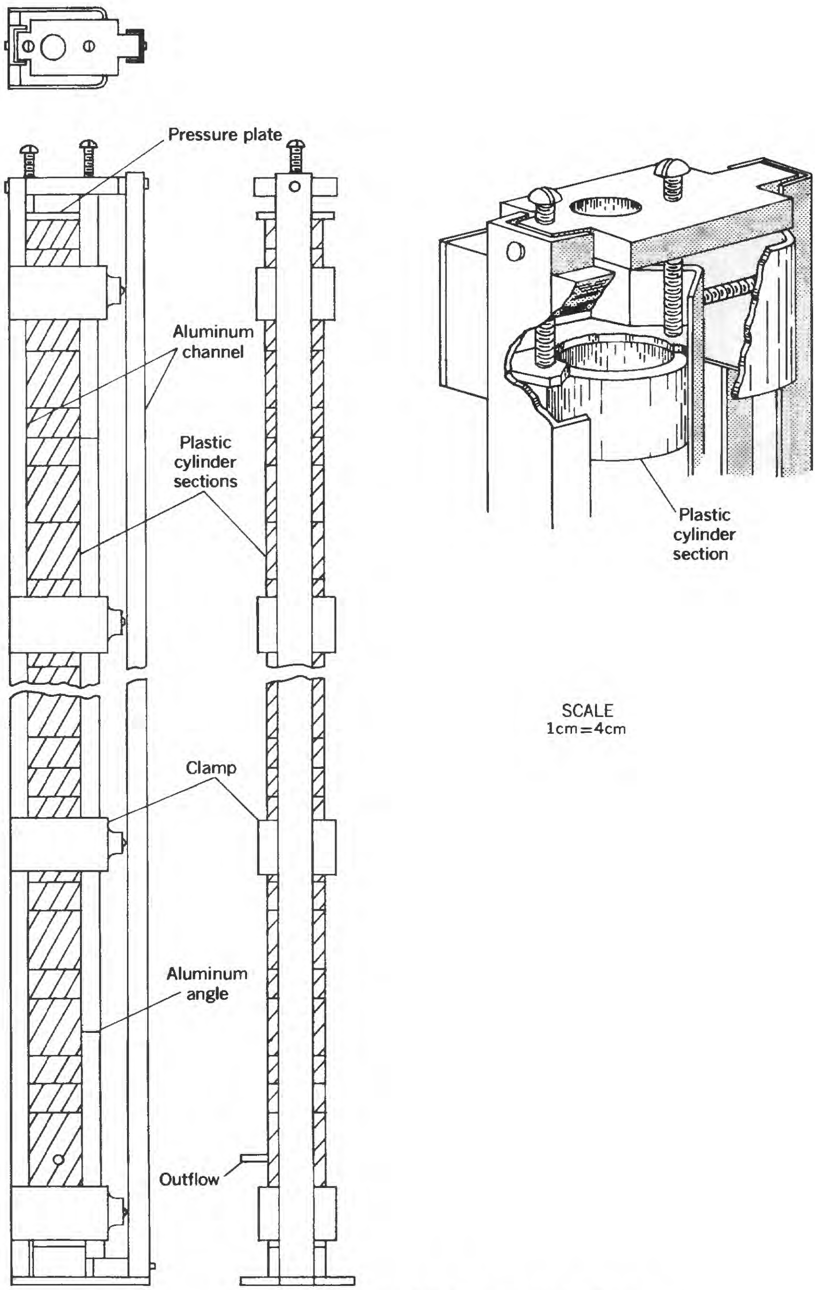

FIGURE 1.—Assembly for segmented column.

chanical packing pertaining to this application were discovered. It was apparent that additional laboratory study was needed to evaluate this problem and to develop a better packing technique. After a cur-

FIGURE 2.—Large cylinder sample of an alluvial sand.

sory study of several commercial packers, including jolting as well as oscillatory equipment, the Syntron VP–60 packer was chosen as the most suitable for the evaluation.

WETTING FLUID

De-aired Denver tap water was used as the wetting fluid. The air was removed by means of a vacuum apparatus especially designed in the laboratory. The chemical analysis of the water is shown in table 2.

OBSERVATION OF WATER LEVEL

De-aired water and de-aired water containing green dye (0.307 gram fluorescein dye per liter) were used as the saturation fluids. Observation under white light and under ultraviolet light indicated that the

TABLE 2.—*Chemical analysis of water from Denver, Colo.*

Chemical constituent [1]	Concentration (ppm)	Chemical constituent [1]	Concentration (ppm)
Calcium (Ca)	20	Nitrate (NO_3)	.6
Magnesium (Mg)	4	Dissolved solids	99
Sodium (Na) and potassium (K)	3.4	Hardness (as $CaCO_3$)	66
Bicarbonate (HCO_3)	47		
Sulfate (SO_4)	31	Specific conductance	
Chloride (Cl)	1.5	(micromhos at 25° C)	161
Fluoride (F)	.2	pH	7.3

[1] Analysis by Quality of Water Laboratory, U.S. Geol. Survey, Denver, Colo.

visual line of saturation was as easily discernible when using plain de-aired water as when using de-aired water containing the fluorescein dye. Under ultraviolet light, the intensity of fluorescein changed near the wetting or drying front, but the change was so gradual that the eye could barely detect it.

CLEANING OF POROUS MEDIA

An attempt was made to determine whether acid cleaning would affect the wetting characteristics of glass beads. Using a solution of dichromate cleaning reagent (35 ml saturated potassium dichromate solution added to 965 ml of concentrated sulfuric acid), 0.47-mm glass beads were thoroughly acid washed and drained. After thorough flushing with de-aired water, the beads were subjected to the usual wetting and draining treatment given to unwashed beads.

METHODS OF WETTING

Four methods were used to evaluate the effect of wetting on the pattern of moisture distribution after drainage. In the first 3 methods segmented columns, 1½ inches in diameter and 50 inches in length, were used; in method 4, a segmented column, 1½ inches in diameter and 70 inches in length was used. The 4 columns were filled with 0.120-mm glass beads and wetted from below.

In the first 3 methods of wetting, a head of water was maintained at a level of 48 inches above the bottom of the columns. In method 1, a wetting period of 76 hours was used. In method 2, a wetting period of about 120 hours was used; during the last 19 hours de-aired water was allowed to flow through the column. In method 3, an initial wetting period of about 77 hours, a drainage period of about 19 hours, and a rewetting period of about 25 hours were used. In method 4, the water was maintained at a level of 50 inches above the bottom of the column, and the column was wetted for a period of about 73 hours, allowing the capillary fringe to develop above the water table.

In wetting the larger diameter columns of glass beads, wetting-method 1 was used. This technique was also used for the Holbrook alluvial sand sample, except that the column was wetted slowly for about a year before drainage.

An attempt was also made to use the vacuum technique in wetting small-diameter segmented columns of glass beads. In this method, vacuum was applied as the segmented columns (segments held together in a pressure brace) were submerged in water in an air-tight chamber. The vacuum was ineffective in the removal of air at the contact between segments. This was caused by the very close tolerances between adjacent milled segments as held together under pressure.

METHODS OF DRAINAGE

Two basic methods of drainage were employed to determine the effect of the method of drainage on the amount and rate of drainage and the moisture distribution after drainage. These were designated "free-drainage" and "hanging-water-column" methods. Two methods of free drainage, the simple and extended-base, and two methods of hanging-water-column drainage, the nonmembrane and membrane, were used. In all tests the columns were packed with 0.120-mm glass beads.

All columns were allowed to drain until discharge had virtually ceased, and the rate was recorded.

In the simple free-drainage method, columns from ¾ to 8 inches in diameter and measuring as much as 70 inches in length were used. The drained water was discharged from a short length of glass tubing fitted in a rubber stopper at the lower end of the drainage column. (See fig. 3)

In the extended-base method, a column 1½ inches in diameter and 53 inches in length was placed with the bottom end in contact with a bed of 0.120-mm glass beads contained in a column that was 4 inches in diameter and 17 inches in length. Drained water was discharged from the bed of glass beads through a short length of glass tubing fitted in a rubber stopper at the lower end of the bed. (See fig. 3.)

In the nonmembrane hanging-water-column method, a column 1½ inches in diameter and 53 inches in length was used. A 17-inch water column consisting of a flexible plastic tubing and lower water chamber completely filled with water was attached to the lower end of the column. The drained water was discharged through a glass tubing fitted to the upper end of the water chamber. (See fig. 3.)

In the membrane method a column 1½ inches in diameter and 16 inches in length was used. A semipermeable plastic membrane (Porvic Filter Sheet, Grade "M," Pritchett & Gold, London) was placed in contact with the 0.120-mm glass beads at the lower end of the column, and a 104-inch water column was extended from the porvic in a manner similar to that used in the nonmembrane method. (See fig. 3.) The advantage of the membrane over the nonmembrane method is that a longer water column can be used, thus reducing the length of sample column required for free drainage. Any water

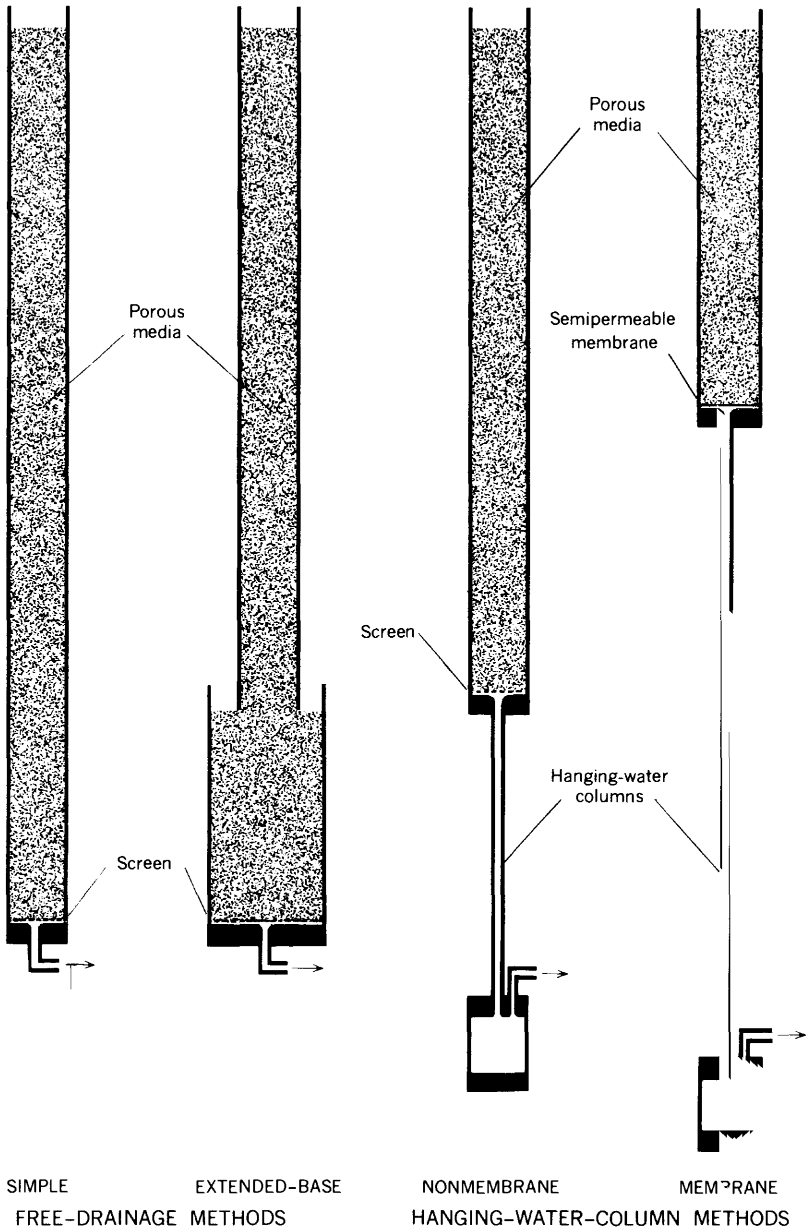

FIGURE 3.—Methods of drainage.

column less than 18 feet long can be used with the porvic membrane, whereas, with the nonmembrane method, the length of the water column to be effective cannot exceed the height of the zone of capillary saturation of the sample.

690-146 O—63——3

In the drainage of the larger diameter columns, the water table was maintained at the bottom of the column. This was done by positioning the discharge tube of the outflow bottle at the bottom of the column. The Holbrook sample was drained by two methods—the simple free-drainage method and the nonmembrane hanging-water-column method. In the latter method a 48-inch hanging-water column was applied.

METHODS OF SAMPLING MOISTURE DISTRIBUTION

The pattern of moisture distribution after drainage was obtained by sampling the drainage column in 1- or 2-inch increments after discharge had virtually ceased and by determining the moisture content for each increment. The sample was taken by using a long spoonlike rod in the small-diameter continuous columns, by using a soil-sampling tube or by sliding the column away from the media in the large-diameter continuous columns, and by separating the sections of the small-diameter segmented columns.

CONTROLS EMPLOYED

The drainage work was done in a room where the humidity was controlled at 40 to 45 percent and the temperature maintained at 20°C. Evaporation from taped segmented columns was reduced to a minimum by sealing the top of each column with cellophane tape through which a single 1-mm perforation was made. Evaporation from pressure-held segmented columns was reduced by the use of a flexible polyethylene jacket, which was wrapped around the column and held together by use of a "Velcro" nylon tape fastener. The humidity within the jacket was thereby kept higher than the normal room humidity (40 percent).

DISCUSSION OF DRAINAGE DATA

EFFECT OF CLEANING POROUS MEDIA

To determine the effect of acid cleaning on glass-bead media, the pattern of moisture distribution after drainage for washed and unwashed 0.47-mm beads was compared. (See fig. 4.) These data suggest that washing with the dichromate solution has little or no effect on the moisture-retention characteristics of the glass beads and is therefore unnecessary.

COMPARISON OF DRAINAGE METHODS

The data in figure 5 indicate the pattern of moisture distribution, after drainage at different heights above the water table in 0.120-mm glass beads by the 4 different methods of drainage (simple, extended-base, nonmembrane, and membrane; fig. 3). The moisture data were obtained gravimetrically by sampling after the column had drained. In the first 3 methods the glass beads were wetted once from below

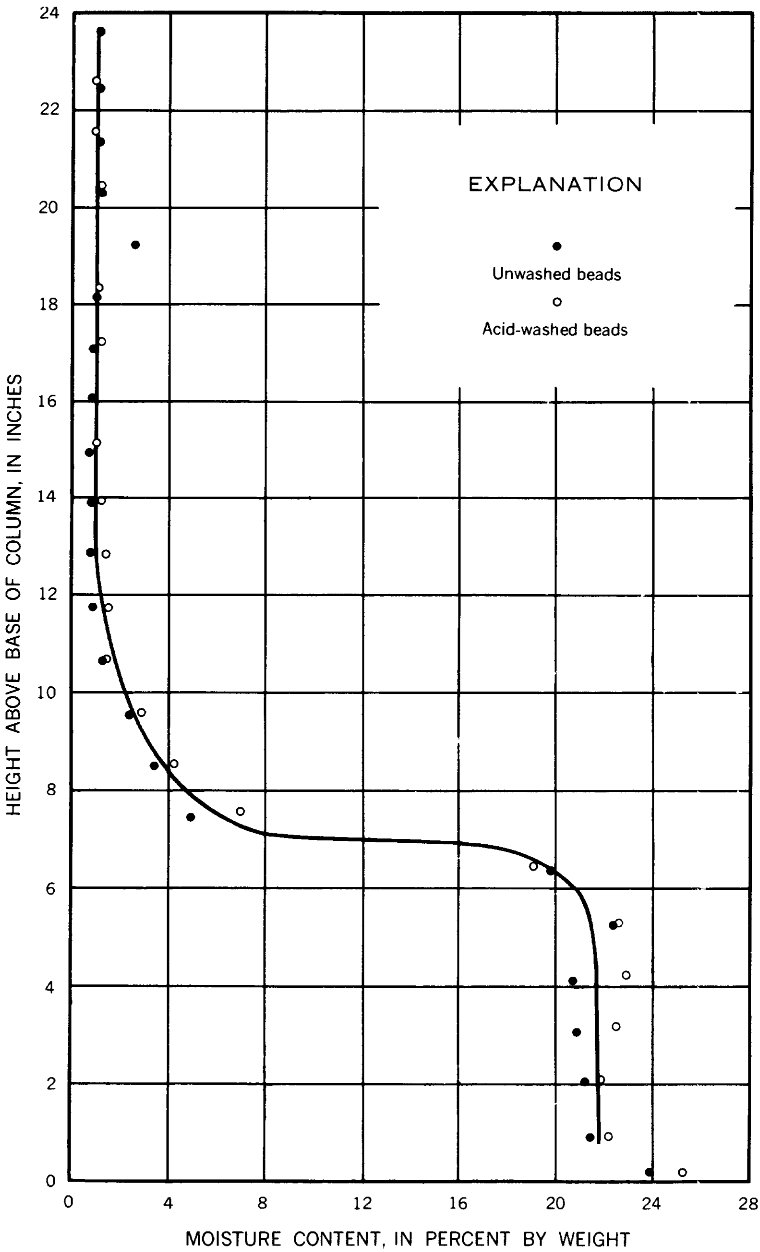

FIGURE 4.—Effect of cleaning 0.47-mm glass beads.

for about 90 hours. Beads in the membrane column were wetted from below through the membrane for about 1 week. Except at the higher moisture contents, the percentages of retained water for the first 3 methods compare closely throughout the total moisture range.

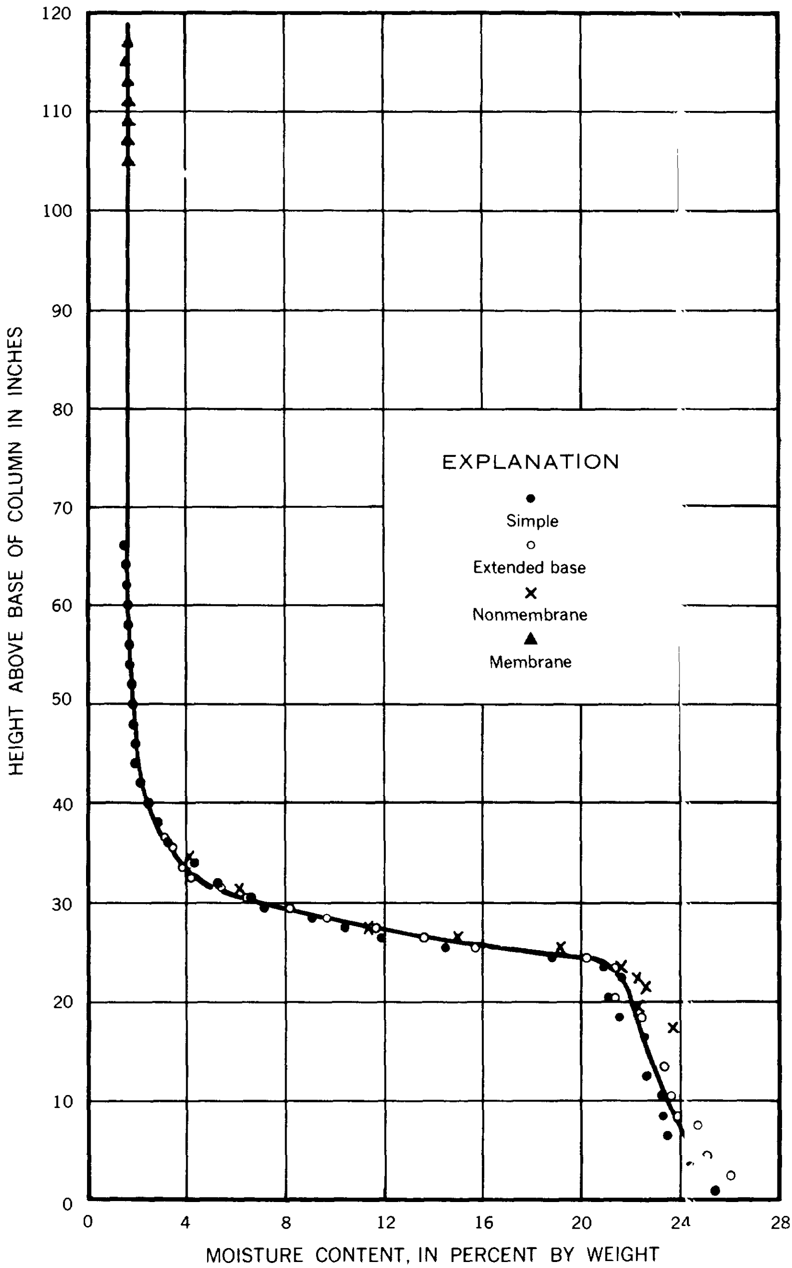

FIGURE 5.—Moisture retained in 0.120-mm glass beads after draining by several methods.

In the membrane method moisture content was obtained for heights of 104 to 120 inches above the water table. The values of retained moisture were similar to those obtained by the other 3 methods at

52 to 68 inches above the water table; thus, the moisture retention in the 0.120-mm glass beads was approximately 1.7 percent at any height above 52 inches.

The pattern of moisture distribution after simple drainage of the Holbrook alluvial sand is shown in figure 6. The pattern of moisture distribution is not so uniform as that obtained from drainage of glass beads, but the nonuniformity is undoubtedly due to slight differences in texture existing in this undisturbed column of natural sediments.

A comparison of the volume of water drained in relation to time for the simple free-drainage method and the nonmembrane hanging-water-column method is shown in figure 7. In the simple free-drainage method the drainage column was 70 inches long; in the nonmembrane hanging-water-column method the drainage column was 53 inches long, and the hanging-water column was 17 inches long. The distance from the top of the drainage column to the bottom of the hanging-water column was thus the same length as the drainage column used in the simple free-drainage method. The columns were wetted once from below and drained until moisture equilibrium was approached. Although the total volumes of water discharged from the 2 columns differed by only 10 cc, the initial rate of discharge was higher for the hanging-water-column method. This is the expected relationship, even though there was no difference in applied tension between the two columns, because a hanging-water column would facilitate the discharge of water initially, owing to a higher permeability at the outlet.

For the Holbrook alluvial sand the rate of drainage using the 48-inch hanging-water column was much higher, and the total quantity discharged was about 20 percent higher than the amount obtained by simple free drainage. (See fig. 8.) This relationship seems reasonable, because tension was applied by the hanging-water column and the effect of the capillary fringe was eliminated. To get comparable results in total-discharge data, equal tension must be applied to the drainage columns either by using longer columns, hanging-water columns, or vacuum.

The pattern of retained moisture for simple free drainage of 3 materials, 0.470-mm glass beads (medium-sand size), 0.120-mm glass beads (very fine sand size), and 0.036-mm glass beads (coarse silt size), is shown in figure 9. These drainage values were determined after the materials had been wetted only once and then allowed to drain for 23 to 72 hours without applied tension.

EFFECT OF COLUMN DIAMETER

It was important to evaluate by a single method of drainage the effect of column diameter on the moisture distribution after drainage. Figure 10 shows the moisture distribution after drainage of mechan-

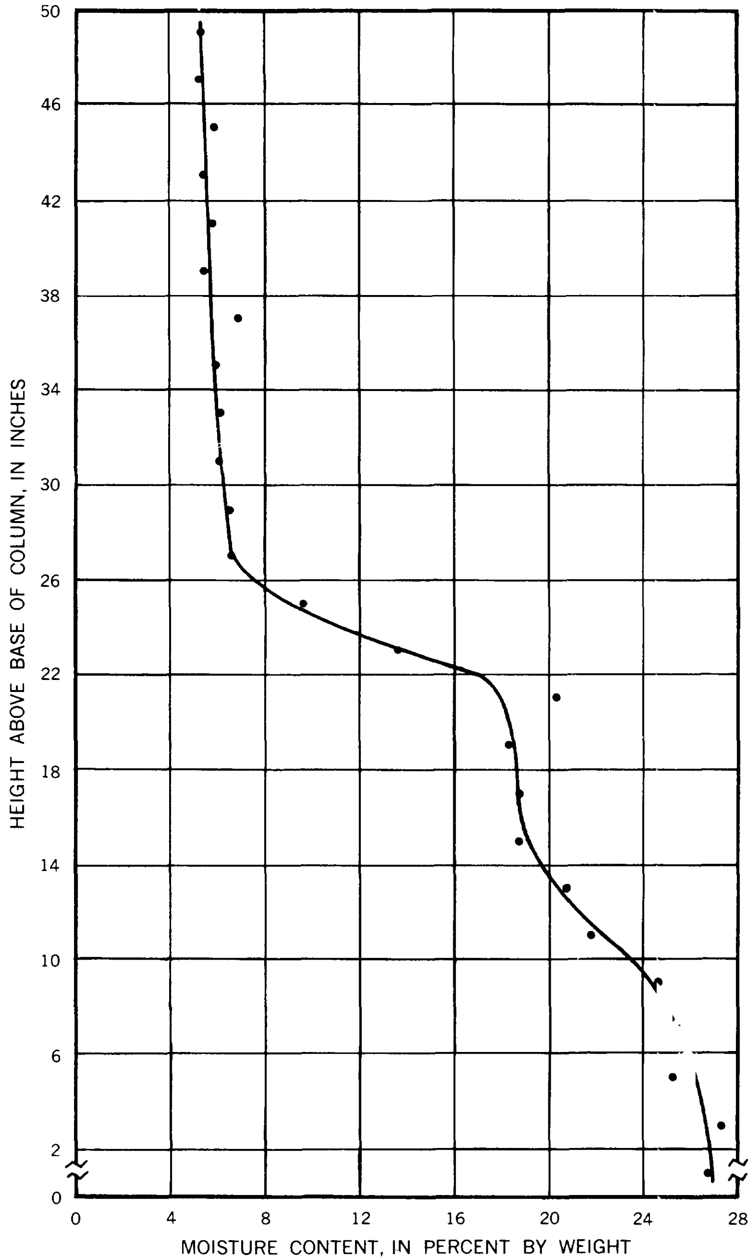

FIGURE 6.—Moisture retained in alluvial sand after 2 weeks of draining by simple free-drainage method.

ically packed 1-, 4-, and 8-inch-diameter columns of 0.12?-mm glass beads. The diameter of the column of drainage materials makes little difference in the general pattern of the moisture distribution

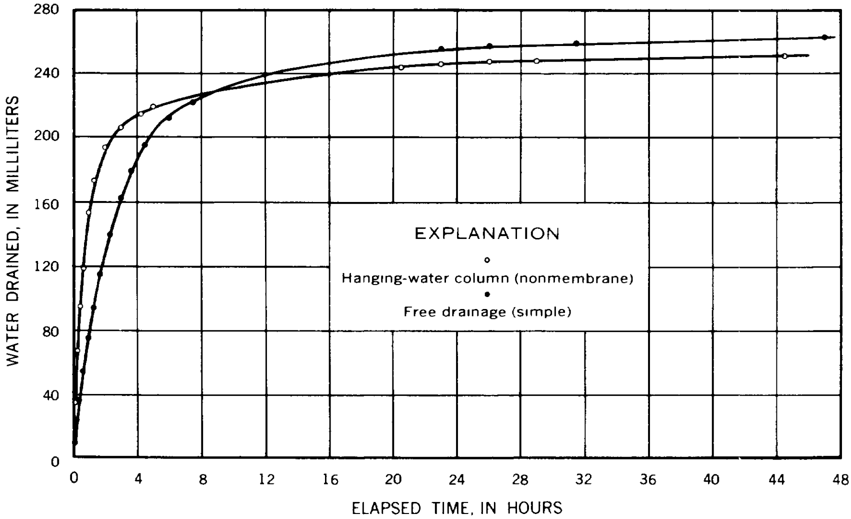

FIGURE 7.—Quantity of water drained from 0.120-mm glass beads by two methods.

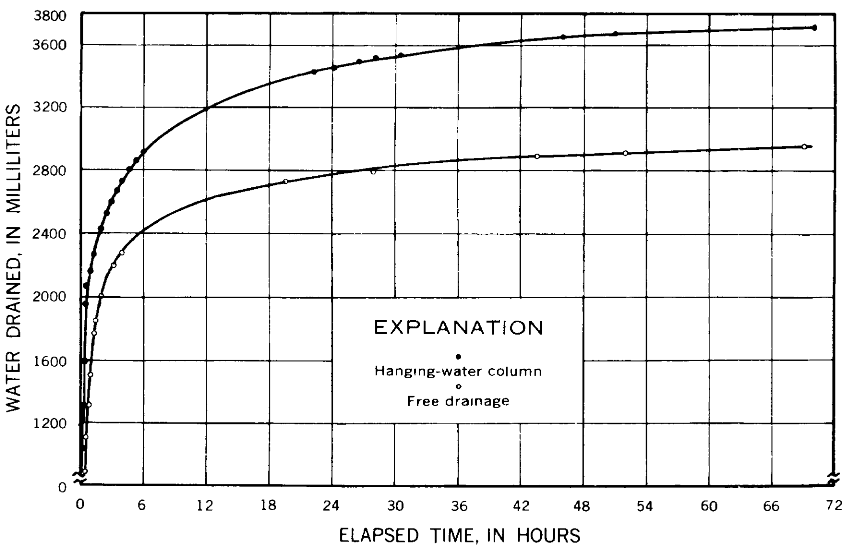

FIGURE 8.—Quantity of water drained from an alluvial sand.

after drainage. In large columns it makes little difference whether the samples are taken at the side of the column or in the middle. Figure 11 shows the moisture distribution at both sides and in the middle of the 8-inch-diameter column.

EFFECT OF METHOD OF WETTING

The quantity of water drained after wetting by three methods is shown in figure 12. The data indicate fairly close agreement between the first two methods and the first drainage of the third method (2

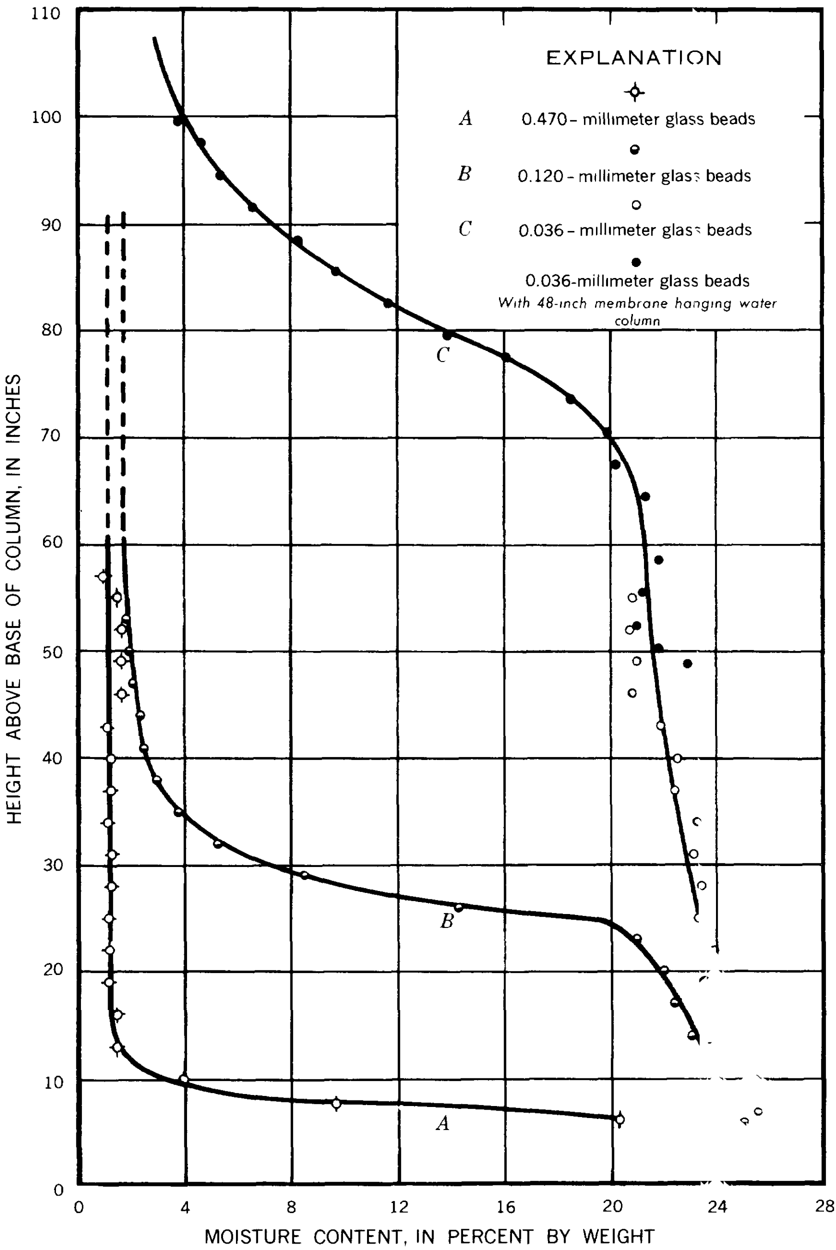

FIGURE 9.—Moisture retained in glass beads after drainage.

wettings—2 drainages) on the quantity of water drained. The data for the second drainage of method 3 show that drainage is considerably less, which may be explained by greater air entrapment on rewetting the moist sample.

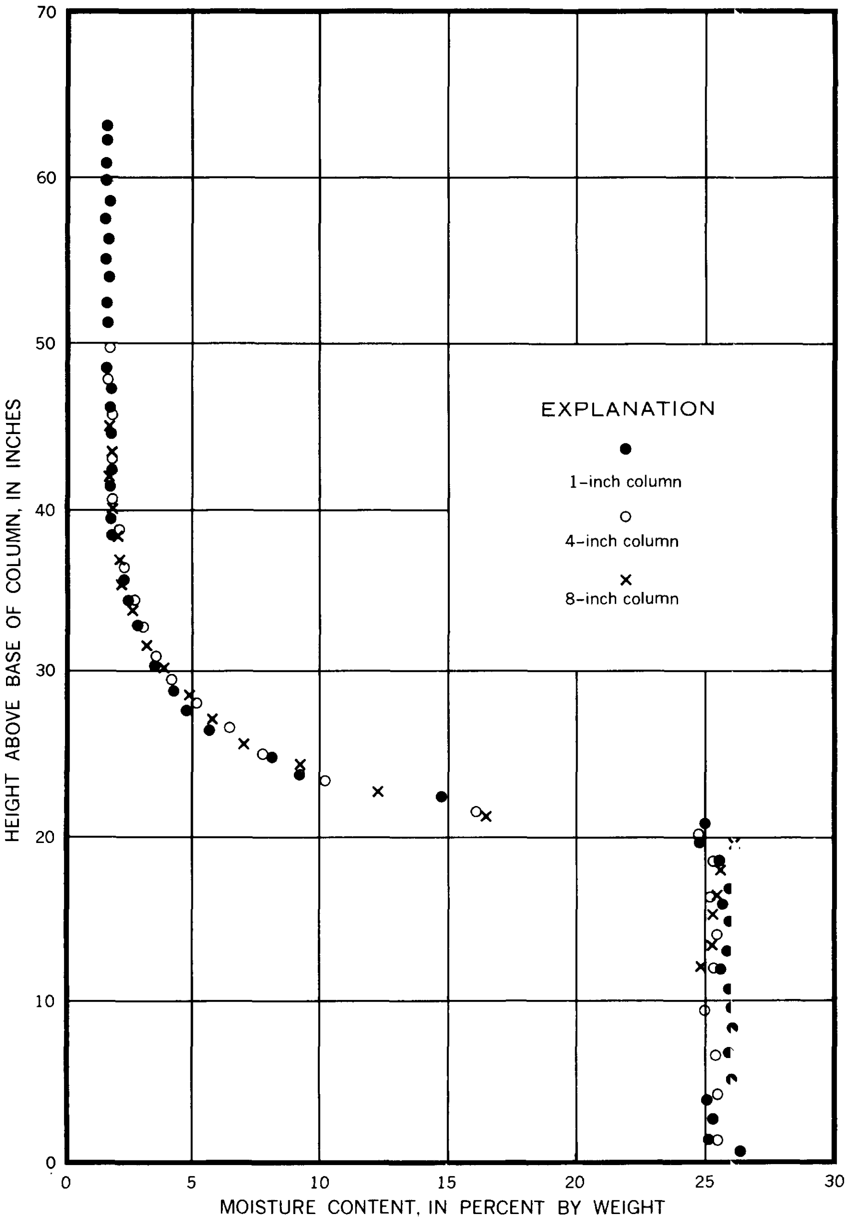

FIGURE 10.—Effect of column diameter on drainage of 0.120-mm glass beads.

The distribution of retained moisture after drainage of the columns wetted by the four methods is shown in figure 13. Although the capillary-rise method was not comparable in technique to the other methods, the data indicate fairly close agreement between all methods. The one-wetting method therefore seems adequate for most purposes.

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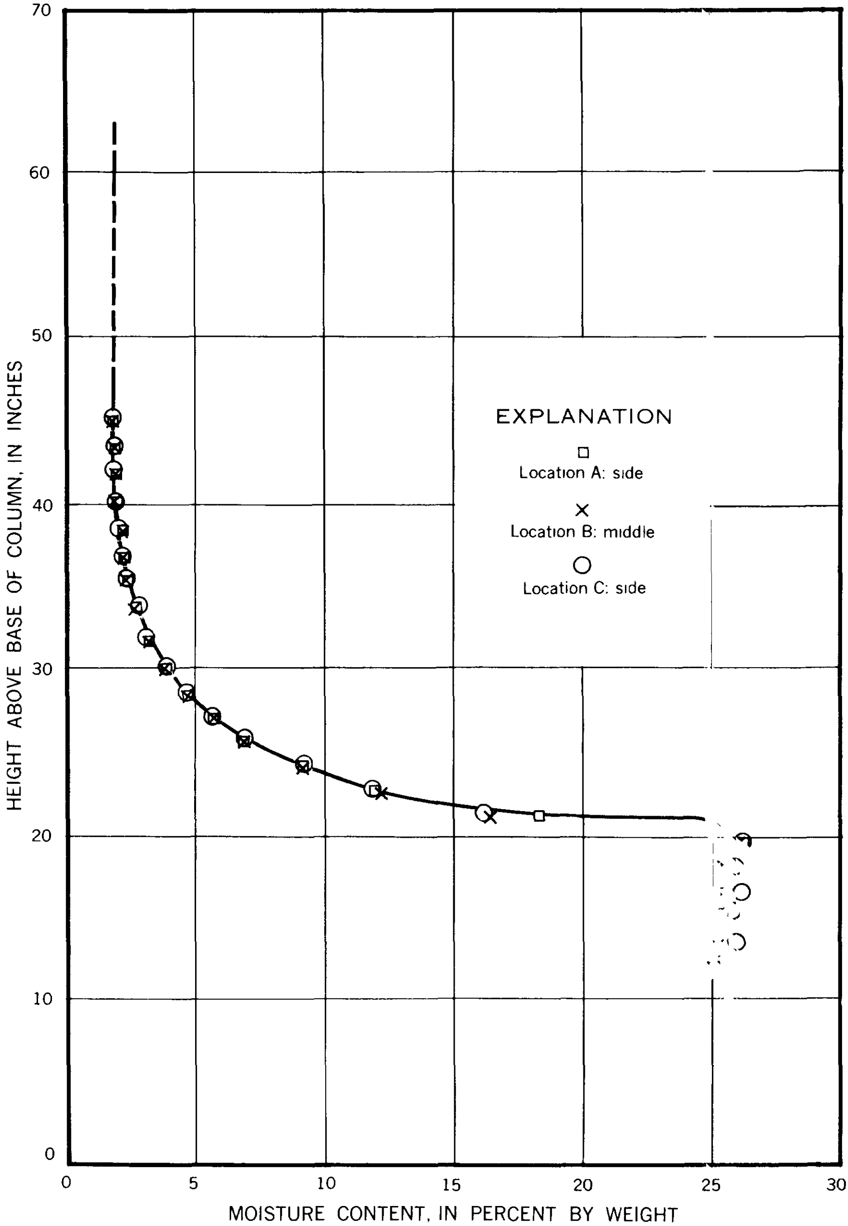

FIGURE 11.—Moisture distribution in an 8-inch-diameter column.

EFFECT OF PACKING METHOD

As mentioned earlier, the Syntron VP–60 vibratory packer was chosen as the most appropriate commercial packer for study. The following discussion describes the development of a laboratory technique of packing that uses this equipment. Unless noted otherwise, 0.120-mm glass beads were used for all packing experiments.

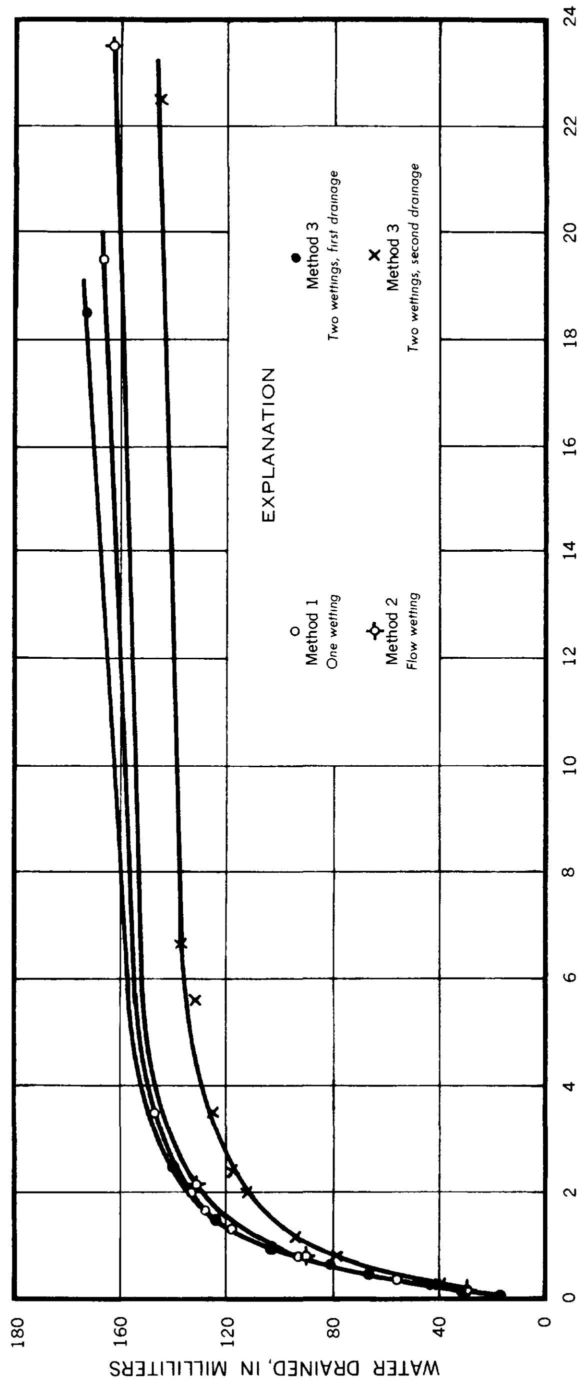

FIGURE 12.—Quantity of water drained from 0.120-mm glass beads after wetting by several methods.

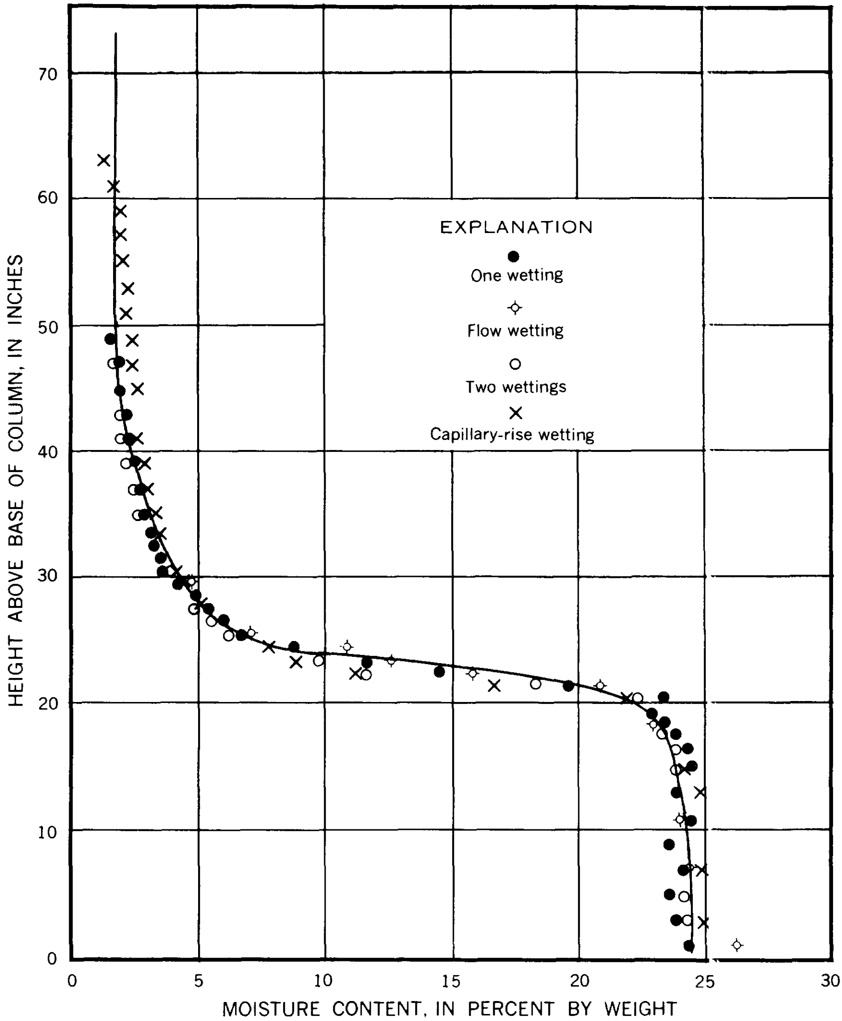

FIGURE 13.—Moisture retained in 0.120-mm glass beads after wetting by several methods.

CHARACTERISTICS OF PACKER

The Syntron VP–60 packer is virtually a noiseless vibratory packer built for loads as much as about 300 pounds. It has a rheostat control for amplitude adjustment and a fixed frequency of 60 vibrations per second (or line frequency). The operational characteristics of the packer were obtained by determining the peak-to-peak amplitude of the vibratory platform at five mechanical settings of the rheostat. Table 3 shows the small variations in amplitude that were measured by a General Electric vibrometer.

The change in amplitude at an arbitrarily chosen rheostat reading (*B*) with change of weight on the vibrator platform was then studied.

TABLE 3.—*Amplitude of vibration, in centimeters, for unloaded Syntron packer*

Rheostat setting	Run			
	1	2	3	4
Minimum	0.04	0.04	0.04	0.04
A	.07	.07	.06	.06
B	.09	.09	.09	.09
C	.13	.13	.12	.12
D	.18	.18	.19	.18

This was done throughout the capacity range of the packer by adding glass beads by 10-pound increments to a large cylindrical tube that was rigidly attached to the packing platform. Figure 14 shows the variation in amplitude with load—a decrease of 0.055 cm in amplitude occurring as the load increased from 13.5 to 300.0 pounds. Seventy-five percent of the change in amplitude took place in the first 80 pounds of loading. Only 15 percent additional change took place over the 80- to 100-pound interval, and the remaining 10 percent change took place beyond 180 pounds.

EFFECT OF VIBRATION ON SETTLING

A study was made of the effect of vibration on the amount of settling in a 4-foot column of glass beads. Table 4 shows the total amount of settling for vibration from 1 to 300 seconds.

TABLE 4.—*Comparison of settling with vibration*

Total time of vibration (seconds)	*Total amount of settling (centimeters)*	*Total time of vibration (seconds)*	*Total amount of settling (centimeters)*
1	2.2	5	4.0
2	2.8	10	4.3
3	3.3	300	6.0
4	3.7		

About 66 percent of the settling took place over the first 10 seconds of vibration; about 33 percent took place during the first second of vibration.

DEVELOPMENT OF PACKING TECHNIQUE

After operational characteristics of the packer became known, the most convenient method of adding media was arbitrarily selected—to fill the column completely with media by a tremie technique and then apply vibration. The effects of surcharge and amplitude were determined by employing this method on a 294-cubic cm cylinder (filled with 0.120-mm glass beads) 5 cm in diameter and 14.5 cm long. Porosity was used as an index of these effects on packing.

EFFECT OF SURCHARGE

The effect of surcharge was determined by obtaining porosities with and without the use of a 200-gram weight placed on the glass

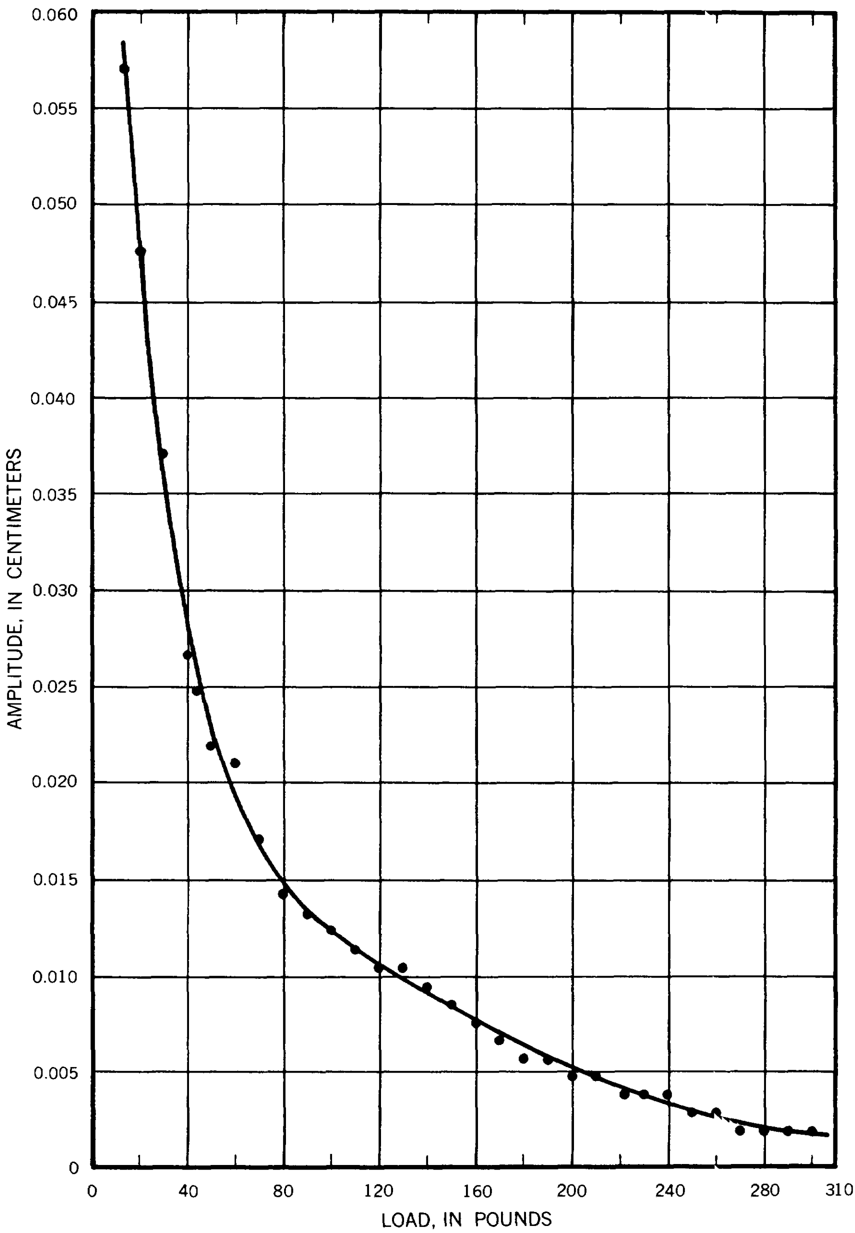

FIGURE 14.—Effect of load on amplitude of packer.

beads during vibration. Figure 15 shows this effect at a rheostat setting of *B* (0.09-cm amplitude) for total vibration of 25 to 200 seconds. The effect of the use of surcharge on porosity was negligible over the period of vibration. The porosity, as determined by the

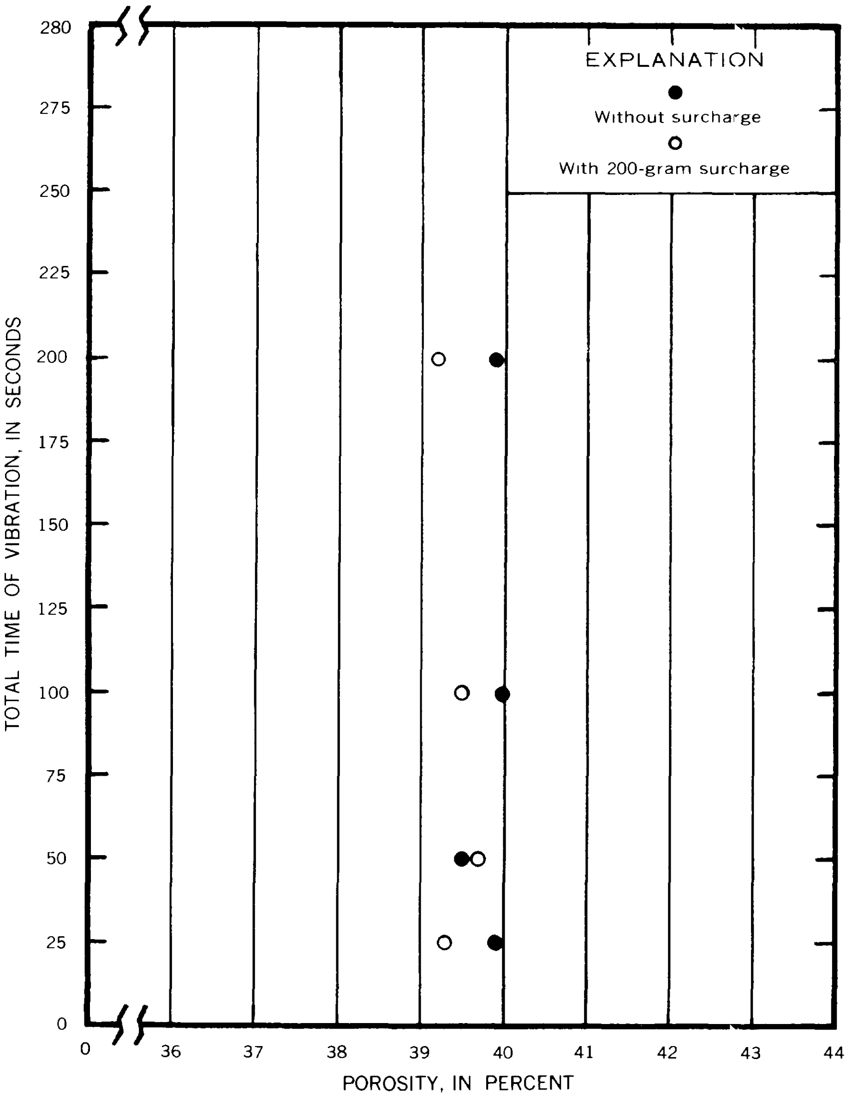

FIGURE 15.—Effect of surcharge packing on porosity.

surcharge and nonsurcharge techniques, ranges between 39.2 and 40.0 percent. The use of the surcharge technique was accordingly considered unnecessary to obtain uniform packing.

EFFECT OF AMPLITUDE ON POROSITY

The effect of amplitude on porosity was determined over a range from 0.05 to 0.17 cm. Figure 16 shows that the effect of amplitude on porosity is small over the range of amplitude tested. The porosity again ranged between 39.2 and 40.0 percent.

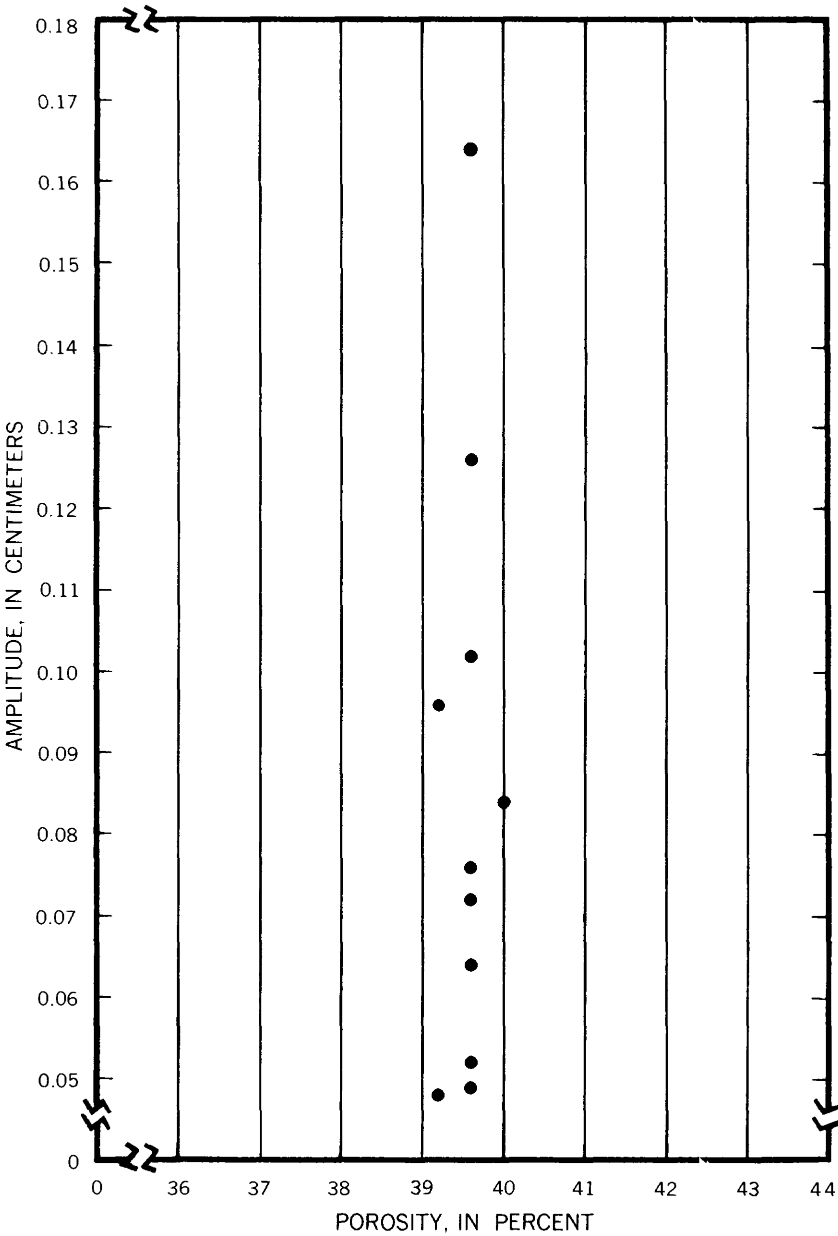

FIGURE 16.—Effect of amplitude on porosity.

The packing research discussed previously suggested that a packing amplitude could be arbitrarily selected for small columns of glass beads. A shorter period of packing may be desirable however, because a lesser amount of sorting may result. Again, working under the same conditions as before, the porosity was determined over a 1- to

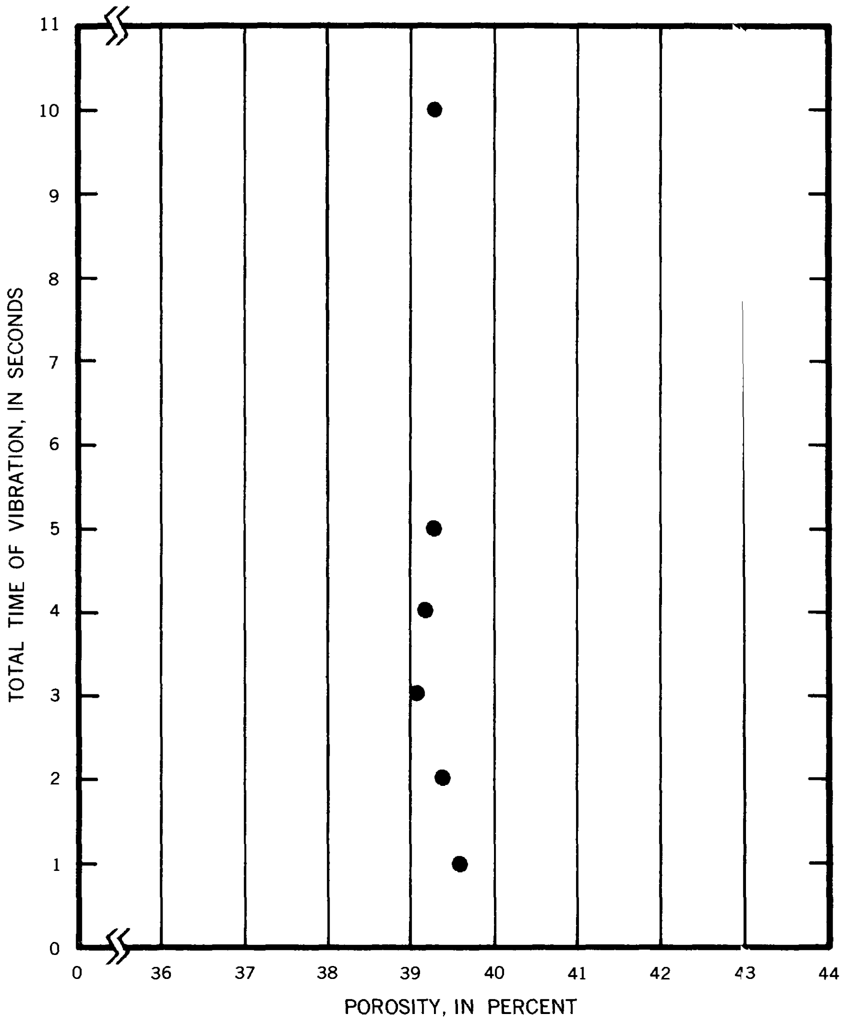

FIGURE 17.—Effect of vibration on porosity.

10-second period of packing at a rheostat setting of *B* (0.09-cm amplitude). The results (fig. 17) indicate that the values of porosity were somewhat erratic over the range of 1 to 4 seconds total time of vibration but seemed to stabilize and give reproducible results at a porosity of approximately 39.3 for vibration periods of 5 seconds or longer. The porosity was similar to that obtained when the longer period of vibration was used. From the results of this study, a technique using the Syntron packer for small volumes of glass beads was standardized at 10 seconds vibrations and a rheostat setting of *B* (0.09-cm amplitude).

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PACKING OF LONG COLUMNS

The drainage research necessitated the use of 60-inch segmented columns of porous media. The small-volume technique therefore needed to be projected into this work to test its application. To do this, duplicate columns of taped segments were filled with 0.120-mm glass beads and were packed for 10 seconds using the short-column technique. After vibration, the columns were segmented and porosities determined for the individual segments. Figure 18 shows the distribution of porosity vertically throughout a 1-inch segmented column. The porosity ranged from about 38 to 40 percent and averaged about 39 percent, a value slightly less than that obtained when the technique was applied to small volumes. There was, however, no consistent increase or decrease in porosity throughout the column, and the vertical reproducibility was good. To test this technique further and improve it, duplicate segmented columns held together by a pressure brace were filled with 20-mesh Del Monte sand, and the former testing conditions were duplicated. Figure 19 shows the range of porosity after drainage for duplicate runs and shows, as before, that vertical distribution of porosity was reproducible and no consistent trend away from the average porosity. The above technique of packing was therefore considered to be applicable to long- as well as short-column packing and was used as a standard method for all future packing.

EFFECT OF PACKING ON SORTING

To study the amount of sorting caused by packing, a 234-cc cylindrical container was filled approximately two-thirds full with two layers of glass beads; the lower layer was composed of colored glass beads 0.120-mm in diameter, and an upper layer was composed of uncolored glass beads 0.036 mm in diameter. During the first 5 seconds, the interface between layers shifted slightly downward along one edge, and the interface became more irregular on the downward side, an interpenetration of about 0.3 cm occurring on this side. As the vibrational interval was increased to about 10 seconds, the downward shift of the interface increased and the downward side of the interface became even more irregular. The maximum interpenetration was approximately 0.7 cm.

As an additional means of evaluating the sorting qualitatively, a 4-foot column, 1½ inches in diameter, was filled with a mixture of colored 0.120-mm glass beads and uncolored 0.036-mm glass beads and vibrated for a 300-second interval at an amplitude of 0.03 cm. During the first 10 seconds, the only noticeable sorting occurred in the upper quarter of an inch of material. As the total time of vibra-

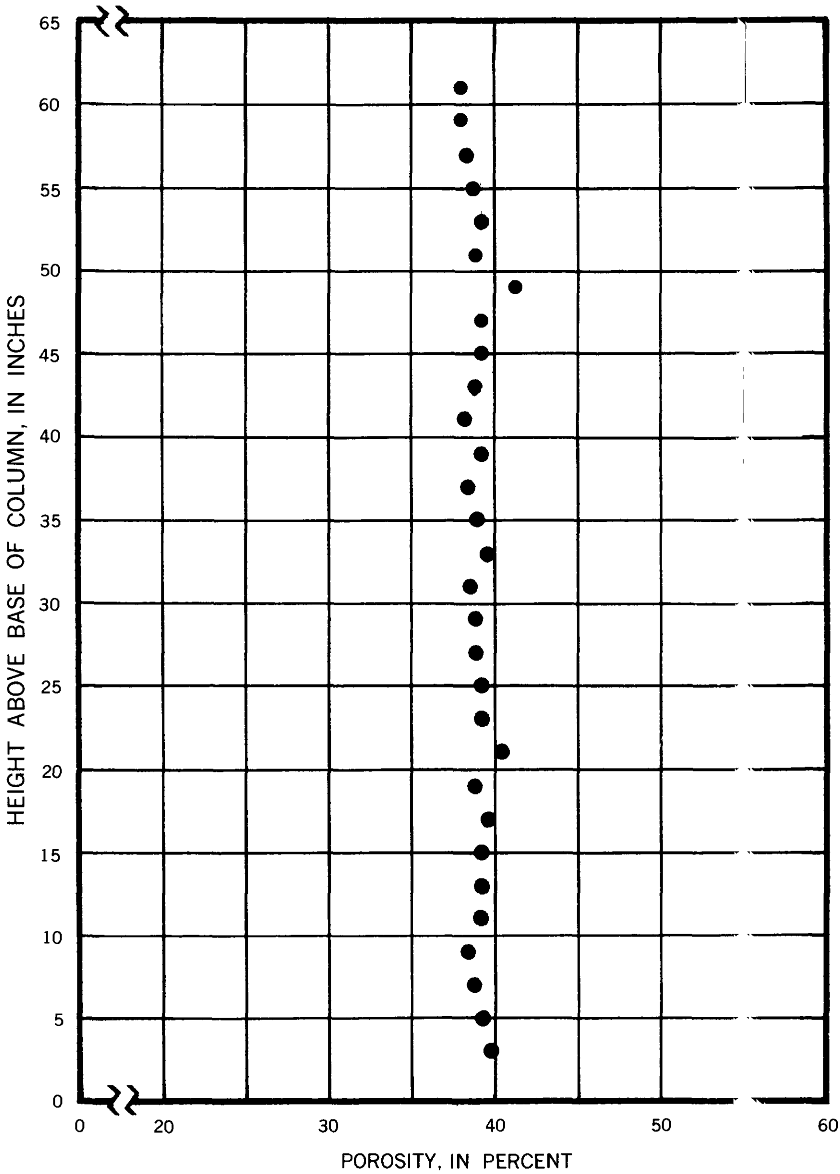


FIGURE 18.—Distribution of porosity in a long column of 0.120-mm glass beads.

tion increased, the circulation and sorting increased in the upper part of the column, and at the end of 150 seconds there was definite stratification in the top 6 inches of the glass beads. After 300 seconds of vibration, the upper 8 inches of glass beads showed obvious layering; the central section of the column of beads showed vague stratification, and the lower part still showed no noticeable sorting.

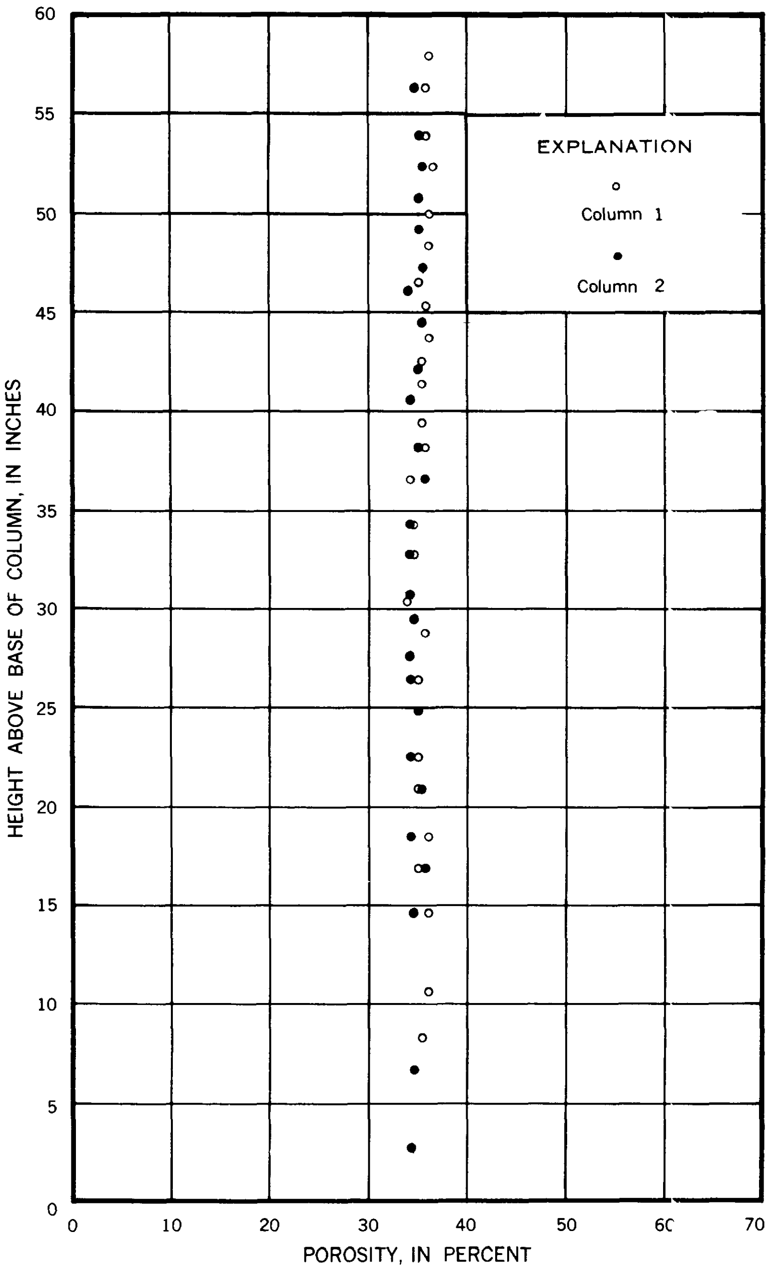


FIGURE 19.—Distribution of porosity in long columns of 20-mesh Del Monte sand.

To investigate more fully the effect of vibration on sorting throughout the length of a 4-foot column, 1-inch layers of colored glass beads of 0.120-mm diameter were placed with the base of the layer at 9, 17,

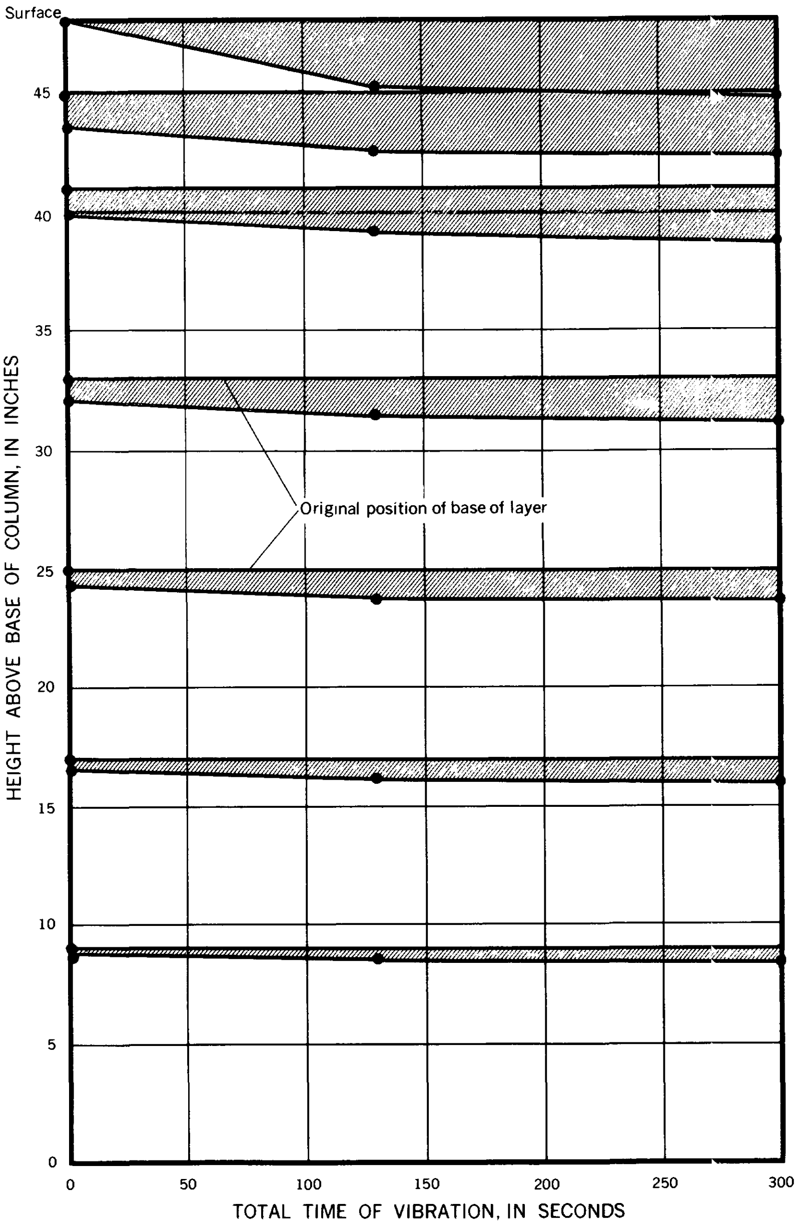


FIGURE 20.—Settling throughout a long column of glass beads.

25, 33, 41, and 45 inches above the base of the column, separated by uncolored 0.036-mm glass beads. The migration of these layers was then observed during vibration. Figure 20 shows the relative settling throughout the column for total time of vibration from 0 to 300 seconds. The width of the cross-hatched bars shows the amount of settling that occurred. Because the uppermost layers would be more greatly affected by the total volume change, the bars become progressively wider toward the top of the column. The zone of interpenetration below each interface, along with this increase in settling, initially thickens toward the top of the column and migrates progressively downward with increasing total time of vibration. Because the amount of sorting was negligible for short periods of vibration, the previously established standard of 10-seconds vibration was concluded to be valid.

EFFECT OF DYE ON DRAINAGE

The results of the column drainage in which a solution of fluorescein dye in water was used as the wetting fluid, as compared to de-aired water, are shown in figures 21 and 22. The 50-inch columns, 1½ inches in diameter, were manually packed with 0.120-mm glass beads. Two of the three columns were wetted with dye, and the other was wetted with de-aired water. The one-wetting method was used, allowing periods of about 76 hours, with the head maintained at the top of the columns. The rate of discharge was determined during drainage periods of as much as 22 hours. The columns were then disassembled, and the moisture content retained after drainage was determined for the sections of the column. The rate of drainage and pattern of moisture distribution after drainage was very similar for both the fluorescein solution and the de-aired water. Although an increase in yield per unit of time occurred, possibly due to the wetting effect of the dye, more data should be obtained if dye is to be used for future testing because it is possible that the increase is within the limits of repeatability between drainage runs using the same material. The content retained after drainage agreed within about 1 percent for the two different fluids, which also is within the range of repeatability between runs.

EFFECT OF TIME ON DRAINAGE

When an air-water interface is maintained during drainage, discharge continues at a gradually decreasing rate until the unsaturated permeability becomes extremely low and drainage finally ceases. Consequently, knowledge of the length of time of drainage is essential in the analysis of specific-yield data.

The effect of time on drainage for the alluvial-sand sample is shown in the drainage curve in figure 23. The decrease in rate of discharge with increasing time of drainage is emphasized by noting that the quantity of discharge increased only about 4 percent between 6 and 70 hours of drainage. In addition, the previous discussion

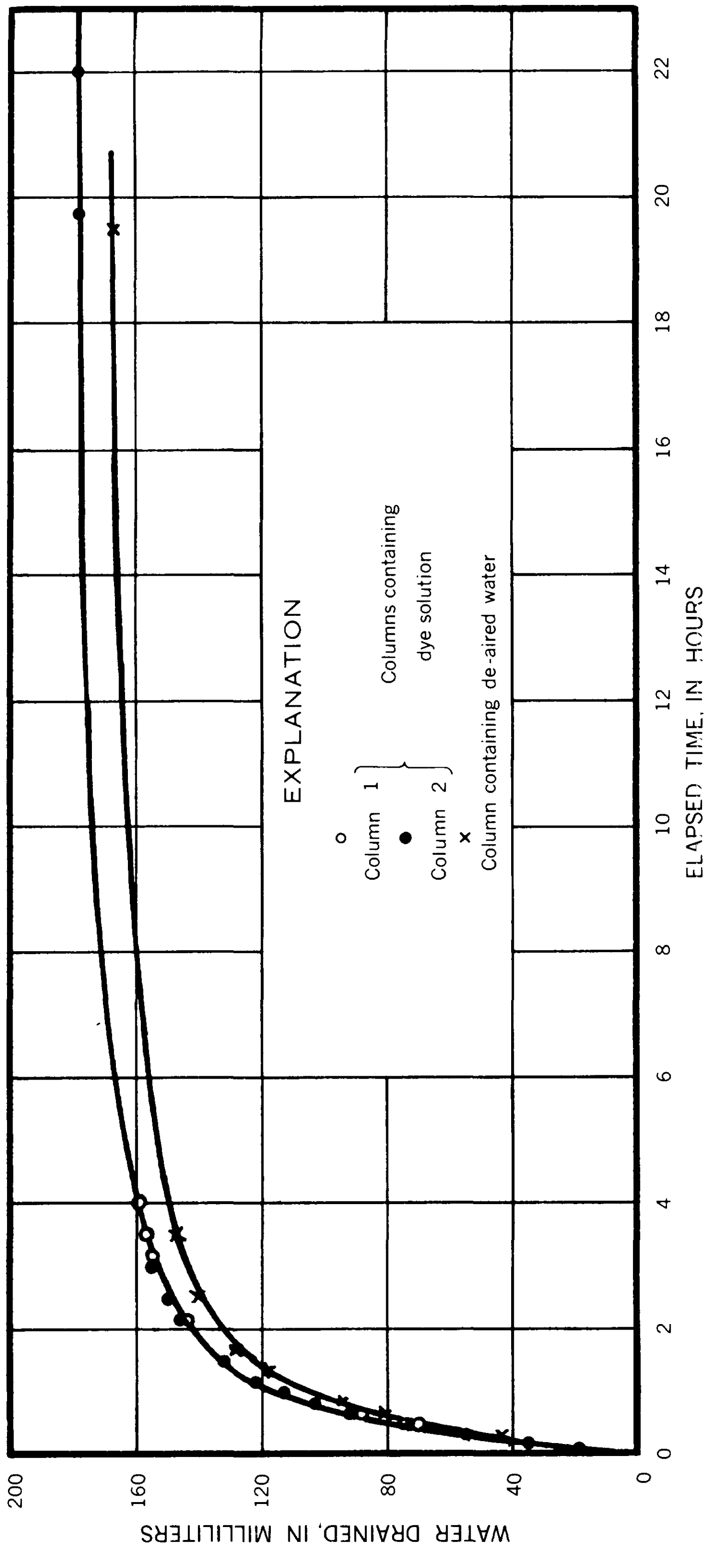


FIGURE 21.—Effect of fluorescein dye on quantity of water drained from 0.120-mm glass beads.

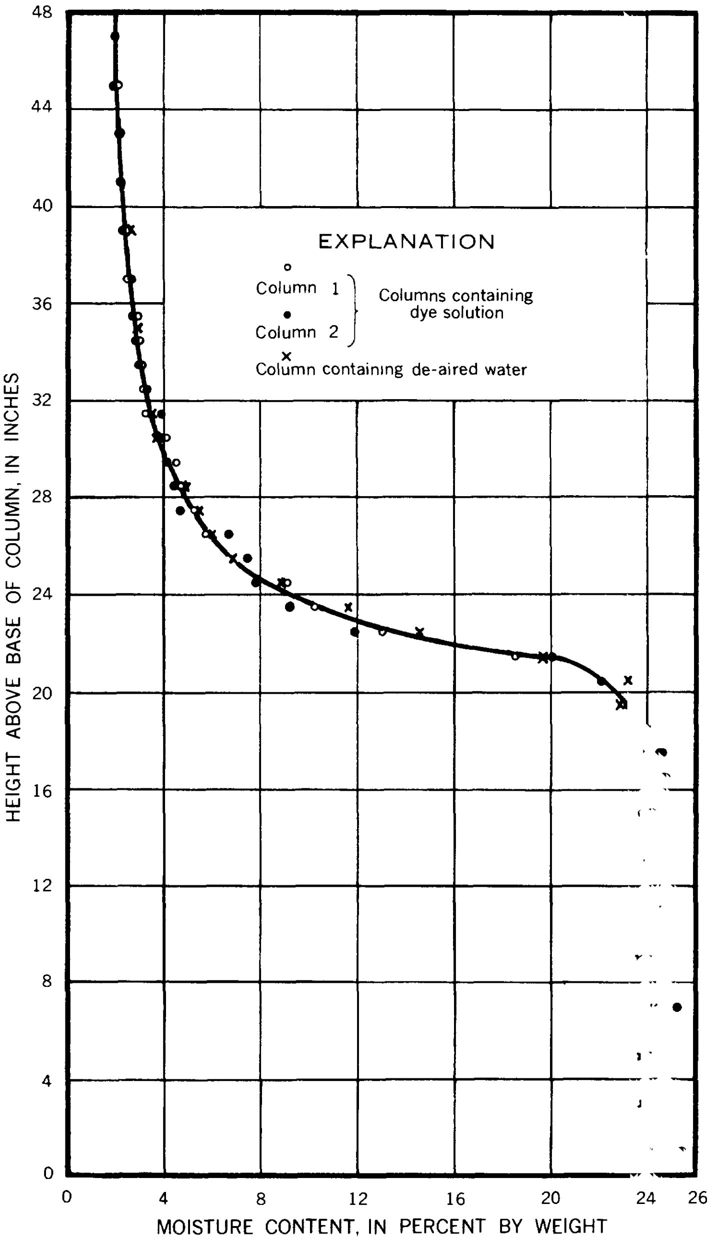


FIGURE 22.—Effect of fluorescein dye on moisture retained after drainage of 0.120-mm glass beads.

indicated that drainage after 70 hours was by no mears complete, because the other methods of determination obtained quantities at least twice that determined after 70 hours.

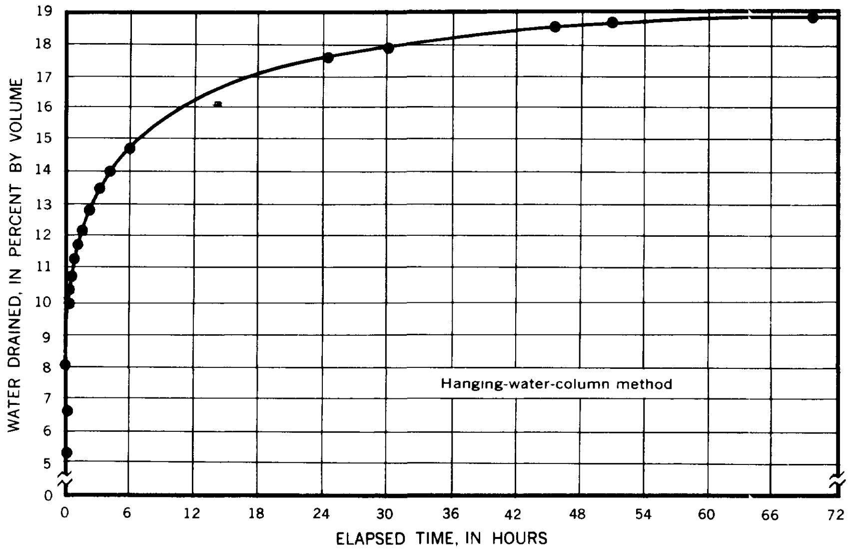


FIGURE 23.—Effect of time on drainage from an alluvial sand.

INVESTIGATION OF THE CENTRIFUGE MOISTURE CONTENT

The American Society for Testing Materials (1958, p. 12) has defined centrifuge moisture equivalent as "the water content retained by a soil which has been first saturated with water and then subjected to a force equal to one thousand times the force of gravity for one hour." It normally is expressed as a percentage by weight. The test reported in this study was designed to evaluate the centrifuge-moisture-equivalent test as a laboratory method for estimating specific retention. Consequently, the research work involved the centrifuge moisture equivalent, but was not limited by the scope of the definition because many factors, such as the force times gravity and the length of time of centrifuging, were changed in the tests. The term "centrifuge moisture equivalent" is used in this report only when the standard centrifuge test was used. If the standard test was modified in any way, the resulting values are reported as "centrifuge moisture contents."

TECHNIQUE

MATERIALS

As shown in table 5, materials covering a wide range of centrifuge moisture equivalents were selected for study. These materials included glass beads of 0.036-, 0.120-, and 0.47-mm diameter; Del Monte sand in 20-, 30-, and 60-mesh sizes; loess obtained from near Trenton, Nebr., and Bonny Dam, Colo.; fuller's earth (200-mesh,—Western

Clay Minerals Co., Ivy, Utah); kaolin (EPK—Edgar Plastic Kaolin Co., Edgar, Fla.), and N.F.—national fine colloidal, powdered, No. 5645 (Mine & Smelter Supply Co., Denver, Colo.). Carefully selected alluvial materials from field sites near Fresno, Calif., and along the Arkansas River in Arkansas and Oklahoma also were used. Table 1 presents particle-size distribution data for all samples.

TABLE 5.—*Centrifuge moisture equivalents of selected materials*

Material	Centrifuge moisture equivalent	Material	Centrifuge moisture equivalent
Del Monte sand:		57CAL106	17.6
30-mesh	0.4	Loess (Trenton, Nebr.)	19.0
20-mesh	.5	59CAL248	[1] 20.2
Glass beads:		58OKL42	[2] 20.4
0.47-mm	1.2	57CAL155	21.6
0.120-mm	1.3	59CAL130-131	[1] 23.1
Del Monte sand:		57CAL139	24.8
60-mesh	1.4	57CAL152	28.8
59CAL191/244	1.9	57CAL162	30.0
Glass beads: 0.036-mm	3.4	57CAL173	32.3
57CAL122	4.0	58ARK146	[2] 37.2
57CAL66	4.2	57CAL112	40.9
57CAL110	5.4	57CAL123	43.2
57CAL118	6.0	57CAL2	46.4
59CAL258-261	[1] 9.8	57CAL205	49.3
59CAL251-252	[1] 10.6	Kaolin (N.F.)	49.6
59CAL253-254	[1] 12.4	Kaolin (EPK)	61.2
59CAL137-138	[1] 13.2	Fuller's earth	109.0
57CAL72	14.1	57CAL14	[3] 120.0
58OKL15	[2] 16.5		
Loess (Bonny Dam, Colo.)	17.3		

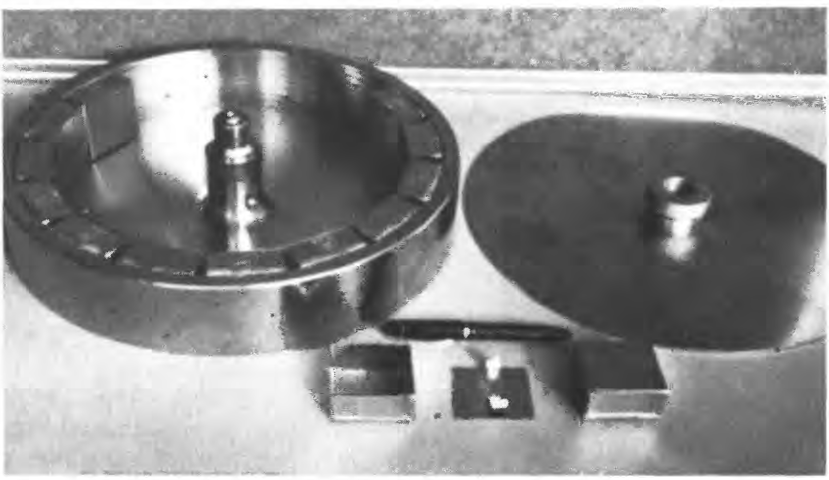
[1] Cenrifuged for a period of 2 hr.
[2] Centrifuged for a period of 3.5 hr.
[3] Water was standing on sample after centrifuging.

PROCEDURES

Centrifuge moisture equivalents are determined by several techniques in scientific laboratories throughout the United States. The principal difference in the technique is in the type of container and the size of samples that are used. Two types of containers are generally used—the moisture-equivalent box and the Gooch crucible, in which 30 and 5 grams of soil are placed, respectively. The Hydrologic Laboratory normally uses the Gooch crucible method, details of which are as follows:

1. A 5-gram sample is placed on a filter paper at the bottom of a Gooch crucible 1½ inches high, about 27 milliliters in volume, and perforated at the bottom to allow the free discharge of water. (See fig. 24.)
2. The crucible is placed in a pan, and water is added to the pan to the level of the top of the sample. The sample is allowed to saturate from below for at least 16 hours.
3. The crucible is placed in a humidifier, and the sample is allowed to drain for at least 4 hours.

A. Gooch crucible and trunnion cup.



B. Moisture-equivalent head and boxes.

FIGURE 24.—Centrifuge equipment for crucible and box methods.

4. The crucible is placed in the centrifuge and rotated at a force of 1,000 times gravity (at the center of gravity of the sample) for 1 hour.
5. The sample is transferred to a moisture can and weighed.
6. The moisture can containing the sample is placed in a drying oven, and the sample is dried at least 16 hours at a temperature of 110°C.
7. The moisture can containing the soil sample is placed in a desiccator to cool and then reweighed.
8. The moisture equivalent is expressed as the moisture content, in percentage by dry weight, and is calculated as follows:

$$w=\frac{W_{wsc}-W_{sc}}{W_{sc}-W_c}\times 100=\frac{W_w}{W_s}\times 100$$

where

w=moisture content, in percentage by dry weight
W_{wsc}=weight of wet sample and container after centrifuging, in grams
W_{sc}=weight of dry sample and container, in grams
W_c=weight of container, in grams
W_w=weight of water, in grams
W_s=weight of dry sample, in grams.

This procedure was used as standard in the experiments evaluating the centrifuge-moisture-equivalent test. Usually only one of the factors affecting the test was changed in any one experiment. A controlled-temperature centrifuge was used, except where data on the uncontrolled-temperature centrifuge were obtained for comparison. The temperature of the controlled-temperature centrifuge was maintained at 20°C, except in experiments where the effect of temperature on the centrifuge moisture content was being evaluated. A thin film of water was placed at the bottom of the controlled-temperature centrifuge chamber to assure a high relative humidity during centrifuging. In most of the experiments 5-gram samples in the smaller crucibles were used, and tests were made in duplicate. Soil samples were prepared through a No. 10 sieve (2 mm). When larger samples were needed, Gooch crucibles having a height of 3 inches and a volume of 125 ml were used.

The procedure for the moisture-equivalent box method was nearly the same as for the crucible method, except 30-g samples were used; and square metal boxes, rather than crucibles, were used to hold the samples.

FILTER PAPER

Judging from evaluation tests, the retentivity of the filter paper did not seem to have any consistent effect on the centrifuge moisture equivalent.

The wet strength of the filter paper, however, was found to be a factor to be considered in the selection of a filter paper. For example, most papers tore when an attempt was made to remove them from the kaolin samples.

Whatman filter paper 540 (factory-cut to crucible size) was selected for use in the smaller crucibles. Whatman filter paper 50 was selected for use in the larger crucibles.

DUMMY COLUMN

The dummy column provides an extended water column beneath the sample. Thus, a lower force times gravity may be used to obtain a desired average moisture tension in the sample, and, in addition, the range in moisture tension from the top to the bottom of the sample may be reduced. Porvic—a semipermeable plastic sheet, 0.8 mm thick—was selected as the material for use as a dummy column. The column was prepared by cutting a cross-shaped porvic strip in the configuration shown in *D* of figure 25. The strip was folded so that the four

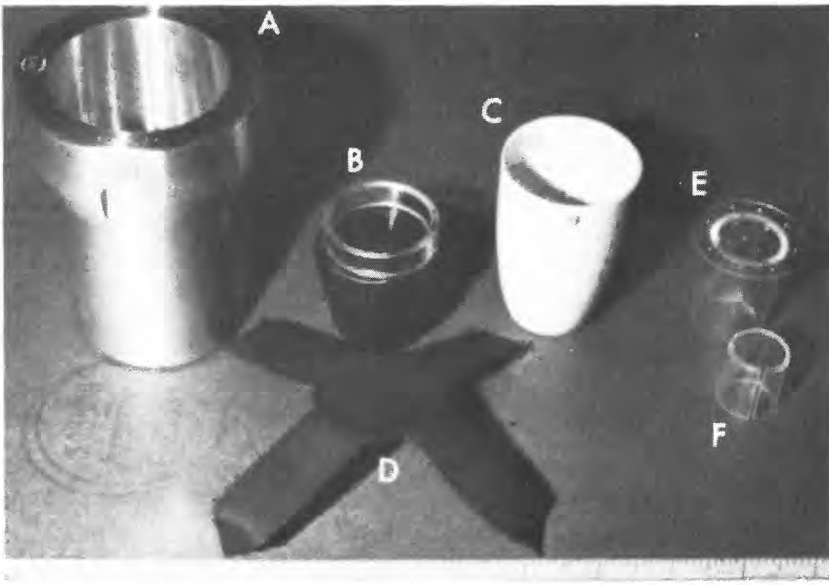


FIGURE 25.—Large-size dummy column and accessory centrifuge equipment. *A*, trunnion cup and crucible holder. *B*, assembled dummy column with plastic sample ring. *C*, Gooch crucible. *D*, porvic strip. *E*, plastic disk cemented on plastic cylinder. *F*, plastic cylinder for holding porvic strip in place.

arms extended downward from a circular center. The center of the strip was then placed over a plastic disk cemented to one end of a plastic cylinder (*E*). The triangular ends of each arm were held in place by inserting a small plastic cylinder (*F*), cut to give spring action, inside the first cylinder. This assembly then fitted snugly in a Gooch crucible. The length of the porvic column was 2 cm in the small crucibles and 5 cm in the large crucibles. Air was purged from the porvic by placing it in warm water and applying vacuum for 1 hour.

In one procedure, 5- and 15-gram samples were placed over the 2- and 5-cm columns, respectively, giving samples of similar thickness in the two sizes of crucibles. A force times gravity that would give a tension of 500 cm of water at the bottom of the sample was applied in the centrifuge. This is the approximate tension at the center of gravity of coarse- and medium-textured materials when centrifuged at 1,000 times the force of gravity. A force of 250 times gravity for the 2-cm dummy column and a force of 100 times gravity for the 5-cm dummy column were used to give a tension of 500 cm of water at the bottom of the sample.

In another procedure, values of centrifuge moisture content at a tension of 345 cm of water (1/3 atmosphere) for undisturbed and disturbed materials were obtained by placing a 1-cm-thick sample on a 5-cm porvic strip and centrifuging at a speed that would apply a tension of 345 cm of water (1/3 atmosphere) at the center of gravity of the sample.

DISCUSSION OF CENTRIFUGE DATA

COMPARISON OF CRUCIBLE AND BOX METHODS

Moisture equivalents obtained in the controlled-temperature centrifuge, using both the Gooch crucibles and the moisture-equivalent boxes, are given in table 6.

TABLE 6.—*Moisture equivalents obtained by crucible and box methods*

Material	Centrifuge moisture equivalent (percent)	
	Gooch crucible	Moisture-equivalent box method
Del Monte sand:		
20 mesh	0.5	0.6
60 mesh	1.4	1.6
Glass beads (0.120 mm)	1.3	1.9
59 AL191/244	1.9	2.2
Loess (Bonny Dam, Colo.)	17.3	17.3

EFFECT OF TEMPERATURE IN THE CONTROLLED-TEMPERATURE CENTRIFUGE

The effect of changing the temperature in the chamber of the controlled-temperature centrifuge on the centrifuge moisture content was studied for 12 materials covering a wide range of particle-size distribution. All materials were centrifuged over a range from 5° to 30°C for 1 hour except kaolin and fuller's earth, which were centrifuged for 6 hours. The time of centrifuging was considered adequate for moisture equilibrium to be obtained. The effect of changing the temperature on the results of centrifuge moisture content is shown in figures 26 and 27. This illustration shows that there was a significant decrease in moisture content as temperature increased. The difference in moisture content between 10° and 30°C ranged from a

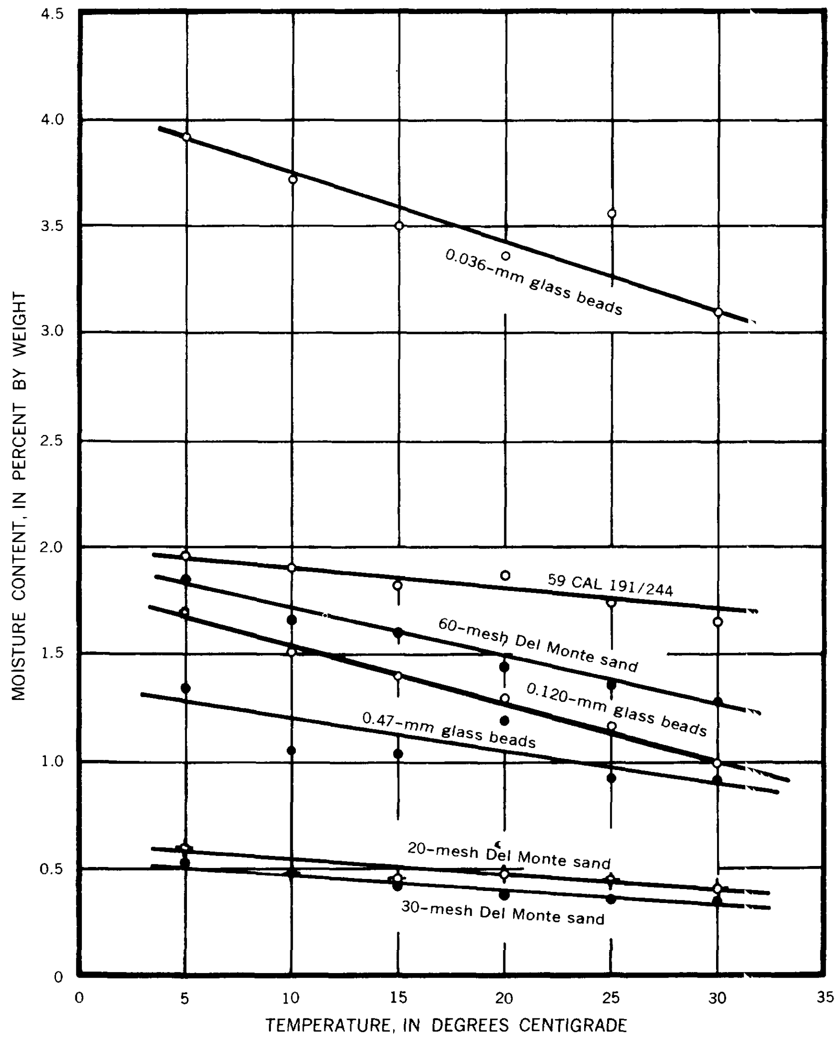


FIGURE 26.—Effect of temperature in the controlled-temperature centrifuge on the centrifuge moisture content of coarse-textured materials.

fraction of 1 percent in the coarse-textured materials to 6 percent in some of the fine-textured materials. For the coarse-textured materials, the percentage change in moisture content over the range of 10° to 30°C ranged from 13 to 34 percent, as compared to a range of 4 to 27 percent for the fine-textured materials.

An increase in temperature could affect the moisture content of the sample by a decrease in surface tension of the pore water and an increase in evaporation from the sample. The relative humidity in the centrifuge chamber was measured and found to be near 100 per-

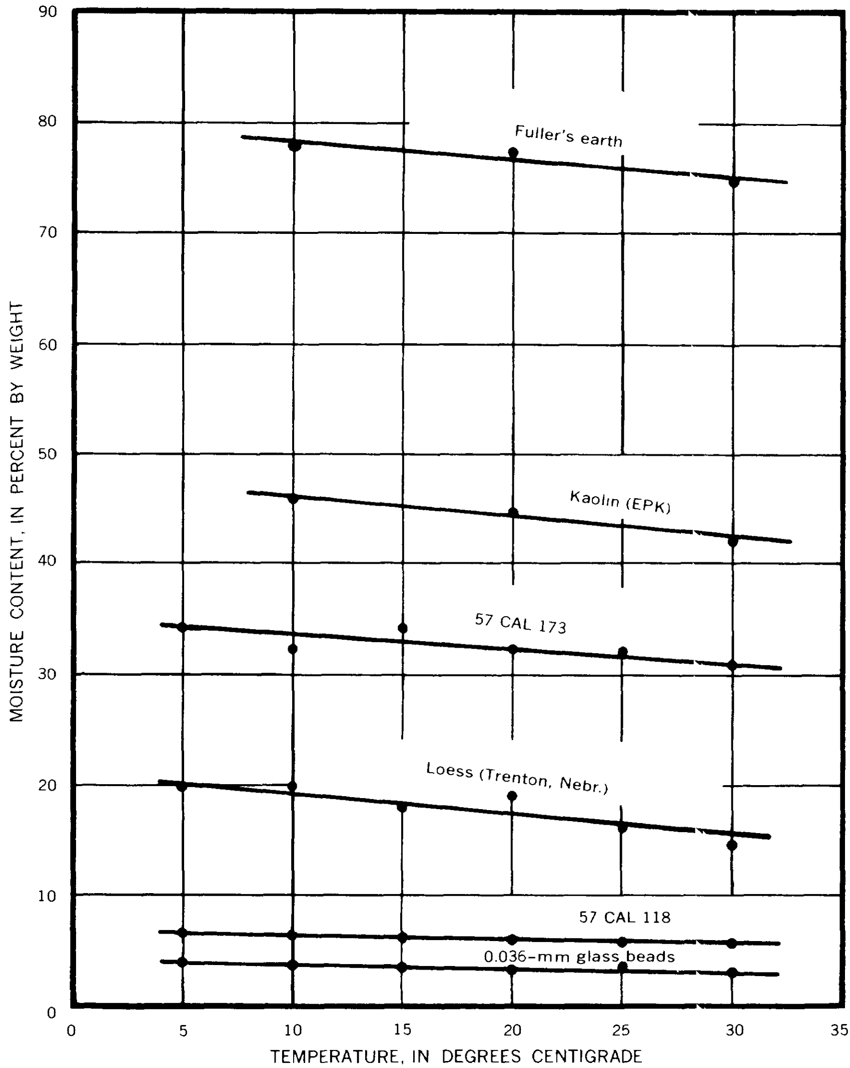


FIGURE 27.—Effect of temperature in the controlled-temperature centrifuge on the centrifuge moisture content of fine-textured materials.

cent throughout the period of centrifuging. Therefore, because evaporation from the sample was negligible, the decrease in moisture content seems to be due to a change in the surface tension of the water.

These tests indicated that temperature should be controlled at a preselected value. A temperature of 20°C was used as a standard in all later studies, except those dealing further with temperature effects.

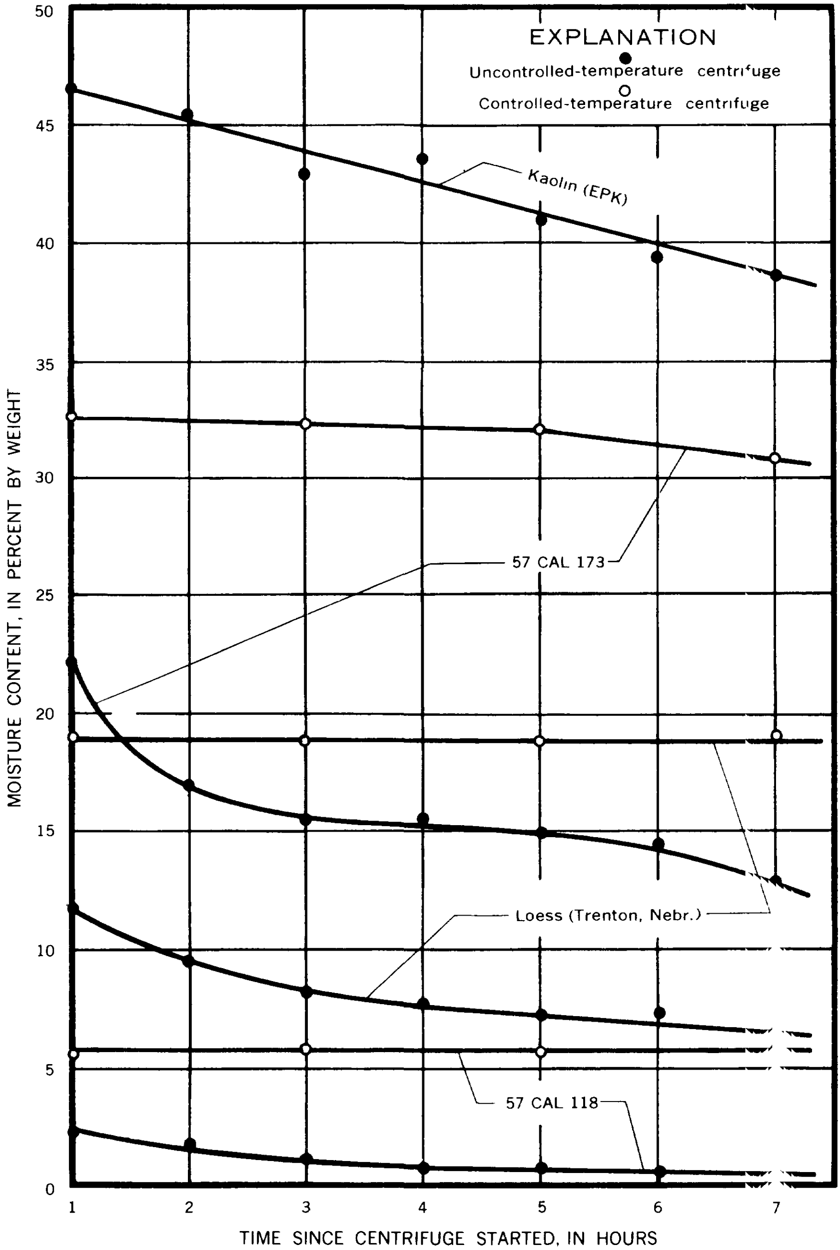


FIGURE 28.—Effect of length of period of centrifuge operation on the centrifuge moisture content.

COMPARISON OF CONTROLLED- AND UNCONTROLLED-TEMPERATURE CENTRIFUGES

Samples were centrifuged for 1 hour each during a 7-hour span of nearly continuous centrifuge operation to determine the effect of changes in prevailing conditions during the period of centrifuge operation. Results of the tests are shown graphically in figure 28. In these tests the centrifuges were operated almost continuously from the start of the experiment until the last group of samples was removed from the centrifuge. The only interruptions were those when the samples were being placed in, or removed from, the centrifuges. In the uncontrolled-temperature centrifuge, some samples were centrifuged during each hour of the 7-hour period. In the controlled-temperature centrifuge, samples were centrifuged only during the 1st, 3d, 5th, and 7th hours (the centrifuge was run empty during the other hours). A continuous record of the temperature and relative humidity in the chambers of both centrifuges was made.

The relative humidity ranged from 98 to 100 percent in the controlled-temperature centrifuge throughout the period of testing. The relative humidity in the uncontrolled-temperature centrifuge was close to 100 percent in the early minutes of each hour of testing and then decreased to the humidity of the room (which ranged from 32 to 34 percent during the day). During the beginning period, the humidity in the centrifuge decreased to room humidity within half an hour. During each succeeding period of operation, however, relative humidity in the centrifuge decreased to room humidity in less than 5 minutes.

The temperature in the uncontrolled-temperature centrifuge was initially 27.8°C and increased progressively during succeeding hours of operation. After the first hour of operation, the temperature was 38.3°C; after the second hour, 41.1°; and after the seventh hour, 46.7°. The relation of this increase in temperature to the centrifuge moisture is shown in figure 29. Shown also is an extrapolation of the moisture-content temperature lines from figure 27, which were drawn from data obtained in the controlled-temperature centrifuge. The kaolin (EPK) data were not extrapolated because a centrifuging time of 6 hours was used for obtaining the data in figure 27. The centrifuge moisture content of the materials decreased linearly with increased temperature. The plotted values are somewhat below the extrapolated lines of the controlled-temperature data, supporting the conclusion that evaporation and surface tension are factors accounting for the decrease in moisture content with an increase in temperature.

The centrifuge moisture contents of the same materials tested in the controlled-temperature centrifuge at different times were nearly the same. The length of time the centrifuge had been in operation had little, if any, apparent influence on the centrifuge moisture contents obtained. The data indicated also that temperature and humidity were accurately regulated in the temperature-controlled centrifuge.

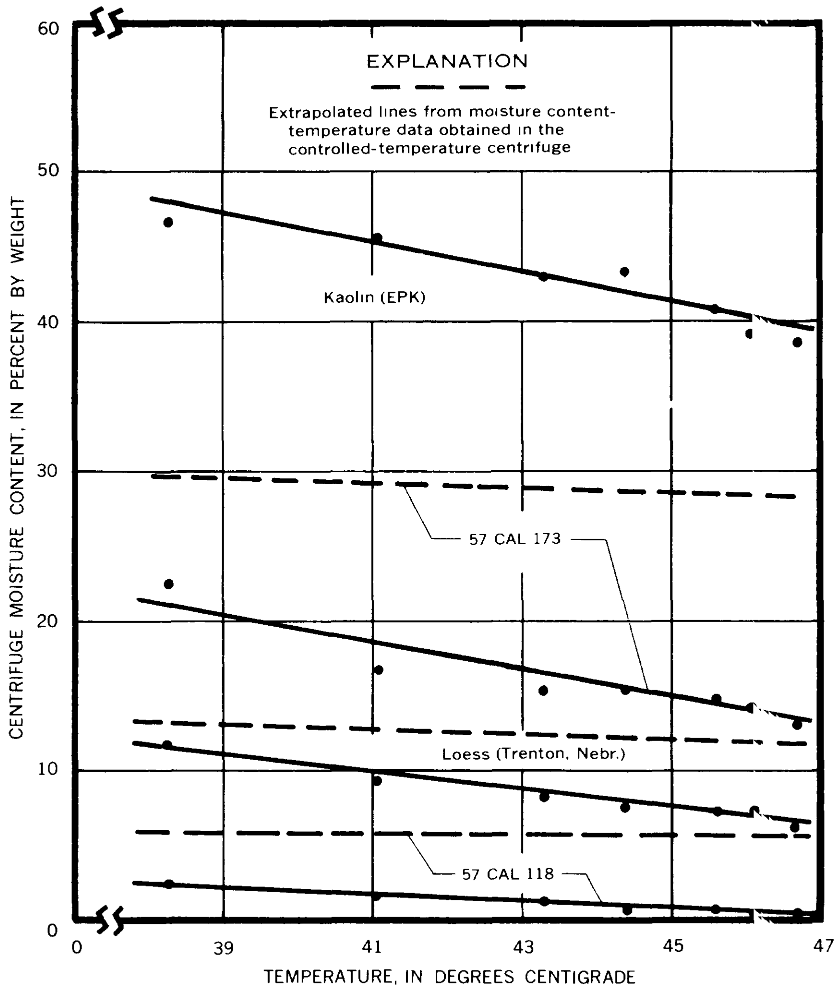


FIGURE 29.—Effect of temperature in the uncontrolled-temperature centrifuge on the centrifuge moisture content.

Results obtained in the uncontrolled-temperature centrifuge were very different from those obtained from the controlled. The centrifuge moisture content of the materials studied decreased as the length of time of centrifuge operation increased. After the centrifuge had been in operation for 7 hours, the centrifuge moisture content for 57CAL118 was about one-fifth of the value obtained when the centrifuge had been in operation for only 1 hour. For loess (Trenton, Nebr.) and 57CAL173, the centrifuge moisture contents after 7 hours of operation were about half the values obtained after 1 hour of operation. For kaolin (EPK), the moisture content after 7 hours of operation was about five-sixths of the 1-hour value.

The difficulty in obtaining good duplication of results for samples run in the uncontrolled-temperature centrifuge has long been a matter of concern. Results from the present research indicate that the progressive heating of the uncontrolled-temperature centrifuge as the length of period of centrifuge operation is increased may be the explanation for this lack of duplication. The data shown in figure 28 indicate that repeatability of results is obtainable when samples are run at different times in the controlled-temperature centrifuge.

Another comparison of the controlled-temperature and uncontrolled-temperature centrifuges was made using 16 samples from the subsidence study area of California. The results are reported in table 7.

TABLE 7.—*Centrifuge moisture content obtained from the controlled- and uncontrolled-temperature centrifuges*

Laboratory sample	Uncontrolled-temperature centrifuge		Controlled-temperature centrifuge
	Average centrifuge moisture equivalent (percent by weight)	Average centrifuge moisture equivalent multiplied by conversion ratio [1]	Average centrifuge moisture equivalent (percent by weight)
57CAL66	1.4	3.0	4.2
57CAL122	1.2	2.7	4.0
57CAL118	3.0	5.1	6.0
57CAL110	1.2	2.7	5.4
57CAL72	8.0	9.7	14.1
57CAL139	25.5	24.0	24.8
57CAL155	12.4	13.1	21.6
57CAL106	7.4	9.2	17.6
57CAL152	21.1	20.5	28.8
57CAL162	20.2	19.8	30.0
57CAL173	27.2	25.3	32.3
57CAL123	32.8	29.2	43.2
57CAL2	41.4	34.8	46.4
57CAL205	46.9	37.5	49.3
57CAL112	34.6	30.4	40.9
57CAL14	81.9	--------	[2] 120.0

[1] See Piper (1933, p. 484).
[2] Water standing on sample after centrifuging included in moisture equivalent.

The samples are arranged in the table according to a decreasing content of sand. The average centrifuge moisture equivalent obtained in the uncontrolled-temperature centrifuge was multiplied by a ratio (Piper, 1933) used for converting centrifuge moisture-equivalent values to specific retention (by weight). It is not known at present whether a conversion ratio is necessary for centrifuge moisture contents obtained from the controlled-temperature equipment. If a conversion ratio is necessary, it will be different from that used for the uncontrolled-temperature centrifuge and must be obtained from a comparison of centrifuge moisture contents with field and laboratory drainage data.

Except for sample 57CAL139, the moisture content after centrifuging was higher in the controlled-temperature centrifuge than in the uncontrolled-temperature centrifuge. For sandy materials, the moisture contents obtained from the controlled-temperature centrifuge were two or more times higher than those obtained in the uncontrolled-temperature centrifuge, whereas for the finer textured materials, the moisture contents obtained from the controlled-temperature centrifuge were of the magnitude of one- to two-tenths higher. These results seem reasonable because centrifuge moisture equivalents for sandy materials (usually obtained in an uncontrolled-temperature centrifuge) generally have been considered to be lower than moisture contents obtained in the field. The moisture contents for the sandy materials obtained in the controlled-temperature centrifuge appear to be of the magnitude that would be expected in the field.

EFFECT OF LENGTH OF PERIOD OF CENTRIFUGING

The values of centrifuge moisture content obtained in the controlled-temperature centrifuge for the fine-textured samples from the subsidence area of California are somewhat higher than might be expected from field samples. In studies reported in the literature, a period of centrifuging of 1 hour in the uncontrolled-temperature centrifuge was not considered adequate to allow the fine-textured materials to approach an equilibrium moisture content. Length of period of centrifuging, therefore, was considered in this study for the controlled-temperature centrifuge. The effect of the length of period of centrifuging on the centrifuge moisture content is shown graphically in figure 30 for six materials, two of which are from the California subsidence area. A centrifuge time of 6 hours was inadequate for moisture equilibrium to be approached for a fine-textured material, such as fuller's earth. The 0.036-mm glass beads required less than 1 hour to reach moisture equilibrium, whereas 1 to 2 hours were required for 57CAL2 and 2 to 4 hours for 57CAL14.

Data from this study indicate that 1 hour of centrifuging provides adequate time to approach moisture equilibrium in most coarse- and medium-textured materials. However, for some materials, such as the fine-textured materials studied in this experiment, a centrifuge time in excess of 1 hour is necessary.

EFFECT OF APPLIED TENSION

Three methods of varying the tension applied to a sample during centrifuging were investigated in the controlled-temperature centri-

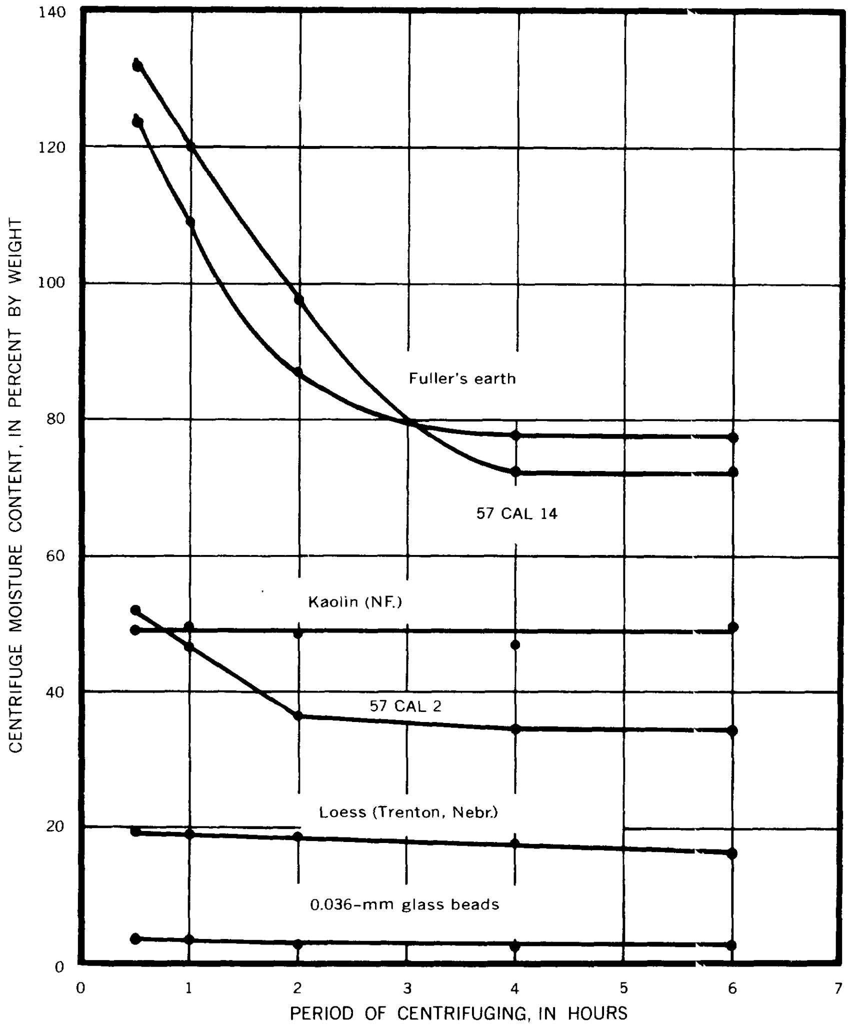


FIGURE 30.—Effect of length of period of centrifuging in the controlled-temperature centrifuge on centrifuge moisture content.

fuge: changing the force times gravity, changing the thickness of the sample, and using dummy columns of different lengths below the sample.

If the influence of the filter paper below the soil sample on centrifuge moisture content is ignored, the soil-moisture tension at the periphery or bottom of the sample being centrifuged is considered to be zero. The soil-moisture tension at any distance from the bottom of the sample can be calculated from the equation (Richards and Weaver, 1944)—

$$T=\left(\frac{\omega^2}{2g}\right)(r_1^2-r_2^2)$$

where

T=tension, in centimeters of water
ω=angular velocity, in radians per second
g=acceleration of gravity, in centimeters per second per second
r_1=distance of bottom of sample from center of rotation, in centimeters
r_2=distance of specified point in sample from center of rotation, in centimeters.

If a force of 1,000 times the force of gravity is applied to a sample having a center of gravity 4 mm from the bottom of the sample, then, by the equation, the soil-moisture tensions at successive millimeter increments from the bottom to the top of the sample will be 101, 201, 301, 400, 498, 596, 692, 789, 884, and 979 cm of water. Decreasing the force times gravity at which a sample is centrifuged would lower the soil-moisture tension at the center of gravity of the sample. Increasing the sample thickness would increase the soil-moisture tension at the center of gravity of the sample. The use of a porvic dummy column beneath the soil sample would also increase the soil-moisture tension at the center of gravity of the soil sample.

FORCE TIMES GRAVITY

Three homogeneous mixtures of glass beads (0.036, 0.120, and 0.470 mm) and a loess (Bonny Dam, Colo.) were used in the study on the effect of changing the force times gravity. The effect of changing force times gravity on the centrifuge moisture content of these materials is shown graphically in figure 31.

The height of the zone of capillary saturation, measured in the column-drainage study of glass beads (fig. 9), was about 72, 24, and 6 inches for the 0.036-, 0.120-, and 0.470-mm beads, respectively. Dividing the height of the zone of capillary saturation by the sample thickness, which is approximately 0.32 inches, gives the calculated force required to start the sample to drain. The calculated values of force times gravity are 225 for the 0.036-mm beads, 75 for the 0.120-mm beads, and 19 for the 0.470-mm beads. The values of force times gravity obtained by extrapolation (fig. 31) of the experimental data are about 235 for the 0.036-mm beads, 74 for the 0.120-mm beads, and 15 for the 0.470-mm beads. These values agree closely with the calculated results, indicating that the given soil-moisture tension was reproduced by changing the force times gravity in the controlled-temperature centrifuge. Thus, by applying the proper force times gravity, the moisture content at a specified height within a centrifuge sample will be similar to that at a given height in the drainage column.

The curves in figure 31 illustrate that for homogeneous materials, such as glass beads, drainage occurs over a relatively narrow tension range; whereas for more heterogeneous materials, such as loess, drainage occurs over a much wider tension range.

The study of the effect of changing the force times gravity was expanded to include medium- and fine-textured materials. These materials were centrifuged over a range of 1 to 2,000 times the force of gravity. The results of the centrifuging are shown in figure 32. For

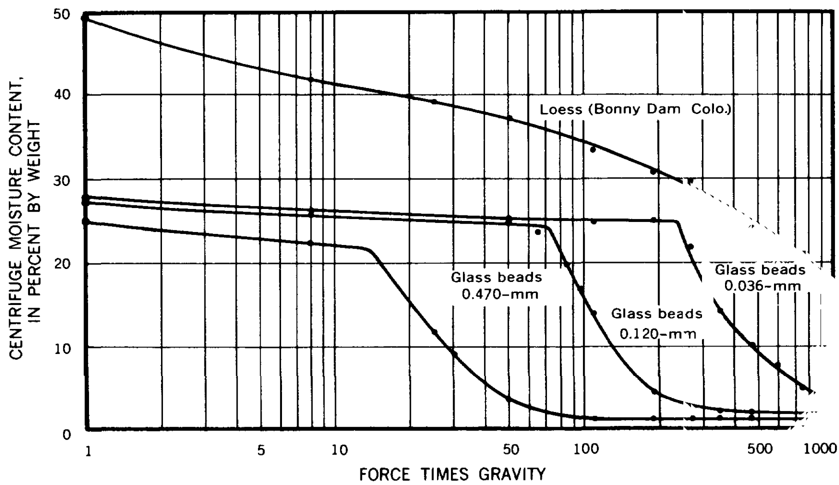


FIGURE 31.—Effect of force times gravity on centrifuge moisture content for coarse- and medium-textured materials.

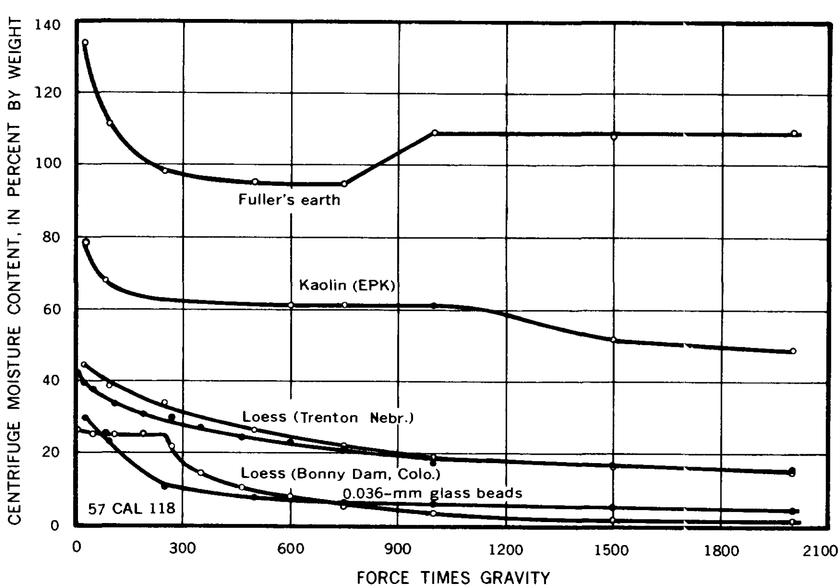


FIGURE 32.—Effect of force times gravity on centrifuge moisture content for medium- and fine-textured materials.

sample 57CAL118, the moisture content decreased rapidly as the low centrifugal forces were applied and decreased only slightly thereafter. Results with loess from Trenton, Nebr., were similar to those for loess from Bonny Dam, Colo., the moisture content decreasing at a decreasing rate as centrifugal force increased. The values of moisture content for kaolin (EPK) were similar for forces of 500 to 1,000, but they decreased about 10 percent between 1,000 and 2,000 times gravity. The values of moisture content for fuller's earth decreased continually up to a force of 500, remained about the same for forces of 500 to 750, increased from 750 to 1,000, and then remained at the same level for forces from 1,000 to 2,000 times gravity. The increase above 750 could be a result of an increased compression at the higher centrifugal forces and a resultant lower permeability.

SAMPLE THICKNESS

The effect of changing the sample thickness on the centrifuge moisture content required a study of the change in moisture content at different heights within a sample and a study of the moisture content for samples of different thicknesses. In these studies a force of 1,000 times gravity was applied.

The data on the centrifuge moisture content at different heights within samples of 0.120-mm glass beads and loess (Trenton, Nebr.) are illustrated in figure 33. The samples were about 2.1 cm thick and were segmented with a spatula at selected vertical increments from the top to the bottom of the samples. The moisture content was then determined for each increment. The centrifuge moisture content for the 0.120-mm glass beads was nearly the same for all measured increments, whereas the measured centrifuge moisture content of loess decreased with increased distance from the bottom of the sample.

The actual decrease in moisture content from bottom to top in the centrifuged sample may be more pronounced than is shown in figure 33 because there probably was some redistribution of moisture upward after the centrifuge was turned off and before the sampling was completed. This fact is explained by the high-tension gradient between the top and bottom of the sample developed during centrifuging. If redistribution of moisture in the sample did not occur after centrifuging, the curves in figure 33 would represent a drained column of about 2,100 cm long. As discussed and illustrated previously in this report, the retained-moisture content of 0.120-mm glass beads would be similar over all but the lower part of such a column, whereas for loess, the moisture content would show a continual decrease with increased distance from the bottom of the column.

The centrifuge moisture content of different sample thicknesses of 0.036-mm glass beads, loess (Trenton, Nebr.), kaolin (EPK), and fuller's earth is shown graphically in figure 34. The centrifuge moisture content of 0.036-mm glass beads and loess decreased, at a decreasing rate, as the sample thickness increased. This is to be expected because the soil-moisture tension at the center of gravity of a sample is increased with increased thickness of sample, and the moisture content should, therefore, decrease. However, the results for kaolin (EPK) and fuller's earth did not follow the expected trend because moisture content increased as the sample thickness increased. Tests were made on samples of kaolin (EPK) and fuller's earth 3 cm thick to determine if this discrepancy might be due to the low permeability of the materials. Table 8 provides a comparison between the values of moisture content obtained after 1 and 4 hours of centrifuging and after 1 hour of centrifuging followed by 1 hour of storage in the centrifuge chamber.

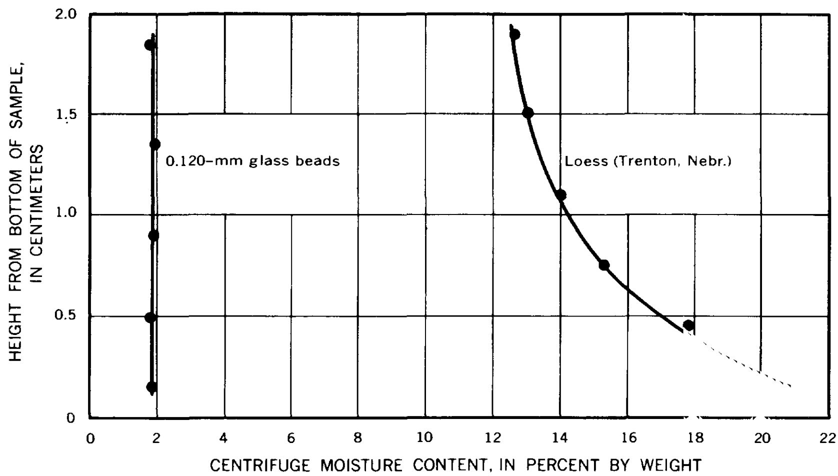


FIGURE 33.—Moisture content at different heights within samples after centrifuging.

TABLE 8.—*Moisture content after centrifuging samples of fine-textured materials, 3 cm thick*

Centrifuging (hours)	Average centrifuge moisture content (percent by weight)			
	Fuller's earth		Kaolin (EPK)	
	Water standing on sample excluded	Water standing on sample included	Water standing on sample excluded	Water standing on sample included
1	108. 5	140. 3	55. 8	87. 6
1 [1]	129. 4	142. 1	63. 7	85. 8
4	104. 3	104. 3	54. 2	64. 5

[1] 1-hr storage in centrifuge.

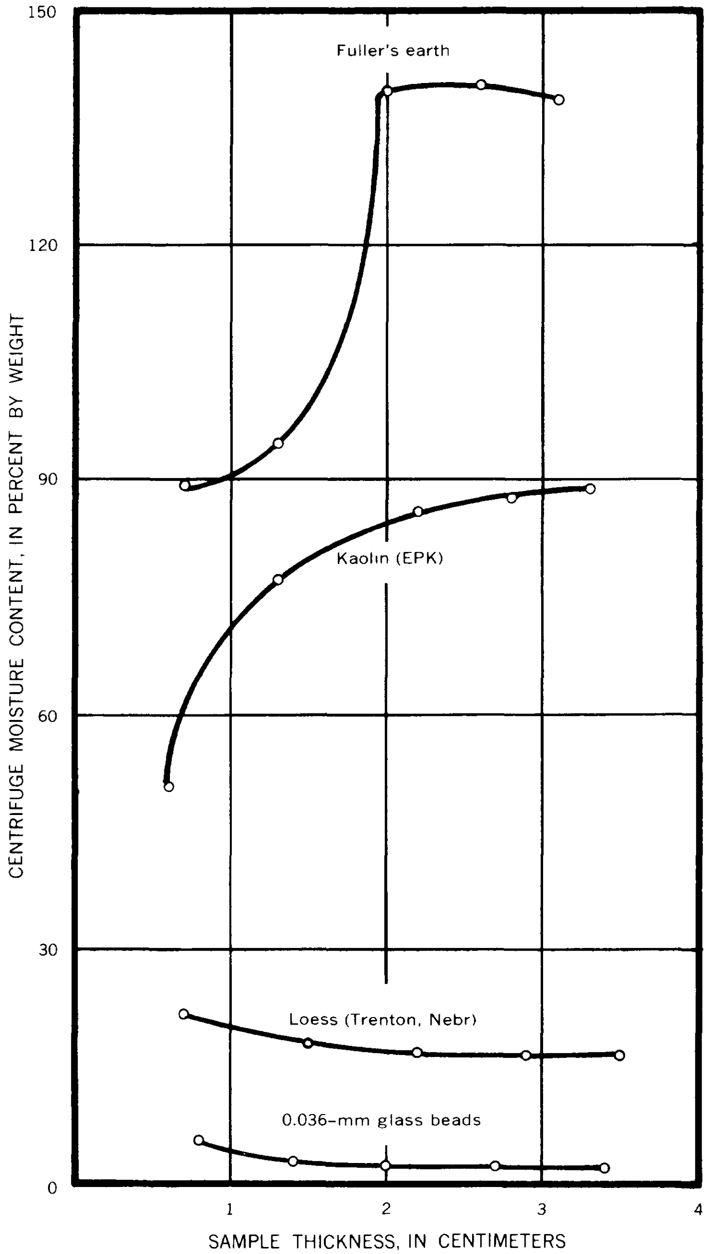


FIGURE 34.—Effect of sample thickness on centrifuge moisture content.

When water was found standing on the samples after the test, two calculations of moisture content were made—one excluding the water standing on the sample and the other including it. When the water on top of the samples after centrifuging was excluded, the values of centrifuge moisture content obtained after 1 and 4 hours of centrifuging were virtually the same. However, when the water standing on the sample was included, the values of centrifuge moisture content after 1 hour were 35 percent higher for fuller's earth and 36 percent higher for kaolin than after 4 hours of centrifuging. These data indicate that a period of centrifuging considerably in excess of 1 hour would be required to obtain moisture equilibrium in the 3-cm-thick sample.

When the water standing on the sample was included, the values of centrifuging moisture content obtained after 1 hour of centrifuging were not appreciably different from those obtained after 1 hour of centrifuging followed by 1 hour of storage in the centrifuge chamber. However, when the water standing on the sample was excluded, the centrifuge moisture content after the 1-hour storage period was 22 percent higher for fuller's earth and 14 percent higher for kaolin than after 1 hour of centrifuging and no storage. This may indicate that the samples were compressed during centrifuging and that, after the force was released, the samples expanded and absorbed some of the water standing on the sample.

Changing the soil-moisture tension by altering the thickness of the sample apparently has certain practical limitations when materials of low permeability are used. Increasing the thickness of the sample would result in a lower permeability because the increased weight would produce greater sample density. This decreased permeability, along with a longer drainage column, would necessitate an appreciable increase in the length of time of centrifuging to obtain moisture equilibrium.

This research emphasizes that duplication and reliability in the centrifuge-moisture-equivalent test are possible when the sample is accurately weighed (comparable thicknesses are obtained) and when the total thickness of sample is used.

DUMMY COLUMN

The values of centrifuge moisture content for 10 samples, using 2- and 5-cm dummy columns, are shown graphically in figure 35 with data obtained by the standard technique. Except for the fine-textured materials, fairly close agreement in centrifuge moisture content was obtained by the three methods. For fine-textured materials, the centrifuge moisture equivalent was somewhat higher than the values of centrifuge moisture content obtained by use of porvic dummy columns.

The effect of the length of time of centrifuging on the centrifuge moisture content of samples placed on a 2-cm porvic dummy column is illustrated in figure 36. The moisture content for sample 57CAL173 was nearly constant throughout the test, whereas the moisture content for the other three samples decreased slightly between 1 and 2 hours but remained about the same after 2 and 4 hours of centrifuging. Data in figure 30 illustrate that sample 57CAL14 required about 2 hours of additional centrifuging to obtain moisture equilibrium when the porvic dummy column was not used. Because of the shape of the Gooch crucible, a 5-gram sample placed at the bottom of the crucible is about twice as thick as a 5-gram sample placed over a 2-cm porvic dummy column. The thinner sample and the resultant decrease in compaction are possible explanations for the shorter period of time required to approach moisture equilibrium when using the porvic-dummy-column method.

Although the use of a porvic dummy column adds another step to the centrifuge procedure, it has certain advantages over the conventional procedure. Use of the porvic dummy permits a reduction in the range of moisture tension from the top to the bottom of the sample, a reduction in the force times gravity required to obtain a specifed tension on the sample, and a reduction in the length of period of centrifuging required to approach moisture equilibrium.

COMPARISON OF DISTURBED AND UNDISTURBED SAMPLES

A comparison of centrifuge moisture values at ⅓-atmosphere tension for undisturbed and disturbed samples is given in table 9 for 9 materials. The undisturbed and disturbed centrifuge moisture contents were within 1.1 percent for 5 of the materials. For the other 4

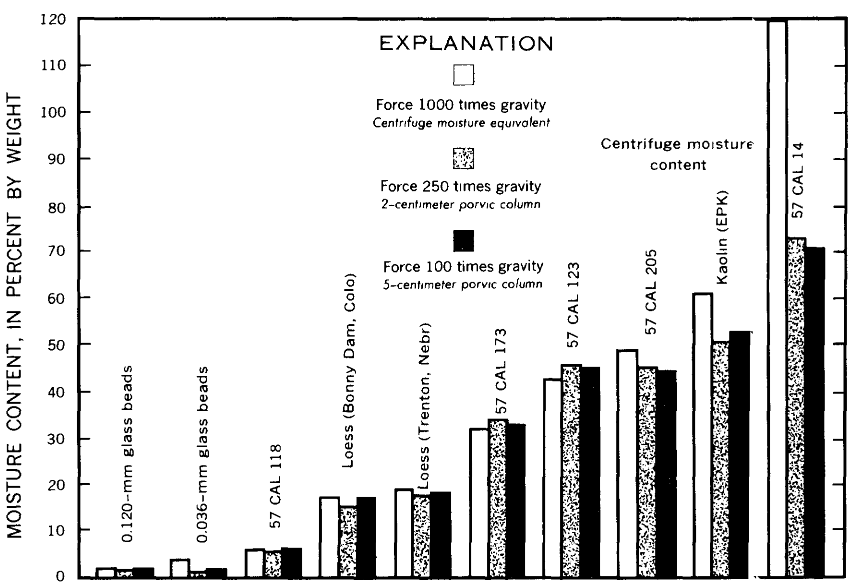


FIGURE 35.—Centrifuge moisture equivalent compared with centrifuge moisture content obtained with porvic dummy columns.

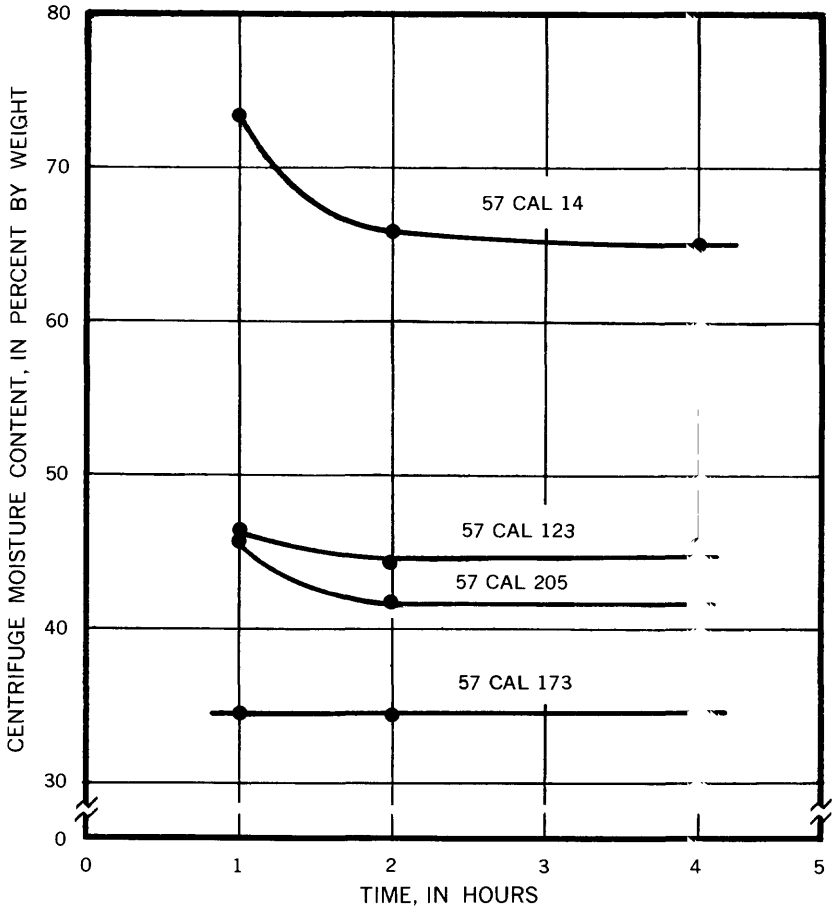


FIGURE 36.—Effect of length of time of centrifuging on the centrifuge moisture content of samples placed on a 2-cm porvic dummy column.

TABLE 9.—*Comparison of centrifuge moisture values at one-third atmosphere tension for disturbed and undisturbed samples*

Soil	Centrifuge moisture content	
	Undisturbed sample	Disturbed sample [1]
59CAL253-254	11.0	14.6
59CAL251-252	13.1	13.6
59CAL258-261	13.6	13.0
59CAL137-138	15.1	14.4
58OKLA42	18.8	23.4
58OKLA15	20.1	19.0
59CAL248	20.6	20.6
59CAL130-131	21.9	25.9
58ARK146	29.4	33.6

[1] Disturbed samples prepared through a No. 10 (2 mm) sieve.

materials the undisturbed centrifuge moisture content ranged from 3.6 to 4.6 percent lower than the centrifuge moisture contents of the disturbed samples.

SUMMARY AND CONCLUSIONS

The first 2 years of research on specific yield have been directed toward a review of the literature relating to this field and a study of the drainage and centrifuge moisture equivalent of porous media. An annotated bibliography (Johnson & others, 1960) presented the first phase of this study, and the present report summarizes the research completed on column drainage and centrifuge moisture equivalent.

INVESTIGATION OF COLUMN DRAINAGE

The principal testing materials used in this study were homogenous glass beads or Del Monte sand; however, carefully selected but less homogenous sandy materials—chiefly from field sites in California—were also used. These materials were mechanically packed into continuous or transparent segmented plastic columns of 1- to 8-inch diameter. The material was wetted with Denver tap water and drained under controlled conditions of temperature and humidity.

The data on moisture retention in 0.120-mm glass beads obtained by 3 methods of drainage (simple, extended-base, and nonmembrane) were comparable, except at the higher moisture contents. In another method, the membrane method, the values of retained water were similar to those obtained by the first 3 methods at 52 to 68 inches above the water table. The membrane method was the most convenient and workable for determining moisture retained in short drainage columns.

The total discharge of water from duplicate columns of 0.120-mm glass beads for the simple free-drainage and nonmembrane hanging-water-column methods was similar, but the initial rate of discharge was higher for the hanging-water-column method.

The distribution of moisture after drainage of a natural alluvial sand was less uniform than that obtained by drainage of the more homogenous glass beads.

The drainage characteristics for glass beads were affected only slightly by cleaning with acid. It was concluded that the increase in cost and effort associated with the acid cleaning of porous media was not warranted.

The diameter of the column made little difference in the moisture distribution after drainage of mechanically packed 1-, 4-, and 8-inch diameter columns of 0.120-mm glass beads. It likewise made little difference in the larger column whether the moisture samples were taken near the side of the column or in the middle.

Four procedures for wetting the porous media—a single wetting, flow-wetting, two wettings, and capillary-rise wetting—gave similar results for the distribution of moisture after drainage and for the rate of discharge.

The line of wetting was sufficiently visible under white light when ordinary tap water was used; therefore, it was not necessary to use a dye solution and ultraviolet light. The effect of the dye on the drainage characteristics of the media was negligible.

The variation in porosity in all similarly packed drainage columns indicated that repeatability was not achieved by the manual method of packing. Therefore, a mechanical method of packing was developed to obtain consistent and reproducible porosity within the glass beads and sands. The variation of porosity (used as an index of packing efficiency) in similarly packed columns was close—generally less than 2 percent. Sorting was considered negligible for short packing intervals.

A knowledge of the effect of time on drainage is important to understand how it affects specific yield. A large percentage of the water is yielded during the first part of a drainage cycle, with the rate of drainage decreasing steadily with time.

INVESTIGATION OF CENTRIFUGE MOISTURE CONTENT

The materials used in this study cover a wide range of moisture-equivalent values. They include glass beads, commercial sands, loess, fuller's earth, kaolin, and selected alluvial materials—principally from field sites in California.

The procedure used to determine centrifuge moisture equivalent was the Gooch crucible method, using the controlled-temperature centrifuge. A modification of this technique involved the use of a plastic dummy column to reduce the force times gravity applied and the range in moisture tension from the top to the bottom of the sample.

A comparison of crucible and box methods of determining centrifuge moisture-equivalent data indicates that the values obtained by the crucible method are slightly lower than those obtained by the box method.

Results of the study indicate that reproducible results are obtained only when both the temperature and humidity are controlled. Changing the temperature on the centrifuge produced a small but significant decrease in moisture content as the temperature increased. The difference in moisture content between 10° and 30°C ranged from 13 to 34 percent of the moisture content at 10°C for the coarse-textured materials, as compared to a range of 4 to 27 percent for the fine-textured materials. The conclusion is reached that the temperature in the centrifuge should be at a preselected value.

Centrifuge moisture contents obtained from the controlled- and uncontrolled-temperature centrifuges were not comparable. For coarse-textured materials, the moisture contents obtained from the controlled-temperature centrifuge were of the magnitude of one- to two-tenths higher. With the uncontrolled-temperature centrifuge, the centrifuge moisture content decreased as the length of time of centrifuge operation increased. This was due to temperature buildup and decrease in humidity in the centrifuge during operation. These tests emphasize the difficulty in obtaining good replication of results for samples run in the uncontrolled-temperature centrifuge.

Although a 1-hour period of centrifuging is probably adequate for coarse- and medium-textured materials to approach moisture equilibrium, a longer period should be considered for fine-textured materials.

The average moisture tension applied to a sample during centrifuging was altered by changing the thickness of the sample and the force times gravity applied to the sample and by placing the sample over different lengths of semipermeable dummy columns. Increasing the thickness of the sample increases the average moisture tension applied, but it has practical limitations, especially for fine-textured materials, because it also increases the period of time required for the soil sample to approach moisture equilibrium. Changing the lengths of semipermeable dummy columns on which the samples were placed had certain advantages over changing the force times gravity by the usual centrifuge procedure. Use of dummy columns reduced considerably the range in moisture tension from the top to the bottom of the sample from that in the conventional centrifuge test. Use of the dummy column also permits a reduction in the force times gravity required to obtain a specified tension on the sample and a reduction in the length of period of centrifuging required to approach moisture equilibrium.

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