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SEDIMENT-SEALING WITH BENTONITE IN A DUNE SAND

by
R. T. Shen

FIELD AND LABORATORY STUDIES OF LATERAL 1,
INTERSTATE CANAL, TORRINGTON, WYOMING
PATHFINDER IRRIGATION DISTRICT
NORTH PLATTE PROJECT



Department of Civil Engineering

Colorado State University Research Foundation
Fort Collins, Colorado
August 1958

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FOREWORD

Sediment-sealing investigations at Lateral 1 were begun by the U. S. Bureau of Reclamation in 1955. The field installation was included in the Bureau's Lower-cost Canal Lining Program. Mr. E. C. Newman¹ conducted fundamental research on the bed material in a project sponsored jointly by the Bureau and the Colorado State University Research Foundation. In 1957, the Agricultural Research Service of the U. S. Department of Agriculture contracted the University for a three-year study of the sediment-sealing method in various bed materials. Lateral 1 was selected as one of the five sites for this study. Thus the present laboratory program has been sponsored jointly by the Agricultural Research Service, the Bureau of Reclamation, and the Colorado State Experiment Station.

The author is indebted to Mr. R. D. Dirmeyer, Jr., Project Leader, for his valuable suggestions through the entire program; Mr. C. P. Cass, graduate assistant, for his help in sampling, testing, and data analysis; Mr. Charles Sekora, Machinist, and Mr. R. V. Asmus, Shop Supervisor, for their cooperation in designing and constructing the equipment; Dr. R. S. Whitney, Professor of Agronomy; Dr. A. T. Corey, Research Engineer; Dr. A. R. Chamberlain, Chief of Civil Engineering Section, Colorado State University Research Foundation, and the numerous University personnel who have contributed to the testing, the computations, and the report production. Acknowledgments are due also to the many Bureau personnel who have made this publication possible, especially Messrs. C. W. Jones, R. J. Willson, W. U. Gartska, Sam Rubenstein, F. M. Roush, W. K. Lundgreen, C. W. Thomas, and R. D. Mason. The author expresses appreciation for the efforts of Mr. L. E. Myers, Jr., who administered the financial support from the Agricultural Research Service.

¹ Graduate assistant at Colorado State University from 1954 to 1956.

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I. INTRODUCTION

The problem of canal seepage has assumed an important role ever since the advent of irrigated agriculture. Today, when preponderant consideration is given to the conservation of soil and water resources, this problem has become vital. Engineers and soil scientists have used various approaches to study seepage and have adopted various methods to prevent it. Many good and effective measures have been devised, with the result of much saving of seepage loss as well as reclamation of water-logged land areas. Since the feasibility of a sealing installation almost invariably depends upon an economic comparison of its cost against its benefits, an effective but inexpensive sealing technique has yet to be developed for use on the innumerable irrigation ditches for which the costs of conventional lining procedures are prohibitive. There is a definite need for a sealing process that is effective and inexpensive enough to make the treating of irrigation canals and ditches economically justifiable.

The sediment-sealing process is aimed at fulfilling this need; various attempts have been made during the past few decades to utilize the sedimentation of clays to render bed material impermeable. In this process, it is intended to avoid such expenses as would be incurred by re-shaping to a uniform channel and transporting and placing lining materials in the canal. The theory of letting water-borne sediments penetrate into the leaky zones as they follow the flow downstream is ideally economical. In a research program conducted at Colorado State University since 1953, bentonite suspensions are being tried. Studies in both the laboratory and the field have been undertaken in co-operation, at one time or another, with the United States Bureau of Reclamation, Geological Survey, and Agricultural Research Service; the Colorado Experiment Station as well as numerous bentonite, chemical, and equipment companies.

The fact that hydraulic and soil conditions vary with each specific field site entails an enormous research task. To understand all factors involved, a very comprehensive program is necessary. With limited funds, and hence personnel, it is possible to cover only certain phases at a time. This report deals with the work done on a 5.7-mile section of Lateral 1, North Platte Project, Torrington, Wyoming. The field work

was carried out by the Bureau of Reclamation; the laboratory work was carried out partly by the Bureau and partly at Colorado State University. The laboratory work reported herein constitutes a part of a detailed study of the above site, which is one of five selected for a three-year study by contract of the University with the Agricultural Research Service. It is therefore necessary to include some materials already contained in previous publications and other records of the Bureau and the University in order to furnish a complete history of the work accomplished at this site.

Lateral 1 was selected as one of two trial sites for bentonite sediment-sealing by the Bureau of Reclamation in the spring of 1955. Studies of seepage loss, soil characteristics, and water quality were made. In the spring of 1956 the actual sedimenting operation was performed by Cronese Products, Inc., Tarzana, California. In the meantime, Mr. E. C. Newman, graduate assistant at Colorado State University, began a series of tests on the bed material in the laboratory. After sedimenting, evaluation measurements were made with inconclusive, if not disappointing, results. Further laboratory studies and detailed analyses are being conducted to obtain a realistic appraisal of the installation and recommend an effective sealing procedure for this site.

As the canal bed lies in a typical dune sand area this report, covering the entire history of the case to date, together with a later report on future experimentation on the bed material, should prove useful to other similar sites as references.

II. PRELIMINARY INVESTIGATIONS

Lateral 1 diverts water from the Interstate Canal operated by the Pathfinder Irrigation District. The Interstate Canal, as part of the North Platte Project, carries the water diverted from the North Platte River at the Whalen Dam (see Fig. 1). Before 1927, the water reaching the Whalen Dam had been carrying considerable silt. The Guernsey Reservoir, approximately ten miles upstream from the Whalen Dam, began operation in 1927, and has since served as a de-silting basin. The formerly muddy water has since become clear. Estimated delivery losses including seepage and operation losses in the records of the District rose steadily from 33 per cent in 1926 to 57 per cent in 1931 (1). Whenever the water level in the Reservoir was lowered, more silt could be moved downstream and reduction in seepage was immediately noticeable (2).

It was therefore speculated that an experiment with bentonite treatment to increase the clay content in the canal bed thereby reducing seepage had a good chance of success. A preliminary inspection was made, followed by seepage measurements and laboratory analyses of the water and the soil.

Preliminary Proposal

After consideration of several potential sandy sites in the North Platte Project area, the Bureau of Reclamation proposed to treat a section of Lateral 1, 5.75 miles long, from the Interstate Canal diversion point to the point where the lateral divides into two branches (3). This section lies entirely in a dune sand area, with an initial discharge at the head end of approximately 100 cfs and an apparent high seepage rate. The channel, as originally constructed, had a bottom width of 7.0 ft, a water depth of 4.0 ft, and side slopes of 1.5:1 for most of the reach. Fig. 2 shows the condition of the section before the experiment.

In a memorandum to Mr. C. W. Jones (4), Mr. W. K. Lundgreen, Soil and Moisture Conservation Engineer for the Bureau Office at Torrington, Wyoming, stated:

"Lateral 1 of the Pathfinder Irrigation District delivers water to lands in Wyoming and Nebraska. The bulk of this land lies north and east of Henry, Nebraska. The lateral headgate is located at approximately Mile

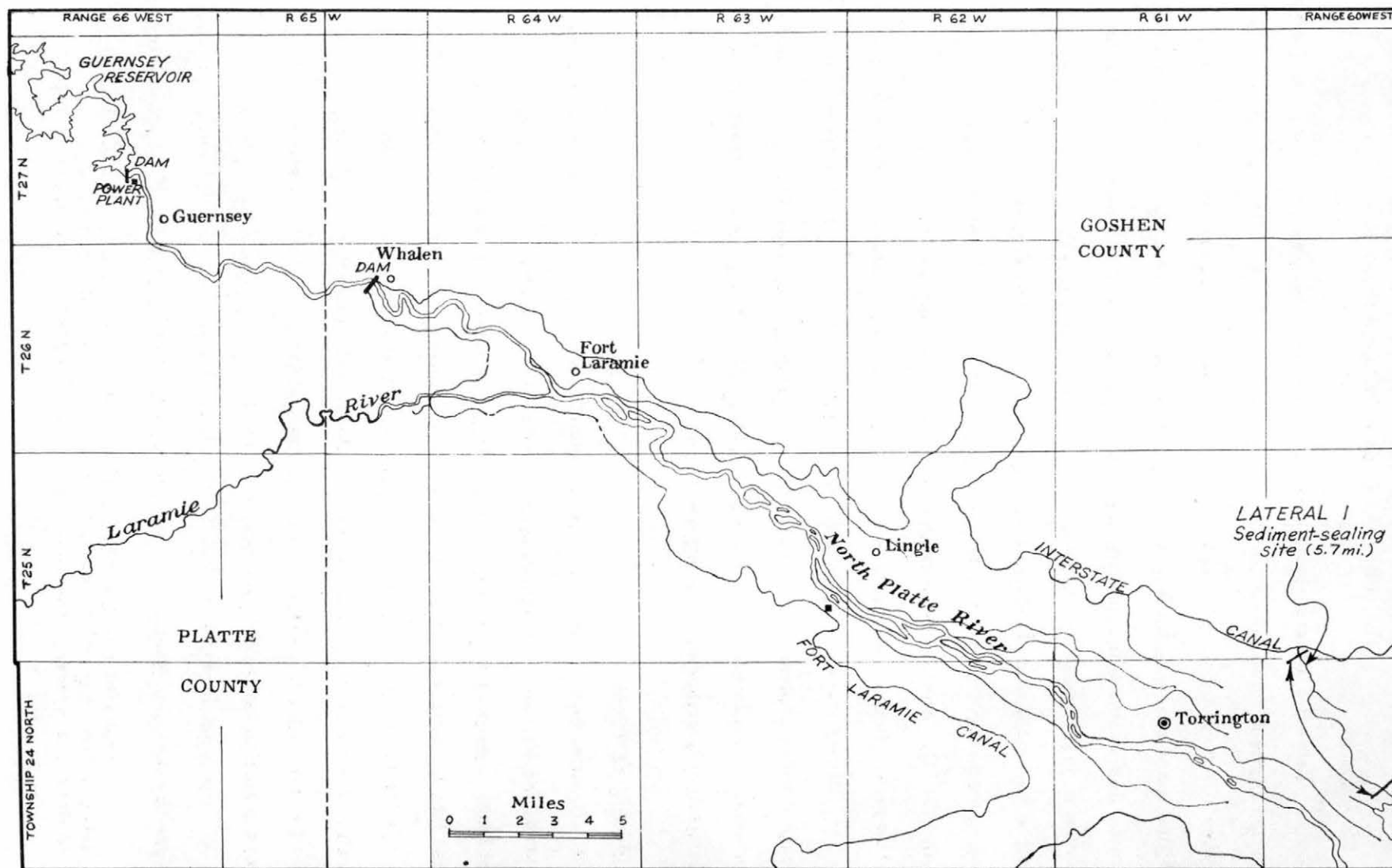


Fig. 1 Vicinity of Guernsey Dam and Lateral 1 sediment-sealing site.

46.7 of the Interstate Canal. From the headgate, the lateral was constructed on a contour. A system of rather steep drops was built to help control the grade. The entire lateral runs through a sand hill area. Much of the land that was proposed for irrigation, under this lateral, has been abandoned by the district.

"---This lateral has shown a high seepage loss and has been a maintenance problem to the district. In addition, it was ideal for the various tests that were to be carried out. The test section, approximately six miles long, had only one farm delivery throughout the entire reach.---"

Plans were made to introduce bentonite sedimentation in the spring of 1956 when the irrigation district would run water to Lake Minatare.

Seepage Measurements

The effectiveness of the sedimenting process was to be evaluated by comparing the seepage rate before and after the installation. Knowing the inaccuracies of measuring methods, Bureau and District personnel used several approaches, namely, inflow-outflow measurements, seepage meter records, observation well studies, and ponding tests.

Inflow-outflow records -- The quantity of inflow (or diversion) was measured by a 14-ft Cipolletti weir (Fig. 3) immediately below the headgate. The quantity of outflow (or delivery) was measured over three weirs: a 7-ft rectangular improvised weir for the delivery past Mile 6.0 down Lateral 1; a 6-ft Cipolletti weir down Lateral 1-2; and a farm weir to the Middlesworth farm. The records of the 1955 irrigation season were: diversion 7,543.19 acre-ft, delivery 6,367.37 acre-ft, showing a loss of 1,175.82 acre-ft or 15.6 per cent.

The weirs were checked for accuracy against current meter readings. The inflow weir was found to have an average error of 10 per cent, and the outflow (7-ft) weir, -4.8 per cent. The daily records were then corrected to show a diversion of 8,346.58 acre-ft and a delivery of 6,693.14 acre-ft, with a loss of 1,653.44 acre-ft or 19.8 per cent.

Losses were also computed directly from current meter measurements periodically from August 1955 through the rest of the irrigation season. The average was determined to be 22.17 per cent.



Fig. 2 View of a typical section on Lateral 1 before sediment-sealing operation.
Note the sand dune topography in the background.
USBR photo by W. K. Lundgreen.



Fig. 3 View of 14-ft Cipolletti weir at the upstream end of the section to be treated.
Note the turnout gate in the background. USBR photo by C. W. Jones.

Seepage meter measurements -- From the section to be tested, two reaches were selected for seepage meter readings: from Sta. 0+00 to Sta. 82+00; and from Sta. 230+00 to Sta. 310+00. The meter was placed at 100-ft intervals. In the first reach, losses ranged between 0.04 and 4.8 cu ft per sq ft per day, with an average of 3.3. In the second reach, losses ranged between 0.25 and 4.8 cu ft per sq ft per day, with averages of 3.1, 1.0, and 3.0 for sandy, silty, and sandy zones respectively.

Observation wells -- It was not possible to plot the levels in the five existing wells because of the great depth of the water table. Three wells showed a rise of more than five feet at the end of the irrigation season; the channel became dry, and by January 20, 1956, the wells showed that the water table had fallen. This may be evidence indicative of the effect of seepage on the water table, although numerous other causes in addition to canal seepage could have contributed to such water table fluctuations.

Ponding tests -- Two ponds were used in the measurement of seepage by ponding (5,6): Pond No. 1 from Sta. 88+32 to Sta. 119+15.2, and Pond No. 2 from Sta. 236+18 to Sta. 258+68.6. During the first 24 hours after the first filling, the level of the first pond dropped by 0.7 ft; that of the second pond dropped by 0.8 ft. A second filling was not possible because the water level in the Interstate Canal at the time was below the gates on the Lateral 1 diversion structure. However, since the lateral has been in use throughout the irrigation season and the dams for ponding were built while water was in the canal, the lateral bed and banks must have been in a well saturated condition except the incremental area of bank covered by increased depth when the ponds became filled (7).

Results from the ponding tests show that the seepage loss varied directly with water depth during these tests, reaching a maximum of 0.99 and 1.35 cu ft per sq ft per day for Ponds No. 1 and No. 2 respectively and a minimum of 0.4 to 0.5 cu ft per sq ft per day. Detailed data are presented in Chapter IV where they are compared with post-installation ponding results.

Laboratory Tests

Laboratory tests were made by the Bureau of Reclamation on soil, water, and sedimenting materials (8). These were aimed at describing the physical and chemical properties of the canal soil and water; determining the amount of clay already present in the soil for comparison after installation; computing the quantities of sedimenting agents needed for effective sealing; and estimating the probable attainable penetration of the bentonite into the canal bed.

Both disturbed and undisturbed soil samples (2-in. core into a 30-in. depth) were taken from three locations along the lateral: Miles 1.1, 4.2, and 6.1. Soil density and moisture content determinations were also made. A water sample from the Interstate Canal opposite the Lateral 1 turnout was collected.

Soil tests -- Results of a mechanical analysis of the soil are plotted in the size-distribution curve shown in Fig. 4. The bentonite present in the soil was found from petrographic examination to be predominantly in the form of strongly attached coatings on the grains, estimated at 5 to 6 per cent by volume. Results of x-ray diffraction analysis are presented later in Chapter IV. Results of chemical analyses of the soil are given in Tables 1 and 2.

TABLE 1 -- CHEMICAL ANALYSES OF CANAL BED MATERIAL BEFORE SEDIMENTING TREATMENT

pH	7.3
Exchange capacity, meq/100 gm soil	2.90
Total sodium	0.50
Soluble sodium	0.03
Exchangeable sodium	0.47
Total potassium	0.25
Soluble potassium	0.00
Exchangeable potassium	0.25
Exchangeable calcium plus magnesium	2.18
Total soluble salts	0.11
Saturation per cent	28.6

Note: Sample collected from Mile 4.2

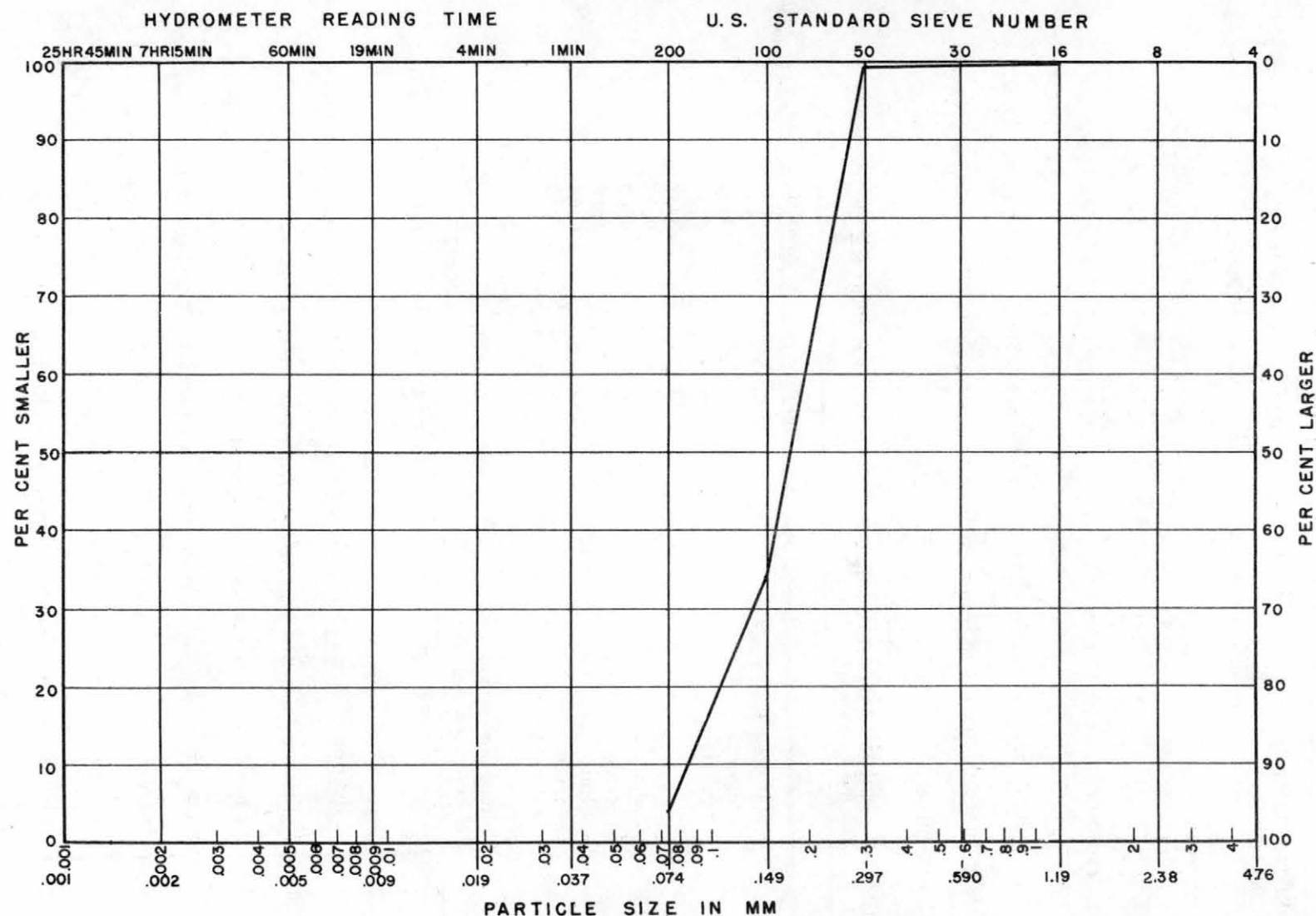


Fig. 4 Particle size-distribution curve for the bed material of Lateral 1 analyzed by USBR before sediment-sealing operation.

TABLE 2 -- DISTRIBUTION OF TOTAL EXCHANGE CAPACITY WITH DEPTH
IN CANAL BED MATERIAL BEFORE SEDIMENTING TREATMENT

DEPTH FROM SURFACE (in.)	EXCHANGE CAPACITY (meq/100 gm of soil)		
	Mi. 1.1	Mi. 4.2	Mi. 6.1
0-5	4.85	4.10	4.85
5-10	4.25	3.65	5.55
10-15	4.30	3.75	2.95
15-20	3.40	3.65	4.10
20-25	3.40	3.55	3.25
25-30	3.45	3.45	4.30

Water tests -- Water analysis results are tabulated in Table 3. As will be discussed later, the quality of water fluctuated considerably, thereby creating operational difficulties.

TABLE 3 -- CHEMICAL ANALYSIS OF CANAL WATER BEFORE SEDIMENTING
TREATMENT

	ppm	meq/liter
Total dissolved solids	622	--
Calcium	66	3.32
Magnesium	28	2.33
Sodium	78	3.37
Potassium	3.5	0.09
Carbonate	0.0	0.00
Bicarbonate	153	2.50
Sulphate	290	6.04
Chloride	25	0.70
Total hardness as CaCO_3	282	
pH		7.4
Sodium percentage	37.0	
Electrical conductivity		0.000882

Note: Sample was obtained on May 3, 1955 from the Interstate Canal at the Lateral 1 turnout.

Evaluation of sedimenting agents -- To determine the quantity of dispersing agent required to keep bentonite suspensions from flocculating, liter-cylinders containing 0.5 and 1.0 per cent concentrations were used. The water used was the canal water collected from the Interstate Canal at the Lateral 1 turnout. Varying amounts of sodium tripolyphosphate were tried. It was found that the 0.5 per cent suspensions could not be maintained in a dispersed state, while the 1.0 per cent suspensions required 0.5 per cent dispersant by weight of bentonite. Increased stability could be obtained with increased amounts of dispersant up to two per cent by weight of bentonite, beyond which the stability seemed to decrease.

Penetration experiments -- These tests were made in small permeameters of 1.25-in. interior diameter with the bed material soil column 9.5 in. long packed at the moisture and density equal to those found in the field at the time of sampling. The sedimenting process was done with gradually increasing head, 0.1 ft for the first eight hours, 1.2 ft for the next 16 hours, and 2.4 ft for the last 24 hours, totaling 48 hours. This process was intended to simulate the gradual build-up of head under actual ponding conditions in the field. The 2.4-ft head was maintained for the remaining period of the test. Increments of soil were removed from the top of the columns at intervals and the permeability fluctuations were computed from percolation rate measurements. Two columns were treated with one per cent bentonite suspensions with 0.01 per cent dispersant; two were treated with 0.5 per cent bentonite suspensions with 0.02 per cent and without dispersant; and two were treated with 0.01 per cent dispersant without any bentonite. Actual canal or synthetic water was used at all times. In Figs. 5 to 7 are presented the results of these tests converted into units comparable to those obtained in the present laboratory program. It is evident that penetration did not exceed 4 in. and no sealing occurred that reduced the percolation rate to below 0.1 cu ft per sq ft per day, which is sometimes considered the goal for conventional type of canal lining.

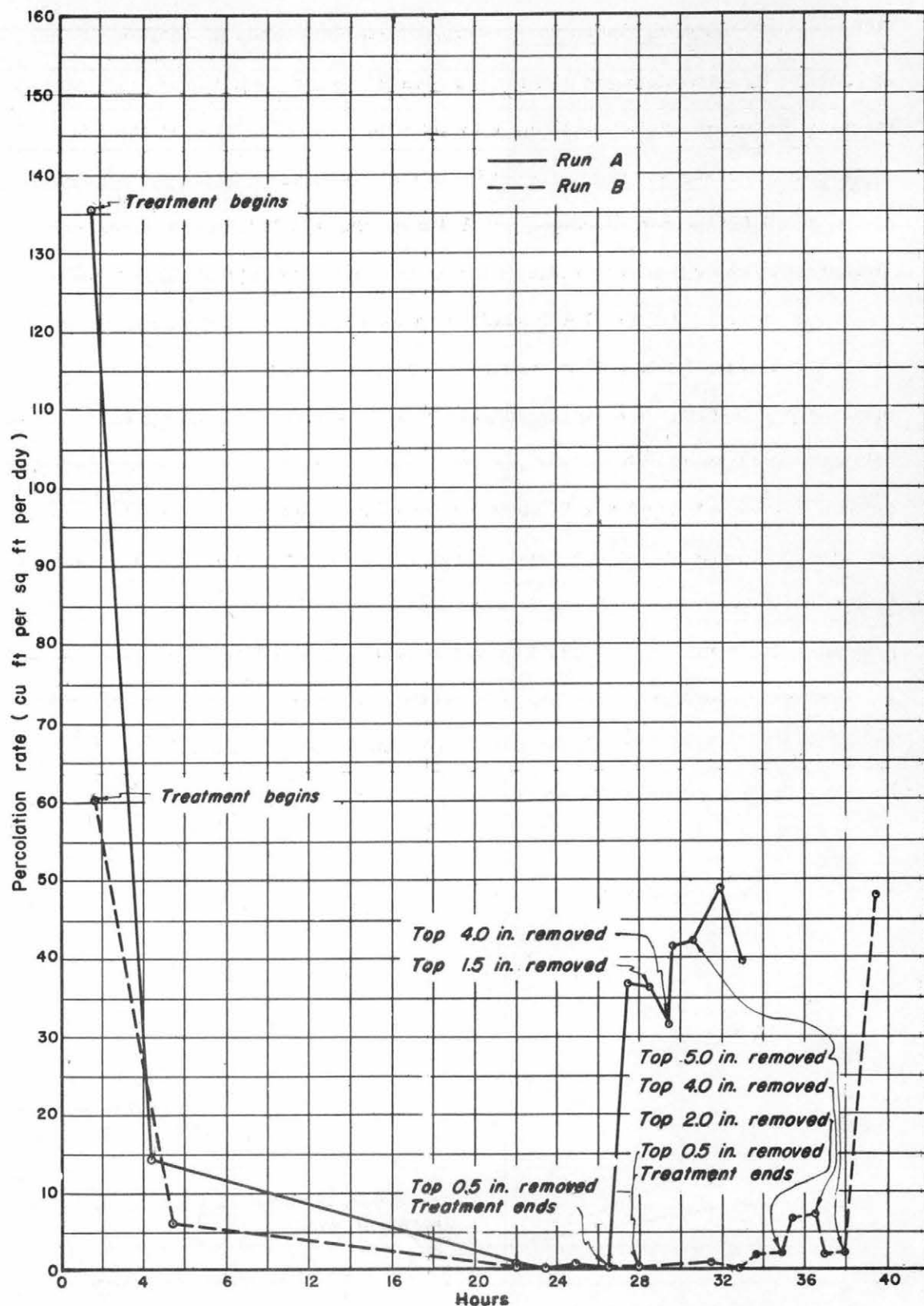


Fig. 5 Results of treatment of soil specimens with 1% bentonite suspensions plus 0.01% dispersant (USBR data converted to 20°C temperature and 2.75 hydraulic gradient)

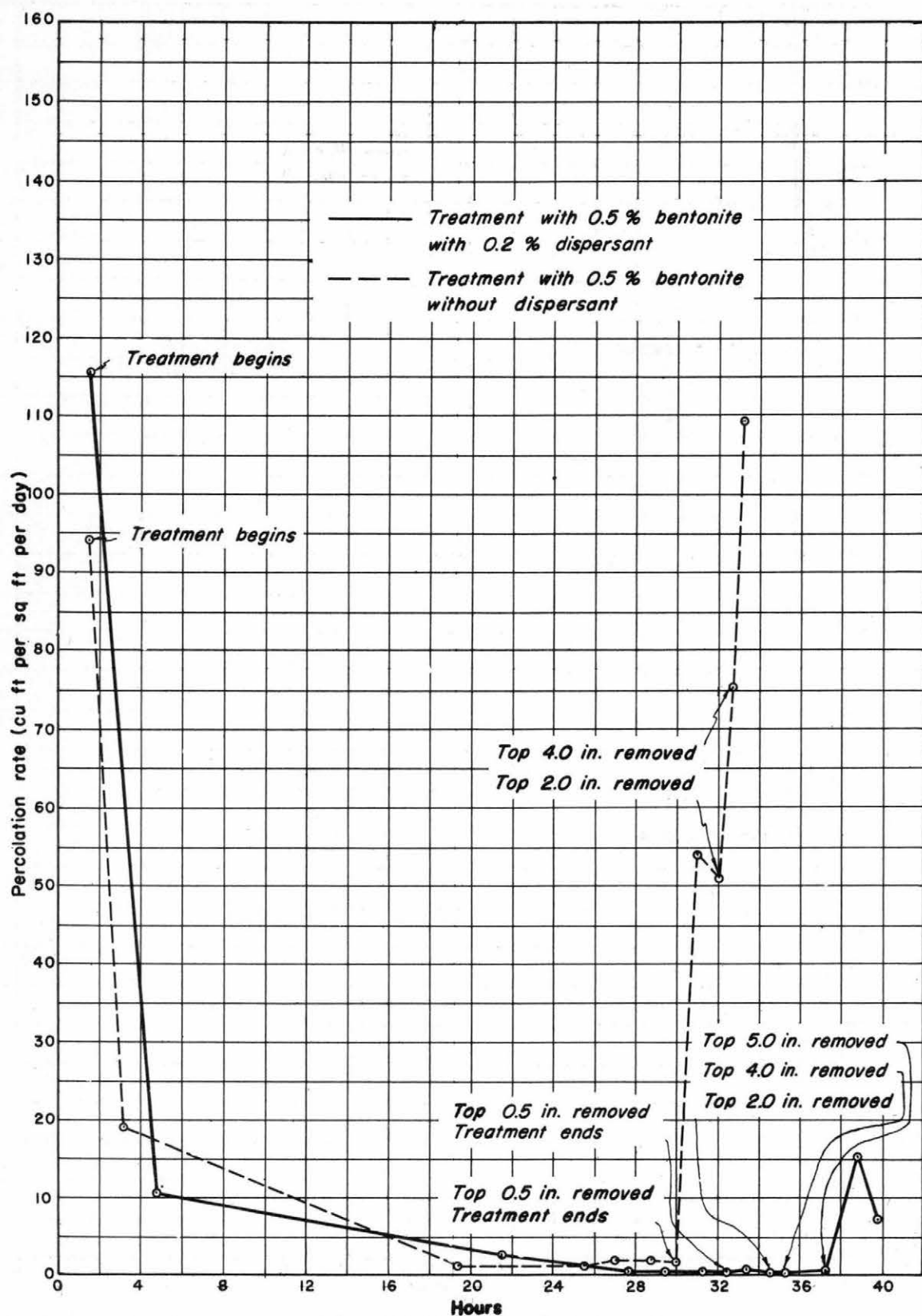


Fig. 6 Results of treatment with 0.5% bentonite suspensions with and without dispersant (USBR data converted to 20°C temperature and 2.75 hydraulic gradient).

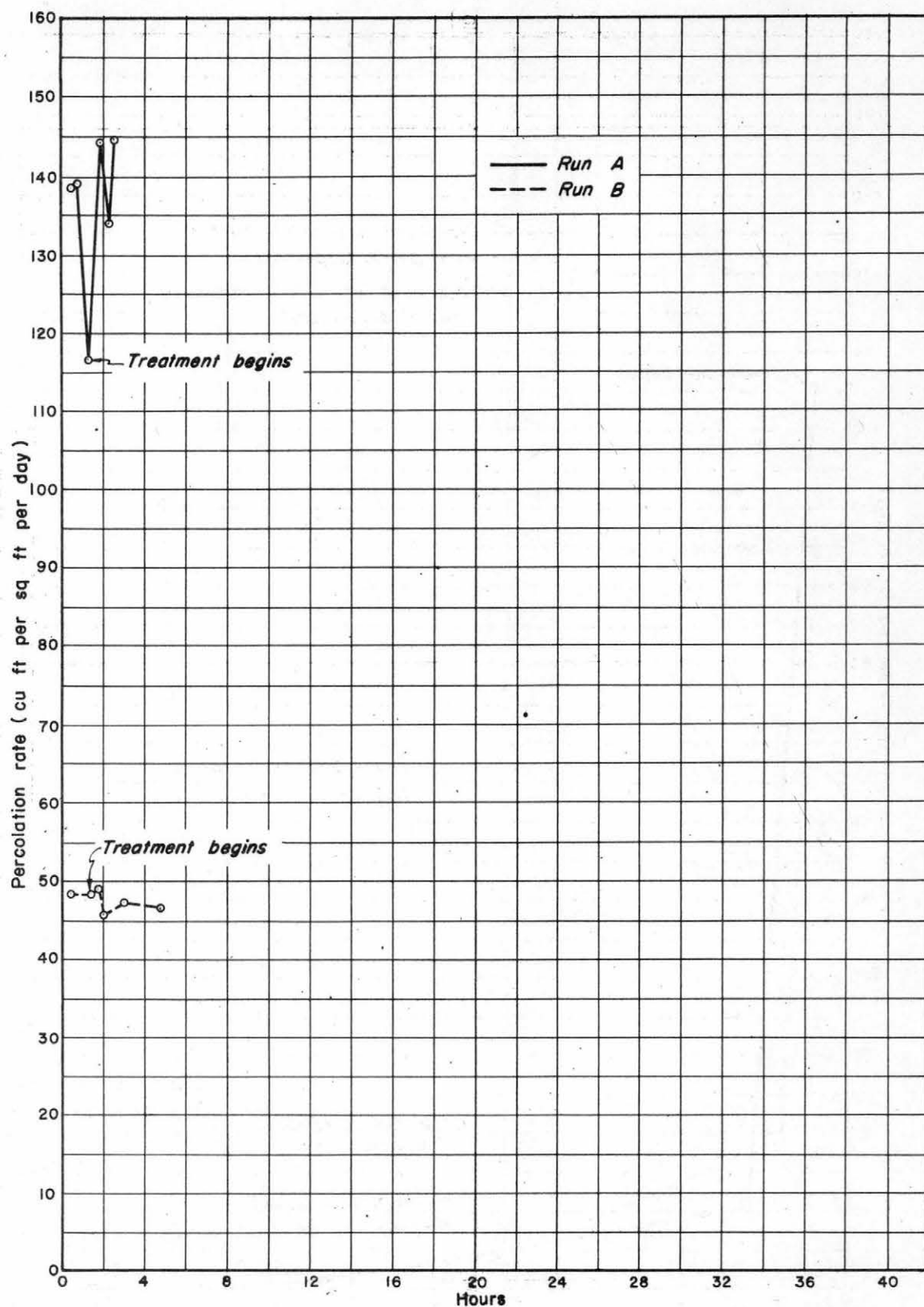


Fig. 7 Results of treatment of soil specimens with 0.01% dispersant solution only (USBR data converted to 20°C temperature and 2.75 hydraulic gradient).

III. INSTALLATION OPERATION

The sedimenting operation of the Lateral 1 installation was carried out in a $3\frac{1}{2}$ -day period from March 29 to April 1, 1956, during which 240 tons of bentonite were applied to the 5.7-mile section. A successive ponding method was used. The job was contracted by Cronese Products, Inc. Tarzana, California, on the basis of unit price per ton of bentonite used. Personnel from the Bureau of Reclamation supervised the entire operation; Colorado State University research team was also present.

Mixing Process (9)

A slurry of about six per cent concentration of bentonite with dispersant was first mixed (Fig. 8). This was accomplished by feeding a stream of bentonite from a hopper into a multiple jet-tube mixer. Compressed air was released into the bottom of the hopper to facilitate feeding. Canal water was forced into a mixing chamber through numerous small jets at 100 psi pressure by a 4-in. centrifugal pump with a 60-hp gasoline engine. The slurry was discharged into a pool, approximately 150 feet long, situated between the Lateral 1 turnout gate and the head weir, where it was diluted to one per cent concentration (Fig. 9). A portable air-jet, supplied by a compressor, was used for agitation in the pool to break up unmixed lumps. Its carrier waded into the mixing pool in order to ensure thorough coverage.

The National Lead Company supplied the bentonite in powdered form from their plant at Osage, Wyoming; evaluation of this bentonite is presented on page 29 of this report. The Bureau of Reclamation supplied the dispersing agent: powdered and granulated tetrasodium pyrophosphate -- a product of Monsanto Chemical Company. This differs somewhat from the sodium tripolyphosphate used in the preliminary laboratory test described in the preceding chapter.

Quality Control

Hardness of the canal water at the time of installation was tested to be about 450 ppm total calcium and magnesium as CaCO_3 . Since this value far exceeded the 280



Fig. 8 View of the mixing process during Lateral 1 sediment-sealing installation.
CSU photo by D. L. Bender.



Fig. 9 View of the mixing pool where the slurry was diluted to 1% concentration
Note the line for air-jet at right. CSU photo by D. L. Bender.

ppm figure obtained during the previous spring, the amount of dispersant had to be increased to avert flocculation of the bentonite. However, the mixture produced in the initial mixing operation failed to remain in a dispersed state during ponding, particularly in the first pond. The total quantity of materials used in the $3\frac{1}{2}$ -day operation amounted to 481,200 lb of bentonite and 7,000 lb of deflocculant (10).

Periodic hydrometer readings were taken of the samples of the mixture collected over the outlet weir of the mixing pool. The headgate was adjusted to regulate the flow of water from the Interstate Canal into the mixing pool whenever these readings indicated a need. At the beginning the concentration was less than one per cent whereas later readings indicated more than one per cent concentration so that, on the average, the mixture had approximately a one per cent concentration.

Ponding Operation

Ponding was executed by Bureau personnel under the direction of Mr. W. K. Lundgreen. The section was divided into nine ponds by means of existing check structures. Stop logs and canvas helped to dam up each pond successively. The ponds varied in size considerably. Each was allowed a sedimenting period of at least 24 hours. Each time when the benonitic water was allowed to drain into the next pond, canal water was introduced to take its place, protecting the filter cake formed at the channel bottom. Ponding operation began on March 29, and ended on April 10, 1956. See Figs. 10, 11, and 12.

After April 10, Mr. Lundgreen attempted to regulate the water inflow so that all the flow would be lost in the nine ponds. He found this impossible because the water loss varied considerably between night and day. Mr. Lundgreen reported subsequent events as follows:

"It was determined, however, that about one and one half cubic feet per second was required to hold these nine ponds full. This was not constant, however. The flow of water into the lateral was completely stopped by April 19, 1956 and the pond levels started to drop. The loss of water was quite slow by comparison with reaches of the main canal. Some water remained in the deeper ponds along the lateral until about May 7, 1956. With the drying of the lateral, considerable cracking of the surface cake of bentonite in the lateral was noticed." (10)

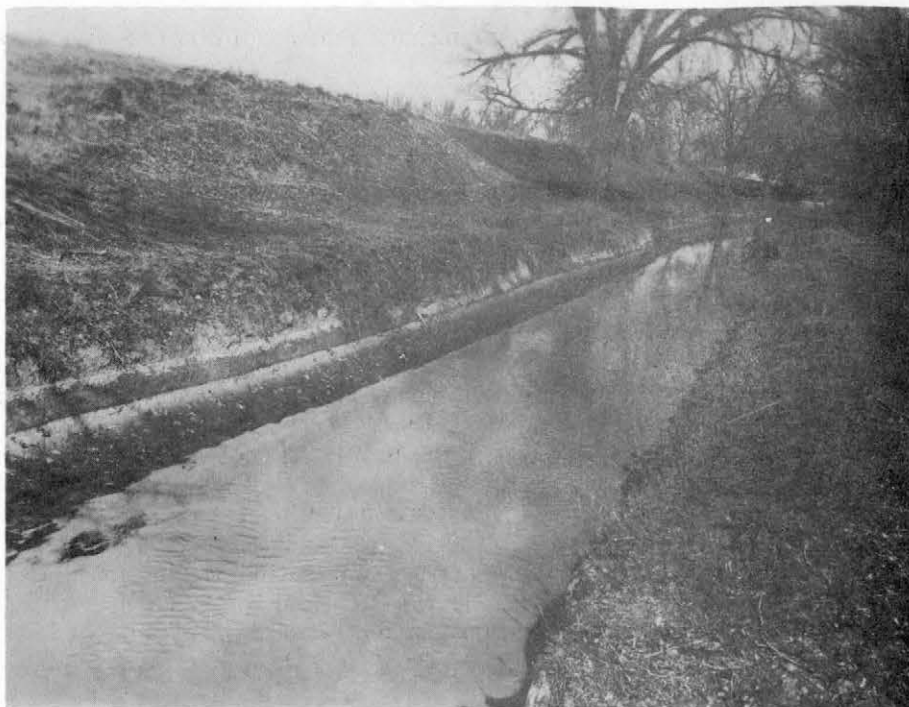


Fig. 10 View of pond No. 1 as it was being drained. Note the deposited bentonite on the left bank in light coloration. USBR photo by W. K. Lundgreen.

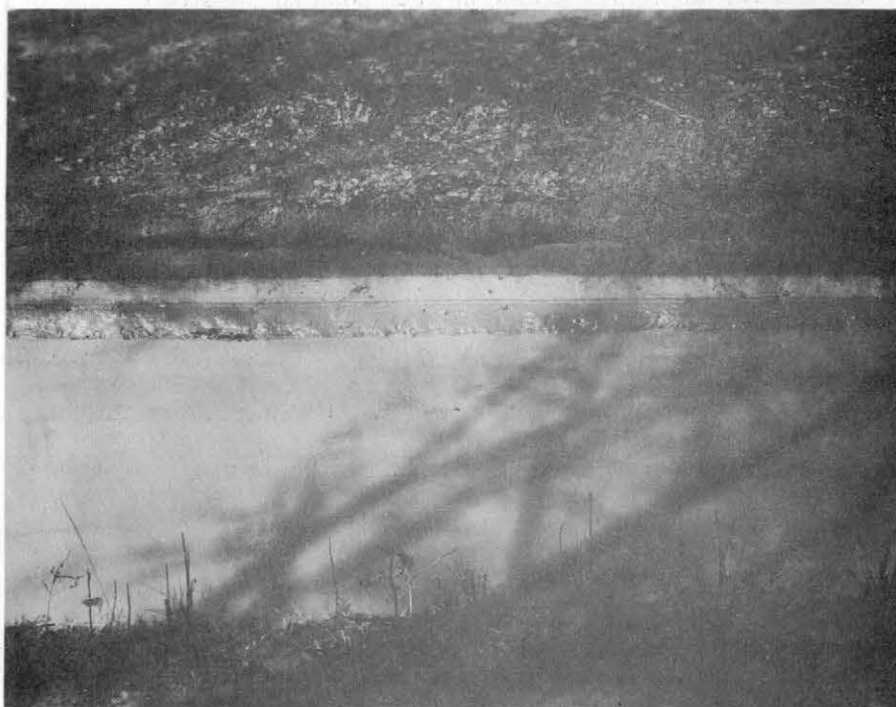


Fig. 11 Close-up view of the bentonite deposit in pond No. 1, thickness $\frac{1}{8}$ to $\frac{1}{4}$ in. USBR photo by W. K. Lundgreen.

Installation Cost

The total contract cost of this installation was estimated at \$11,791. The total area treated was estimated at 72,778 sq yds, including about 4,000 sq yds along the bottom of the lateral beyond the last check structure. Therefore, the unit cost of this job is approximately \$0.162 per sq yd. Since the effectiveness of the sealing must be measured by the water saved, any cost figure cannot be meaningful without being compared with the value of benefits obtained.

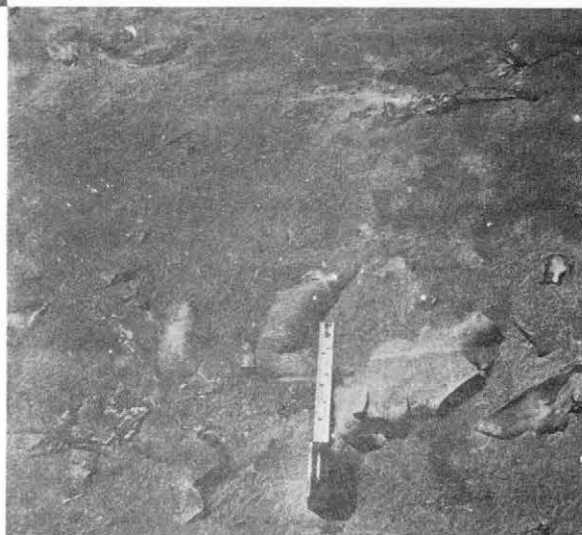


Fig. 12 View of check-drop at the downstream end of pond No. 2, Sta 87+87. Note the agitation remixing the flocculating slurry. USBR photo by W. K. Lundgreen.



Fig. 13 Close-up view of cracking filter cake five weeks after the sedimenting operation. Note the undried gel layer at the right, buried two inches beneath the surface. USBR photo by C. W. Jones.

Fig. 14 Close-up view of dried bentonite cake in the form of blisters, five weeks after the sedimenting operation. USBR photo by C. W. Jones.



IV. POST-INSTALLATION EVALUATIONS

Field inspection and seepage measurements, supplemented by laboratory work, were conducted by Bureau personnel for evaluation of the effectiveness of the installation. All measurements were made with the view of duplicating the same environment in which measurements for the previous year had been made. Obviously it was not possible to obtain precisely identical conditions, therefore the seepage rate comparisons should be evaluated with reservation.

As mentioned in the previous chapter, water was turned out of the lateral on April 19, 1956, thus the treated bed was allowed to dry from April 19 to May 22, 1956, when water was turned in again. This drying period might have affected the penetration of bentonite, and hence the effectiveness of the installation. Another drying period occurred after June 4, 1956, and lasted approximately ten days, during which Mr. C. W. Jones made an inspection trip.

Field Inspection (11)

Mr. Jones found no water remaining in the lateral on June 12 except the small amount leaking through the turnout gate on the Interstate Canal. Apart from shaded areas, the bentonite surface cake had all dried up. Where the sand had washed over the cake it was possible to find a bentonite gel layer several inches below the surface in various stages of drying. See Figs. 13 and 14.

Seepage Measurements

Mr. W. K. Lundgreen made preliminary seepage measurements with a current meter in June 1956. His results are given in the following table (12).

TABLE 4 -- RESULTS OF PRELIMINARY SEEPAGE MEASUREMENTS WITH CURRENT METER

DATE	INFLOW (cfs)	DISCHARGE (cfs)	COMPUTED LOSS (cfs)	LOSS (%)	REMARKS
6-1-56	73.09	61.02	12.07	16.5	water constant
6-15-56	64.45	47.15	17.30	26.8	+15 cfs
6-15-56	62.08	49.63	12.45	20.1	+15 cfs
6-11-56	83.29	70.15	13.14	15.8	+ 7 cfs
6-29-56	72.63	60.61	12.02	16.5	water constant

Note: In the first and last measurements the water was constant; in the other measurements the amounts indicated in the REMARKS column were added at the head end but the increase was not reflected at the lower end.

It may be assumed that the bed was saturated on June 1 and 29 because water was turned into the lateral on May 22, turned out on June 4, and in again sometime before June 15. Using the measurements on these two days, Mr. Lundgreen calculated that the bentonite lining reduced the seepage by 5.6 per cent.

Further measurements through the irrigation season were made by the same means employed in the preliminary investigations prior to the sedimenting operation (13).

Inflow-outflow records -- The Pathfinder Irrigation District recorded the diversion and delivery quantities daily from July 1, 1956, through the entire irrigation season. The same weirs used in 1955 were used, after being repaired and cleaned. Bureau personnel also took current meter readings periodically, which checked closely with the weir readings. Weir records show a total diversion of 7,050.46 acre-ft and a total delivery of 5,927.62 acre-ft, indicating a loss of 15.9 per cent. The same figure for the previous year, corrected for weir error, is 19.8 per cent. The corresponding losses computed from current meter readings are 17.95 and 22.17 per cent. Thus the reduction in seepage is 3.9 per cent by weir readings and 4.2 per cent by current meter readings, in terms of total loss in the treated section for one irrigation season; in each case it is 19 to 20 per cent of the original loss.

Seepage meter measurements -- Seepage meter tests at 100-ft intervals were made in the same two reaches as before. In the first reach, Sta. 1+00 to Sta. 83+00, the average loss was 2.8 cu ft per sq ft per day, showing some reduction (15.8 per cent)

from the previous 3.3 cu ft per sq ft per day. In the second reach, Sta. 230+00 to Sta. 310+00, the average loss was 2.6 cu ft per sq ft per day, showing only a slight reduction (8.2 per cent) from the previous 2.8 cu ft per sq ft per day.

Observation wells -- The depths to water table in the existing five wells were checked from time to time. No appreciable effect of the sealing installation could be discerned. In fact, the water table had risen slightly by 1956. Obviously this cannot be interpreted as a result of increased seepage from Lateral 1 only, many other factors could have been the cause of this behavior.

Ponding tests -- Mr. W. B. McBirney, Engineer of the Bureau of Reclamation, directed the ponding operations, making a special effort to maintain identical conditions as far as practicable for the pre-installation and post-installation tests. In Table 5, a comparison of the two years' results is presented (14).

TABLE 5 -- COMPARISON OF PRE-INSTALLATION AND POST-INSTALLATION PONDING TESTS

POND No. 1 (about 3,072 ft long)					
DATE	W.S. ELEVATION (ft above datum)	SEEPAGE RATE (cu ft/sq ft/day)	DATE	W.S. ELEVATION (ft above datum)	SEEPAGE RATE (cu ft/sq ft/day)
9-26-55	1.658	0.99	9-11-56	1.805	0.35
	1.531	0.80		1.415	0.65
9-27-55	1.208	0.75		1.302	0.58
	1.151	0.66		1.179	0.55
	1.074	0.61		1.075	0.53
	1.005	0.59		0.977	0.54
	0.923	0.53	9-13-56	0.778	Refill
	0.770	0.48		1.364	0.62
9-28-55	0.604	0.42		1.242	0.55
	0.549	0.41		1.137	0.57
	0.469	0.85		1.045	0.54
	0.443	0.46	9-14-56	0.832	0.52
	0.290			0.714	0.54
				0.600	

Note: Datum elevation is arbitrary, but the same for both years.

TABLE 5 -- COMPARISON OF PRE-INSTALLATION AND POST-INSTALLATION
PONDING TESTS -- Continued

POND No. 2 (about 2,161 ft long)					
DATE	W.S. ELEVATION (ft above datum)	SEEPAGE RATE (cu ft/sq ft/day)	DATE	W.S. ELEVATION (ft above datum)	SEEPAGE RATE (cu ft/sq ft/day)
9-26-55	3.039	1.35	9-12-56	2.466	0.97
	2.868	1.01		2.302	0.86
9-27-55	2.493	0.79		2.132	0.89
	2.429	0.71		1.977	0.92
	2.355	0.65		1.811	0.77
	2.285	0.61	9-13-56	1.522	Refill
	2.216	0.53		1.660	0.79
9-28-55	2.054	0.45		1.513	0.56
	1.891	0.53		1.367	1.09
	1.834	0.40		1.249	0.59
	1.741	0.43	9-14-56	1.026	0.61
	1.600			0.887	0.62
				0.751	

Note: Datum elevation is arbitrary, but the same for both years.

After analyzing the results from the pre-installation ponding tests, Mr. McBirney pointed out that:

"Since depth apparently plays an important part in the seepage rate of this lateral, it is not advisable to attempt to select a rate of loss which could be compared with a figure similarly obtained in tests to be made this coming fall, after the installation of bentonite. A more reliable comparison may be had through the use of the curves of seepage loss versus depth for both 1955 and 1956 tests." (7)

These curves are plotted in Figs. 15 and 16 for ponds No. 1 and No. 2 respectively. In pond No. 1, the initial elevations were similar but the first reading of 1956 was probably abnormal; the remaining readings show a slight reduction in seepage at higher elevations, although no positive claim of success can be justified in the main -- what little difference in seepage rate could certainly have been caused by experimental error and uncontrolled factors such as wind, evaporation, and temperature fluctuations.

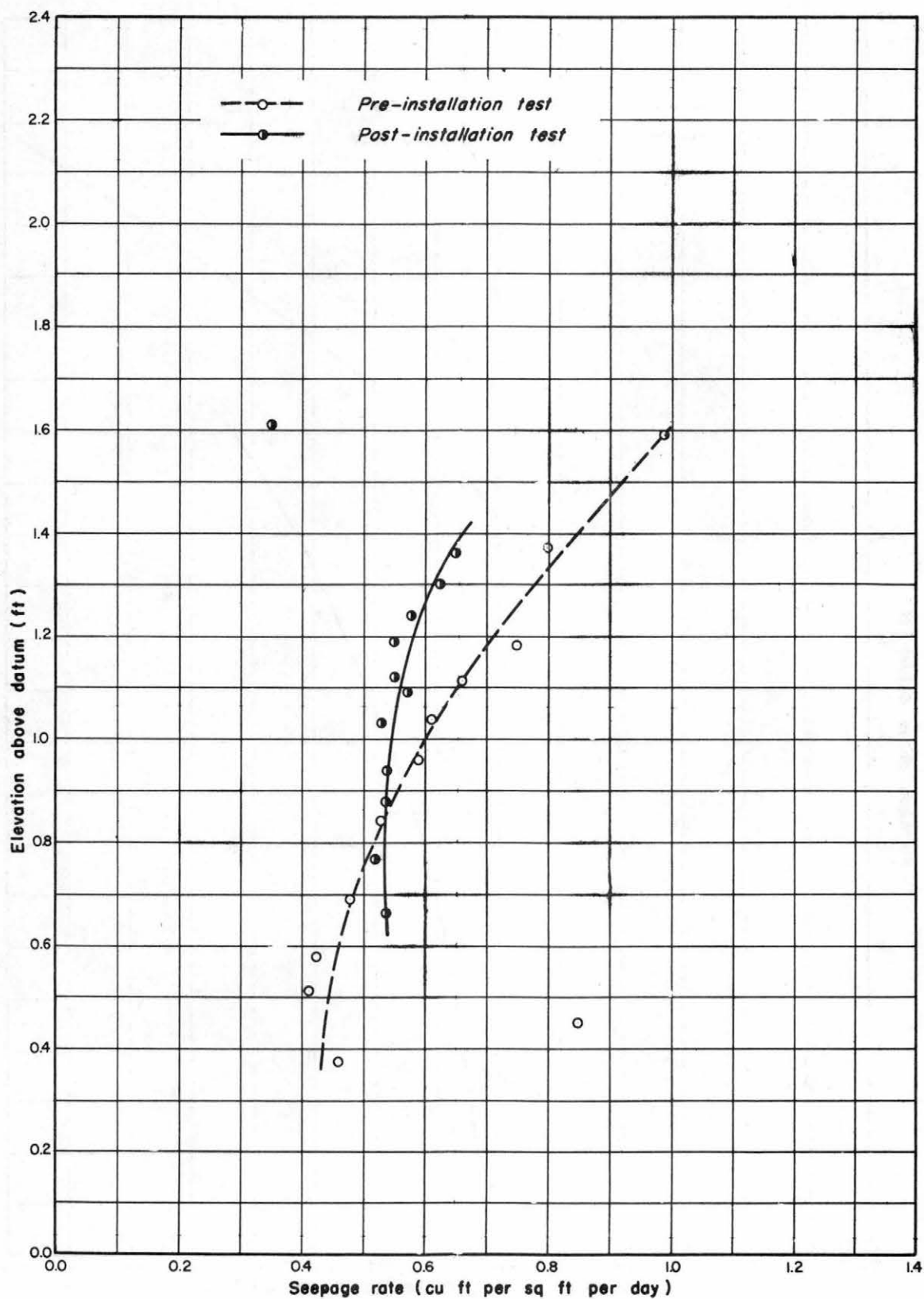


Fig. 15 Results of ponding tests before and after installation - Pond No. 1.

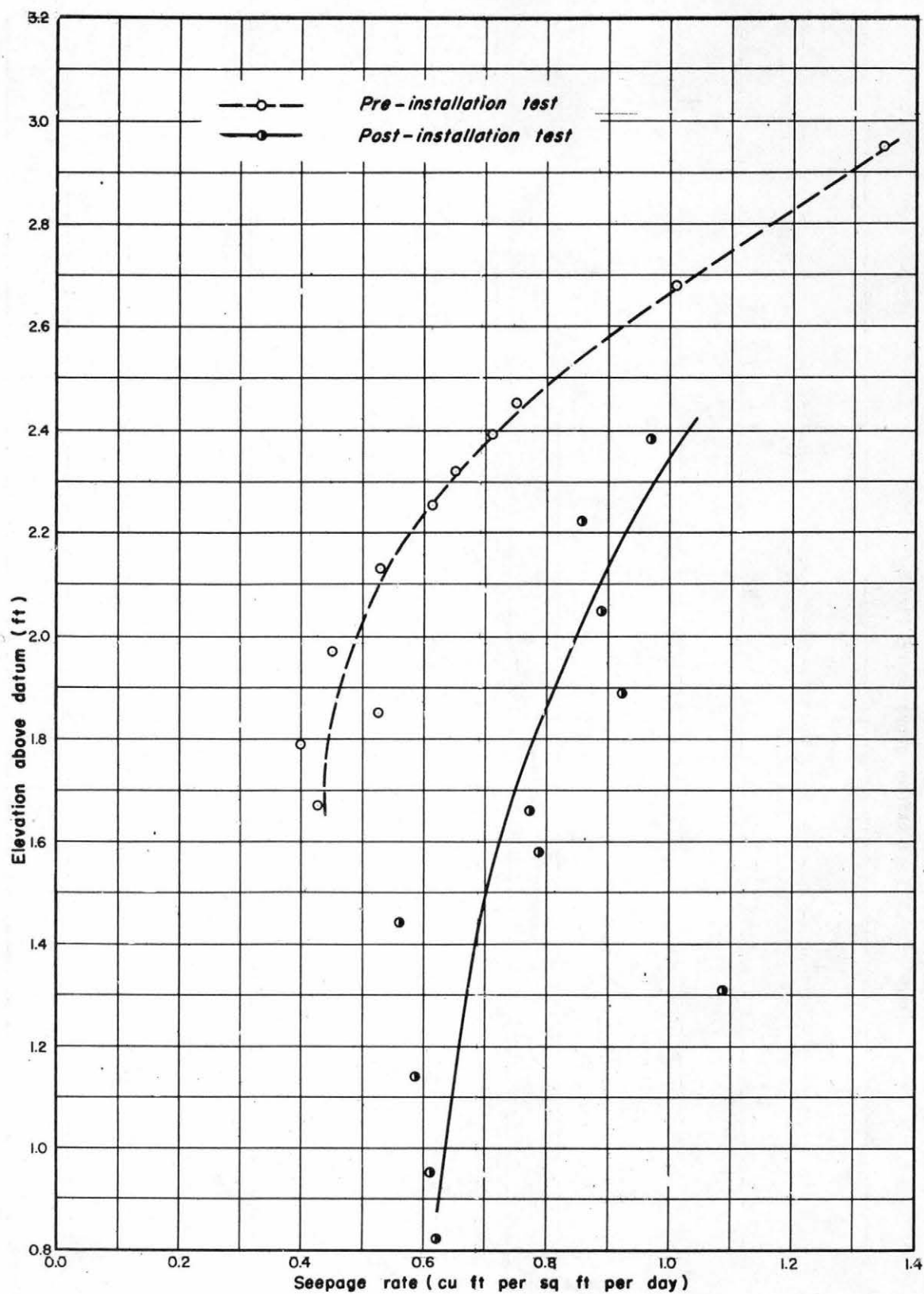


Fig. 16 Results of ponding tests before and after installation - Pond No. 2.

In pond No. 2, the initial water surface elevation in 1956 was more than half a foot below that in 1955. This probably created a different moisture distribution profile in the channel cross-section; consequently only an approximate comparison can be made at similar ponding depths.

Relative efficiencies -- Since the results of the various measuring methods lack evident congruity, a critical discussion here is in order. The observation wells did not cover the entire section (although the portions they covered showed some reduction in seepage). Thus, the results cannot be deemed representative of the over-all effect. The ponding tests, normally regarded as most accurate, showed no reduction in pond No. 1 and were inconclusive in pond No. 2 for reasons stated in the last paragraph. Moreover, they again cannot represent the entire section in question. Consequently, of the various evaluation methods used, the inflow-outflow measurements should have provided the most reliable over-all information. Mr. C. W. Thomas, Hydraulic Engineer from the Bureau of Reclamation, made an exhaustive efficiency study of the facilities that had been employed in these measurements (15).

The following is a summary of Mr. Thomas's comments:

- a. The turnout upstream from Check No. 1: errors in measurement would not reflect appreciably in loss determinations.
- b. The 2-ft Cippoletti weir at the turnout upstream from Check No. 2: measurements at this structure would be of very poor quality, but very little flow was released through this.
- c. The 6-ft Cippoletti weir at Sta. 319: the readings could produce an error of approximately - 10%.
- d. The 7-ft¹ rectangular weir at approx. Sta. 319: the readings could produce an error on the order of -8 to -9%.
- e. The 14-ft Cippoletti weir at the head end: the readings could produce an error of roughly -5%.

These figures, while qualitatively concordant with those given by Mr. Lundgreen in the 1955 measurements, are not quantitatively compatible with them (4).

Using the estimations arrived at by Mr. Thomas, one could show an inflow error of

¹ On page 9 of Ref. 15, this weir is referred to as of 8-ft length. Actually it measures 7 ft $\frac{1}{2}$ in. The error presumably is clerical.

-5 per cent and an outflow error of -9 per cent (in contrast with Mr. Lundgreen's inflow error of -10 per cent and outflow -5 per cent). This line of reasoning would change the total seepage loss for 1955 to 12.4%, quite below the current meter average of 22.17%.

For continuous future record, it was decided that piezometers be placed along the lateral. This has been carried out and will be reported in Chapter VII.

Laboratory Tests

The bed material after installation and the bentonite used were examined in the Denver laboratories of the Reclamation Bureau. The results were compared with those obtained before installation. The bed material in both cases was from Miles 1.2, 4.2, and 6.1 (16).

Benzidine test -- Bentonite presence was detected qualitatively by benzidine staining. All samples showed a concentration of bentonite in the top $\frac{1}{4}$ inch in the form of surface coating on the sand grains. It decreased rapidly with depth. The sample from Mile 6.1 showed more bentonite present than the other two. All samples showed no appreciable effect of the sedimenting operation below 7-in. depth.

X-ray diffraction analysis -- It was found that all the samples, collected before as well as after installation, contained montmorillonite. However, the montmorillonite originally present in the bed material produced a diffused diffraction line in the 14 A region whereas the commercial montmorillonite used for bentonite sedimenting produced a sharper line in this position. No quantitative measurement except a very rough estimate was possible. All samples showed a slight increase in montmorillonite content; and the presence of the commercial bentonite was manifest in only the top inch of the soil.

Chemical analysis -- Since exchange capacity is intimately related to the grain surface area, the increase of clay may be deduced from an increase in exchange capacity. Table 6 shows the comparison.

TABLE 6 -- COMPARISON OF BED MATERIAL EXCHANGE CAPACITY
BEFORE AND AFTER SEDIMENTING

STATION	DEPTH (ft)	EXCHANGE CAPACITY (meq/100gm)	
		Before Treatment	After Treatment
58+16	0 - 0.4	4.85	7.9
	0.4 - 0.8	4.25	2.9
	0.8 - 1.2	4.30	2.9
	1.2 - 1.6	3.40	
	1.6 - 2.0	3.40	
	2.0 - 2.4	3.45	
204+60	0 - 0.4	4.10	2.9
	0.4 - 0.8	3.65	2.5
	0.8 - 1.2	3.75	1.9
	1.2 - 1.6	3.65	
	1.6 - 2.0	3.55	
	2.0 - 2.4	3.45	
306+58	0 - 0.4	4.85	5.9
	0.4 - 0.8	5.55	5.1
	0.8 - 1.2	2.95	4.9
	1.2 - 1.6	4.10	
	1.6 - 2.0	3.25	
	2.0 - 2.4	4.30	

The results given above show no significant increase or decrease in clay content in the bed material. However, the exchangeable sodium and potassium cations decreased considerably. A complete tabulation of the chemical analyses data is given in the Appendix.

Bentonite examination -- The bentonite used in the treatment was supplied by Baroid Sales Division of the National Lead Company. X-ray diffraction and free-swell tests were conducted on two samples (17). It was found to contain 75 to 80 per cent montmorillonite, predominantly of the sodium variety, with some of the calcium variety. The non-clay constituents were chiefly biotite, magnetite, and hematite. Gypsum constituted approximately from a trace to four per cent in the two samples tested.

A free-swell of 1,200 per cent was obtained on oven-dried material. This low rate might have been caused by the calcium in exchange position and the presence of gypsum.

Water analysis -- Presented in Table 7 are the analysis results of canal water sampled at the time of sediment installation. Compared with pre-sedimenting samples (Table 3), the total hardness had greatly increased.

TABLE 7 -- CHEMICAL ANALYSIS OF CANAL WATER DURING SEDIMENTING TREATMENT

	ppm	meq/liter
Total dissolved solids	942	
Calcium	93	4.66
Magnesium	44	3.58
Sodium	116	5.06
Potassium	5.1	0.13
Carbonate	0.0	0.00
Bicarbonate	206	3.38
Sulfate	430	8.95
Chloride	38	1.08
Nitrate	0.4	0.006
Total hardness as CaCO_3	412	
pH		7.6
Electrical conductivity		0.001264

V. NEWMAN'S LABORATORY STUDIES (18)

Mr. E. C. Newman¹ conducted a series of tests on the dune sand from Lateral 1 as a fundamental study of certain phases of the sealing phenomenon. He investigated the effects on penetration of hydraulic gradient, bentonite size-distribution, and flocculation. This series of tests was made at the Colorado State University laboratory.

Equipment and Materials

Mr. Newman used plexiglass permeameters to hold soil columns of 5-in. diameter and 23-in. length. The inflow had a constant-head device and the outflow level was adjustable. Manometers were used to measure the pressure differences along the column. The apparatus could be filled with carbon dioxide before being loaded with sand so that an air-free system could be obtained (Figs. 17-19).

The sand came from a dune adjacent to Mile 2 of Lateral 1; it was not the actual bed material but very similar to it. Its size-distribution curve is shown in Fig. 20. A commercial, high-swell, Wyoming bentonite was used; it contained 5.8 per cent grit and 8.2 per cent moisture. The flocculant was calcium acetate, $\text{Ca}(\text{C}_2\text{H}_3\text{O}_2)_2$, and the deflocculant, granular sodium tripolyphosphate, $\text{Na}_5\text{P}_3\text{O}_{10}$. Fort Collins tap water was used; most of the air in solution was driven out by simple heating; and a cooling temperature gradient in the system prevented any air from escaping during the experimentation.

Procedure

The permeameter was filled with carbon dioxide, and sand was allowed to drop into it freely. With tapping, the column was packed to between 1.55 and 1.56 gm per c.c. density (97 lb per cu ft). Heat-treated tap water was introduced to displace and dissolve the carbon dioxide. The tailwater elevation was then adjusted to obtain the desired over-all hydraulic gradient.

¹ Formerly graduate assistant at Colorado State University.

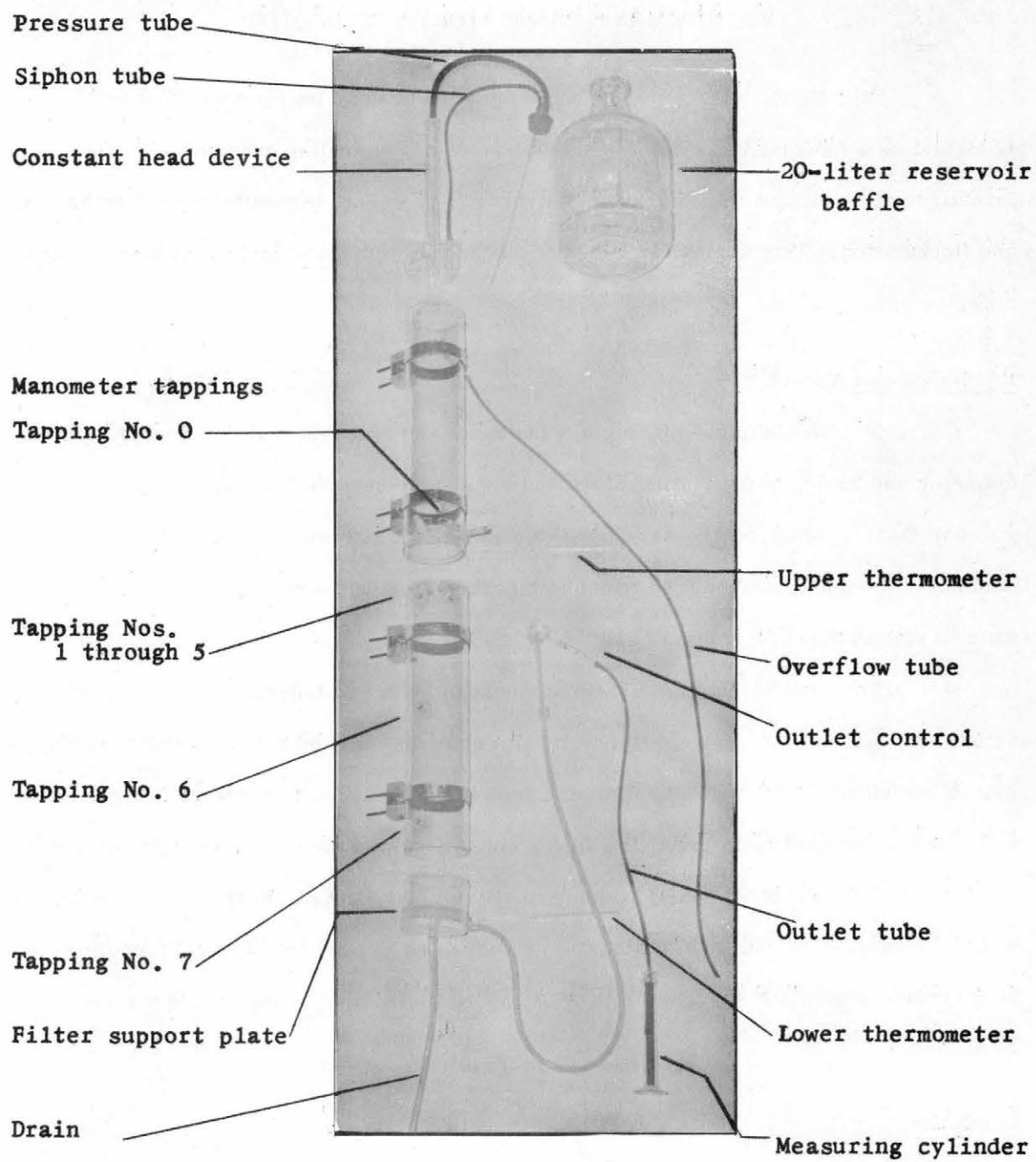


Fig. 17 Exploded view of Newman's permeameter. CSU photo.

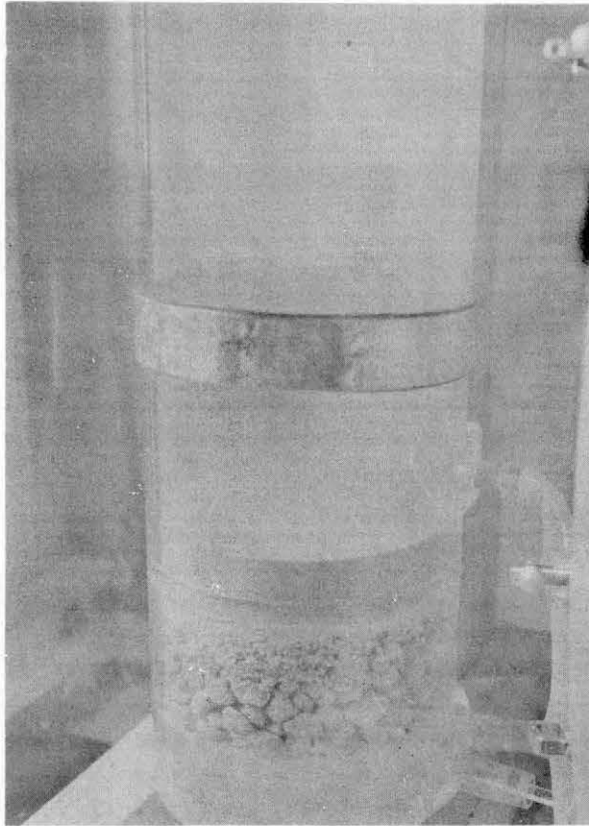


Fig. 18 View of bottom section of a permeameter under Newman's loading system. Note the even surface built up gradually by six streams of sand. CSU photo.

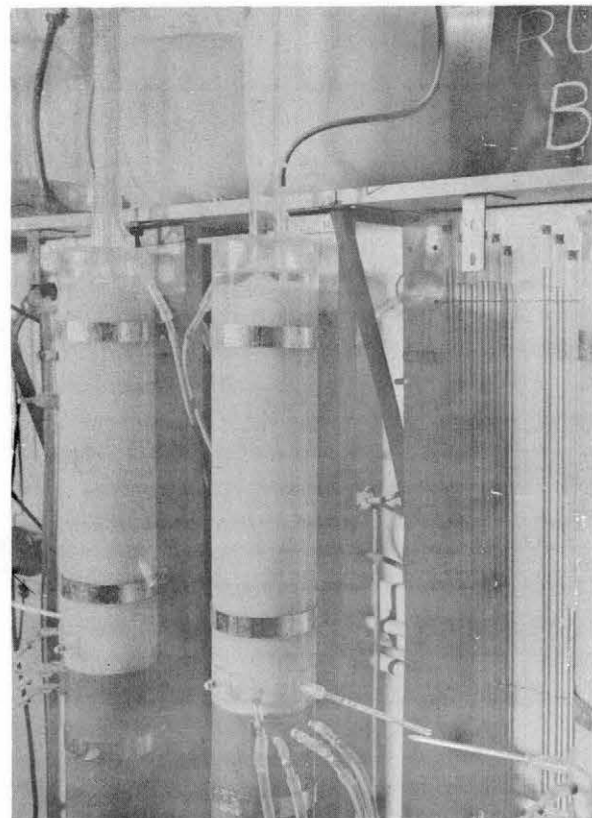


Fig. 19 View of upper section of permeameters during Newman's experiments with flocculated bentonite suspensions. CSU photo.

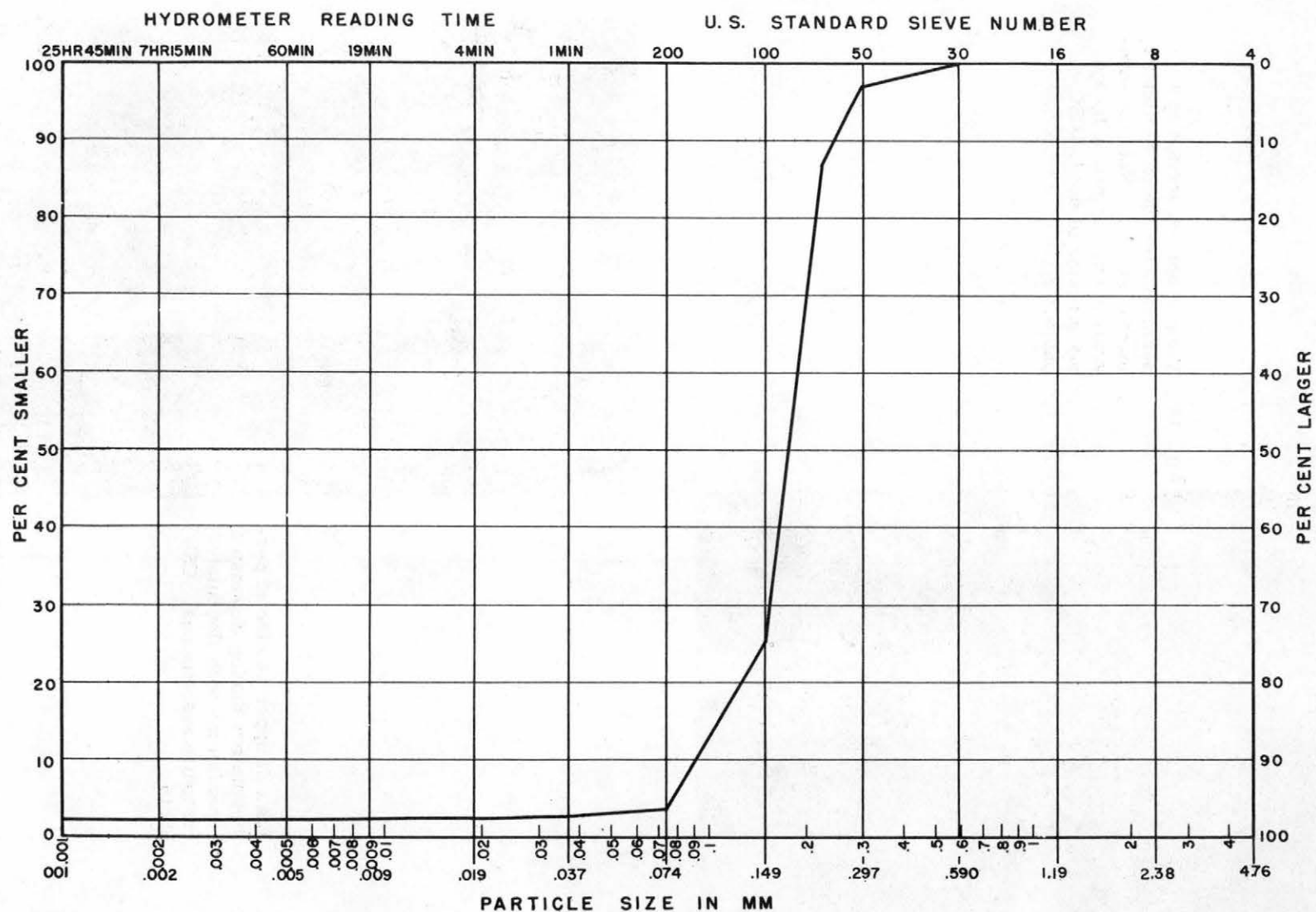


Fig. 20 Particle size-distribution curve of the dune sand tested by Newman. Compare it with Fig. 4.

Determination of initial permeability -- Permeability determinations were carried out in duplicates. The effluent was collected in a graduated cylinder. Manometer readings, temperatures and time were recorded. To keep the sand surface clean, an hour before each reading, Mr. Newman siphoned an approximately $\frac{1}{16}$ -in. layer off the surface.

Sedimenting -- After the permeability stabilized, bentonite suspensions were introduced. The various mixes were (a) flocculated; (b) dispersed with a maximum particle size of 44 microns; (c) dispersed with a maximum particle size of 1 micron; and (d) dispersant only. All bentonite mixes had a concentration of approximately one per cent. The sedimenting process continued until the flow was negligible.

Determination of final permeability -- The surface cake was siphoned off first, then heat-treated tap water was introduced once more. The surface was cleaned by siphoning periodically as before. The concentration of dissolved and suspended materials in the effluent was determined.

Penetration examination -- Samples were taken from several levels of the column for detection of bentonite penetration. Mr. Newman used the hygroscopic moisture ratio method to determine any increase in total surface area. The samples were oven-dried, weighed, and then subjected for five days to an absolute pressure of one cm of mercury, at a constant temperature of 20°C, and under a relative humidity of 90 per cent. The gain in moisture at the end of this treatment bore direct relation to the surface area of the sample; and any gain in clay was reflected in a gain in surface area.

Results

Mr. Newman computed his data in terms of intrinsic permeability and specific discharge. The former term is absolute while the latter term applies to only a specific hydraulic gradient (19). For comparison with the data obtained from the latest test series, these earlier results are presented in new units in Table 8. The values of percolation rate are those assumed to occur under a hydraulic gradient of 2.75, and at

a temperature of 20°C. These values are not realistic as can be seen from the effect of the applied hydraulic gradient on penetration and sealing. However, they do show that flocculated bentonite does not penetrate or bring about any sealing in depth. They also show that much more sealing is needed to achieve the goal of allowing only 0.1 cu ft per sq ft per day percolation.

TABLE 8 -- RESULTS OF NEWMAN'S EXPERIMENTS

TREATMENT	COLUMN DENSITY (gm/c.c.)	APPLIED HYD. GRAD.	PERCOLATION RATES			PENETRATION (in.)
			Initial	Minimum	Final	
			(cu ft/sq ft/day)			
1% bentonite	1.548	0.0263	148	0.660	88.3	None
mix, dispersed	1.554	0.0278	143	0.925	93.3	None
Maximum	1.550	0.101	156	0.546	3.76	12
particle size	1.554	0.100	147	2.08	35.6	22
1 micron	1.554	0.102	133	0.282	8.30	12
	1.554	0.302	158	0.213	51.1	Complete
	1.554	0.305	153	0.189	55.3	Complete
1% bentonite	1.556	0.0315	108	0.505	111	None
mix, dispersed	1.559	0.0318	138	0.665	126	None
Maximum	1.554	0.0312	144	0.558	134	None
particle size	1.556	0.937	117	0.0532	51.7	Complete
44 microns	1.556	0.908	122			
	1.559	0.909	132	0.0773	40.6	Complete
1% bentonite	1.557	0.0297	123		138	None
mix, flocculated	1.557	0.0329	104		101	None
	1.562	0.0347	106		87.4	None
	1.554	0.895	131		131	None
	1.557	0.907	127		124	None
	1.560	0.906	134		130	None

In considering possible causes of the partial sealing attained, Mr. Newman listed the following postulations:

- a. Swelling of colloidal particles, present in the sand originally, due to sodium saturation.
- b. Rearrangement of clay particles into new positions, more effectively blocking pore spaces.
- c. Migration and subsequent accumulation of particles in thin layers relatively impermeable to water having a high sodium content took place (20).

- d. Accumulation of bentonite particles at some irregularity in the packing of the sand, forming a barrier where more particles were filtered out.
- e. A lower velocity of the bentonite particles than that of the water carrying them, leading to a gradual increase in viscosity and, eventually, the formation of a thixotropic gel.
- f. Flocculation of bentonite within the soil when the softened suspending liquid was replaced by the relatively hard tap water.

VI. PRESENT RESEARCH PROGRAM

The results of post-installation evaluations of the Lateral 1 sediment-sealing attempt leave much to be desired. Three basic questions need to be answered:

- a. Is it possible in Lateral 1 to obtain enough penetration by sedimenting to reduce the seepage to less than 0.1 cu ft per sq ft per day?
- b. If such a goal be attainable, by what means can one measure such a low seepage rate?
- c. Has the field installation achieved this goal? If not, why, and how can it be remedied?

A re-examination of the laboratory and field evaluation work previously conducted will demonstrate that these questions can be answered only by further evaluation in the laboratory, and then confirmation from additional field trials.

Previous Laboratory Experiments

In the Bureau's penetration experiments (Figs. 5 to 7) the initial percolation rates were quite at variance with each other, indicating some unequal initial condition such as, density, packing or degree of saturation. In two cases the final rate exceeded the initial rate. A few other facts also beggar explanation in the absence of detailed description and data. Nevertheless, at no time during the test was it reported that the percolation rate had been reduced to less than 0.1 cu ft per sq ft per day (when the hydraulic gradient is converted to 2.75).

In Mr. Newman's experiments, the sand (collected not from the canal bed but from a nearby dune) was packed at approximately 97 lb per cu ft density (1.555 gm per c.c.); the hydraulic gradient was kept below unity; the columns were artificially made air-free by the use of carbon dioxide; heat-treated tap water was used; and the columns were saturated at all times. Thus his results, while enlightening in themselves, cannot be extrapolated to explain field behavior directly.

In view of these considerations, a new series of laboratory tests was necessary in order to determine the feasibility of the sediment-sealing process in Lateral 1. The new program must incorporate features and conditions encountered in the field as far as practicable. It must be conceded, however, that no exact duplication is possible, and therefore, the ultimate test should rest with field measurements provided they can be improved upon to yield sufficient precision.

1958 Series

The Technical Advisory Committee of the sediment-sealing project decided on a new laboratory program for the fiscal year beginning July 1, 1957. The purpose of this program was to conduct fundamental studies of the Lateral 1 sediment sealing experiment in an effort to:

1. find the causes of the formation of the bentonite surface layer, in terms of the physical and chemical properties and reactions of the materials; and
2. recommend practicable field methods of obtaining the desired penetration of the bentonite and/or dispersant in the canal bed materials to form a more permanent seal.

The permeameter approach was to be retained as it was the only economically feasible method at the time. The bed material and the canal water were to be closely duplicated. The soil columns were to be packed at field density. An attempt was to be made to find ways of reproducing the hydraulic gradient and moisture condition in the field.

The initial treatment sequence was to reproduce what had occurred in the field during the 1955 installation. This would, it was hoped, throw light on the effectiveness of that installation. Later runs would include improved treatments to suit the needs of this site. Ultimately it might be possible to recommend a procedure that could reduce the seepage rate to below 0.1 cu ft per sq ft per day.

Delimitations

It must be acknowledged that not all existing conditions could be copied in the laboratory. Lack of understanding of the differences between model and prototype would doubtless lead to spurious generalizations. The following is a discussion of items

included and excluded in the testing program. The exclusion was necessary because of either limited facilities or incomplete knowledge.

Bed material -- The soil used was a composite mixture of the samples obtained from the canal bed at several locations. Field density measurements were taken, and an average value was used in packing the columns. The bed stratification, pronounced in the field, was not reproduced in the laboratory. The effect of this factor cannot be minimized: the primary cause of the difference in percolation rate between the permeameter and the prototype may be ascribed to it. However, until some practicable system can be worked out only homogeneous soil columns can be used. The study of layering would constitute a challenging research project in itself.

Water -- The hardness of the canal water could not be expected to remain constant. Artificial hard water was made in the laboratory to resemble, in chemical composition, one specific sample collected at the time of the field trial. No organic matter nor sediment was included.

Hydraulic gradient -- A constant head was applied, which was judged to be the average depth of the water in the lateral. The tailwater elevation was kept at the same level as the bottom of the soil column where it was at atmospheric pressure. During the very brief periods of changing from clear water to bentonite mix and vice versa the headwater was removed and the tailwater drain was shut off. The actual pressure gradient in the field was not measurable, at least not by the piezometers sunk for the purpose. The probable deviation from field conditions here must produce substantially different results since the hydraulic gradient not only affects the momentous percolation rate but also directly influences the degree of bentonite penetration as has been shown by Mr. Newman (18).

Flow -- As in all permeameter testing, a steady gravitational flow was maintained, with no turbulence. This should be adequate to simulate ponding conditions during the sedimenting process. No claim was made to collate this system with the actual full flow operating conditions of the lateral which may be in a regime of ripples,

dunes, anti-dunes, etc. The removal of the filter cake was accomplished by siphoning, which may be a more severe process than in the lateral where the washing away by turbulence may be far from total removal.

Temperature -- A temperature record was made, each reading interval being roughly eight hours. The temperature was not artificially controlled. Consequently the more extreme quotidian variations in the field were not reproduced. It may be postulated that, in addition to its indirect influence on the percolation rate through viscosity variations, temperature may play a role in the penetration phenomenon by promoting expansion and contraction of the pores in the soil. The over-all effect of this phase is open to prognostication.

Air -- An attempt was made to include the presence of air as a variable. Bentonite treatment was applied to columns of soil containing different amounts of air. This was achieved by controlling the moisture contents of the columns thereby indirectly controlling the void spaces. The relation between permeability and moisture content in the dune sand tested was also investigated. However, the behavior of the air present depended on many other factors that were not controlled, such as temperature and organic matter. While bubbles did not appear throughout the test program, it is difficult to estimate the extent of the passing of air into and out of solution and how these occurrences could have affected the test results.

Other factors -- Aside from the factors listed above, there were a number of incidental field conditions beyond the control of our laboratory. Among them the more important ones were: secondary soil structures such as root holes and cracks; the V-shape of the channel cross-section in contrast to the flat surface of the soil column; and the drying and wetting of the canal bed as described in Chapter IV.

VII. FIELD WORK

Preliminary to the laboratory testing, work was done in the field at the Lateral 1 site for gathering pertinent information as well as collecting samples. Reclamation Bureau personnel worked closely with the University research team at this phase of the project. Unfortunately the canal had undergone a major cleaning after the 1957 irrigation season immediately before the field work was conducted. In fact, the field work began while the cleaning was in progress. The lateral was re-aligned and reshaped in places; the entire section was cleared of trees. This cleaning seriously impaired our hopes of determining the original conditions of the channel. Compare Figs. 21 and 22.

Piezometer Wells (21)

Bureau personnel in Torrington, Wyoming, installed four sets of piezometer wells under the direction of Mr. Lundgreen. These wells were located at Sta. 57+83, Sta. 197+58, Sta. 213+77, and Sta. 290+38. Each consisted of three $\frac{1}{2}$ -in. pipes sunk to depths of 1 ft, 3 ft, and 5 ft below the ground surface at the bottom of the channel. Mr. Lundgreen tried to record weekly readings through the 1957 irrigation season only to find that all except the last piezometer, after the initially added water in them had drained out, stayed dry. The one exception reflected a lag in the water level fluctuation inside the pipe with respect to the outside.

It may be speculated that the hydraulic gradient was very great in most places immediately below the surface, and that the bed material was not saturated even 12 in. from the ground surface. This might have been caused by surface sealing or by impermeable strata very near the surface. For further discussion on the field hydraulic gradient, see Chapter XII under Percolation Rate.

Inspection Trip

After the 1957 irrigation season, when the canal bed became dry, University



Fig. 21 View of a typical section of the Lateral 1 sediment-sealing site on October 2, 1957, before channel cleaning. CSU photo by C. P. Cass



Fig. 22 View of a typical section of the Lateral 1 sediment-sealing site on October 22, 1957, after channel cleaning. CSU photo by R. T. Shen.

and Bureau personnel visited the lateral site¹. The purpose of this visit was to inspect the channel bed for traces of bentonite, determine the bulk density of the soil, and in general probe the field conditions in preparation for a laboratory program.

Examination with Hoffer sampler -- Visual observation with the aid of a Hoffer soil sampler revealed that isolated remnants of the bentonite cake were profusely scattered under the surface, see Fig. 23. Many pieces displayed a curled-up shape, presumably the result of earlier drying as part of the surface cake. These layers were more extensive in the second ponded section where they were found within the top 6-in. depth of the bed. These could have been buried there by sand dune movement or similar other sand bed movement phenomena. A complete list of the visual observation of the sample cores is given in Table 9, which has been transcribed from the notes of Mr. Lundgreen taken between September 30 and October 2, 1957.

Density determination -- Special equipment was built for measuring in-place density of the bed material, consisting of a steel cylindrical tube with a beveled cutting edge at the bottom. This was driven into the soil to a measurable depth, cutting and collecting into the tube the entire bulk of soil in its path. A base plate with an upright sleeve guided the driving in the vertical direction. The soil was carried up with two specially designed augers, each fitting snugly inside the cylinder. These were capable of emptying the cylinder completely and scraping the bottom to a smooth flat surface flush with the cutting edge. For details and operation of this apparatus, see Figs. 24, 25, and 26. The soil was then sealed into a plastic bag. The density and moisture content could be computed from the known volume, the moist weight, and the dry weight of the soil (Table 10).

¹ Representing the University were Messrs. R. D. Dirmeyer, Jr., project leader, and C. P. Cass, graduate assistant. Representing the Bureau were Messrs. W. K. Lundgreen of the Torrington office and John Merriman of the Denver office.



Fig. 23 Close-up view of a core of soil in a Hoffer sampler. Note the layers of bentonite marked by discoloration. CSU photo by C. P. Cass.



Fig. 24 Close-up view of density determination. The last bit of soil is being transferred from the finishing auger into the plastic sack. CSU photo by C. P. Cass.

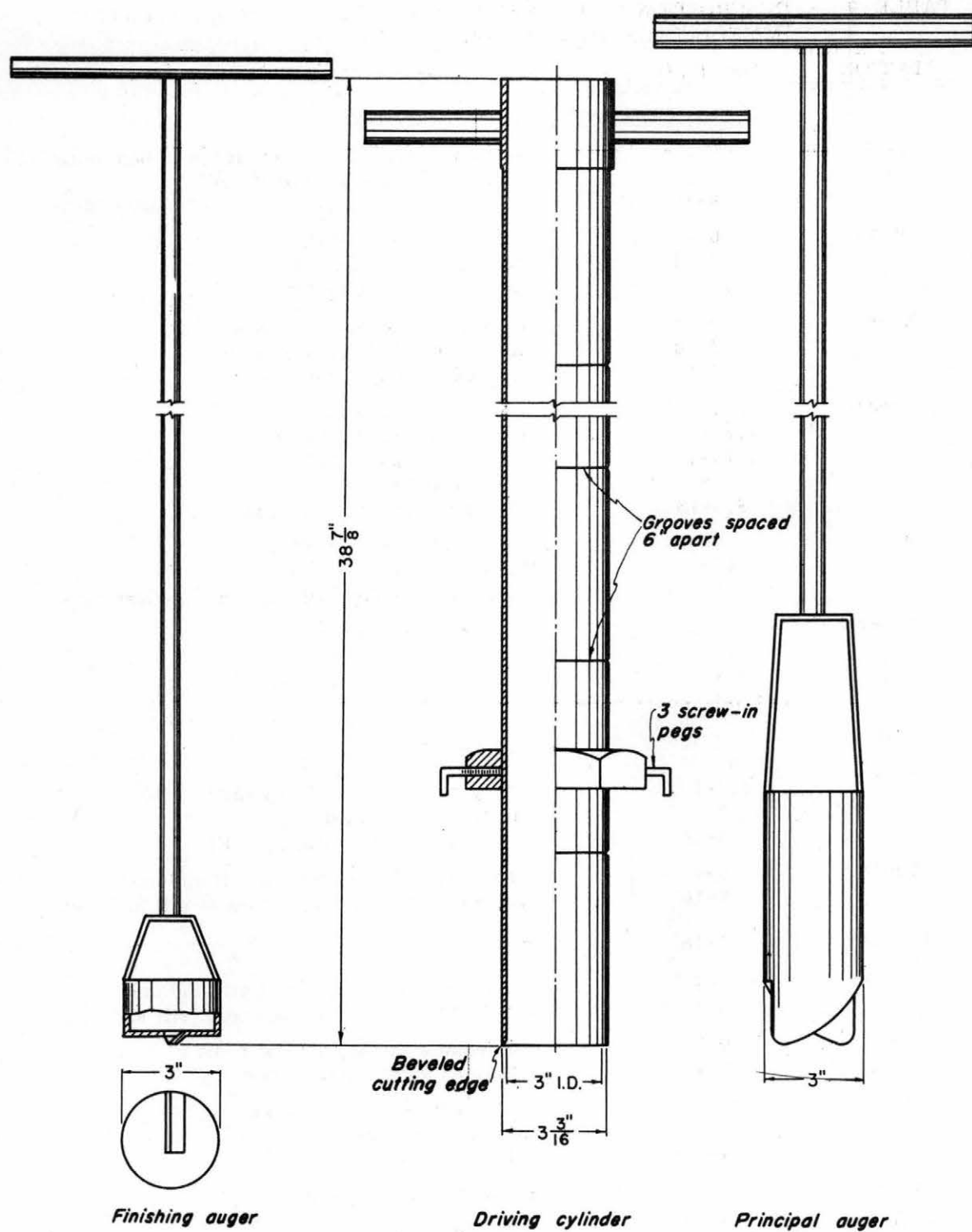


Fig. 25 Design of the soil bulk density determination equipment.

TABLE 9 -- DESCRIPTION OF HOFFER SAMPLES TAKEN FROM LATERAL 1
IMMEDIATELY BEFORE CLEANING IN 1957

STATION	DEPTH (in.)	DESCRIPTION ¹
POND No. 1 SECTION ²		
89+87	0-2	fine sand with binder, evidence of bentonite (SC)
	2-9	fine sand with clay binder (SC)
	9-16	fine sand with lesser amount of binder (SC)
90+87	0-12	fine, clean sand (SP)
	12-13	sand with clay (SC-CL)
	13-16	sand with less clay (SC)
91+87	0-3	clean, fine to medium sand
	3-10	fine sand with clay binder (SC)
	10-15	fine sand, clayey (SC-CL)
92+87	0-1.25	fine, clean sand (SP)
	1.25-1.75	clayey fine sand (SC-CL)
	1.75-8.5	fine, clean sand (SP)
	8.5	organic matter
	8.5-15	silty or slightly clayey sand (SF)
93+87	0-4.5	fine sand with clay (SC)
	4.5	layer of clean sand (SP)
	4.5-1.5	fine sand, clayey, with organic matter (SC)
94+87	0-2.5	fine, clean sand (SP)
	2.5	layer of gravel
	2.5-13	fine sand with binder (SC)
	13-15	caliche
97+87	0-4.5	fine sand (SP)
	4.5	layer of clay, very sandy
	4.5-7	fine sand, silty or clayey (SF)
	7-9	clean, fine sand (SP)
	9-15	fine sand, silty or clayey (SF)
100+87	0-9	fine sand, silty; layers of silt and clay
	9-16	fine sand with binder; layers of silt and clay
102+87	8-16	caliche
103+87	0-9	fine sand, silty; layers of silt and clay
	9-16	fine sand with binder; layers of silt and clay
106+87	0-5	fine sand with layers of silt and clay
	5-16	fine sand with slight binder
109+87	0-4	sand, silty and clay layers
	4	thin plastic layer
	4-16	fine, clean sand
110+87		$\frac{1}{2}$ -in. bentonite layer
111+87	0-4	fine sand with slight binder
	4-7	organic matter with fine sand
	7	thin layer of bentonite
	7-16	fine sand, silt and clay layers
112+87	0-5	fine sand with binder
	5	thin layer of bentonite
	5-16	fine sand with silt and clay layers

TABLE 9 -- DESCRIPTION OF HOFFER SAMPLES TAKEN FROM LATERAL 1
IMMEDIATELY BEFORE CLEANING IN 1957 (Continued)

STATION	DEPTH (in.)	DESCRIPTION ¹
POND No. 1 SECTION (Continued)		
113+87	0-10	fine sand, silty
	10-16	layers of silt, sand and clay
114+87	0-4	very wet fine sand, silty
	4	layer of bentonite
	4-16	sand, silt and clay layers, mostly fine sand
115+87	0-4	very wet fine sand, silty
	4	layer of bentonite
	4-16	sand, silt and clay layers, mostly fine sand
POND No. 2 SECTION ²		
238+00	0-16	silty sand with a thin $\frac{1}{4}$ - in. bentonite
241+00		layer in the top 6-In. section of the samples,
244+00		the bentonite being in discontinuous curled
247+00		up cakes
250+00	0-6	clean fine sand, bentonite layer same as above
253+00		
256+00		
258+00		
	6-16	silty fine sand

¹ Letters in parentheses are group symbols given by the Bureau of Reclamation unified soil classification system (22).

² Ponds refer to the same two used in the ponding tests by Mr. McBirney in 1955 and in 1956: No. 1 extends from Sta. 88+32 to Sta. 119+15.2, No. 2 from Sta. 236+18 to Sta. 258+68.6.

TABLE 10 -- BULK DENSITY OF LATERAL 1 BED SOIL IMMEDIATELY
BEFORE CLEANING IN 1957

DEPTH (in.)	BULK DENSITY (lb per cu ft)			
	Location 1	Location 2	Location 3	Location 4
0-6	103.6	98	83	107
6-12	102	100	83	96
12-18	100	102	101	100
18-24	96	103	99	108

Sample Collection

The soil sample for testing in the permeameters was collected three weeks after the inspection trip reported in the last paragraph. By this time the lateral had been cleaned as mentioned in the beginning of this chapter. The cleaning operation



Fig. 26 View of density determination in operation. Note the guide plate with a vertical sleeve. CSU photo by R. T. Shen.



Fig. 27 View of sampling operation. The 6" x 6" trench transecting the estimated wetted perimeter is in the foreground. CSU photo by R. T. Shen.

altered the soil conditions and thereby widened the difference between this series of laboratory tests and the prototype. Unfortunately this was unavoidable.

Participating in this operation were Mr. R. D. Dirmeyer and the author from the University, and Messrs. W. K. Lundgreen and R. D. Mason from the Bureau's Torrington office.

Method used -- Six locations were selected along the Lateral 1 treated section. At each location a trench, approximately 6 in. wide and 6 in. deep, was excavated. It transected the channel, covering what was judged to be the normal wetted perimeter. The excavated soil was then stored in barrels, without any attempt to separate it by locations. Separation was not necessary because a composite mixture was desired. The total soil sample obtained amounted to about 3,000 lb, see Fig. 27.

Density determination -- After canal cleaning, the bed soil should be in a more compacted state. The bulk densities measured previously were no longer valid. Therefore, at each sampling location the new density was determined to a depth of 12 in. The results of this operation are tabulated below:

TABLE 11 -- BULK DENSITY OF LATERAL 1 BED SOIL IMMEDIATELY AFTER CLEANING IN 1957

DEPTH (in.)	BULK DENSITY (lb per cu ft)					
	Sta. 95+75	112+46	163+00	204+60	241+00	255+44
0-6	103	98	99	103	101	101
6-12	106	96	101	105	100	101

From Tables 10 and 11 it may be seen that the cleaning process compacted the bed material slightly and also made its density more uniform. The average density in the first 12 in. before cleaning was 96.6 lb per cu ft (approximately the same as Newman's packing) with a standard deviation of 2.2; after cleaning it increased to 101.2 lb per cu ft with a standard deviation of 0.8.

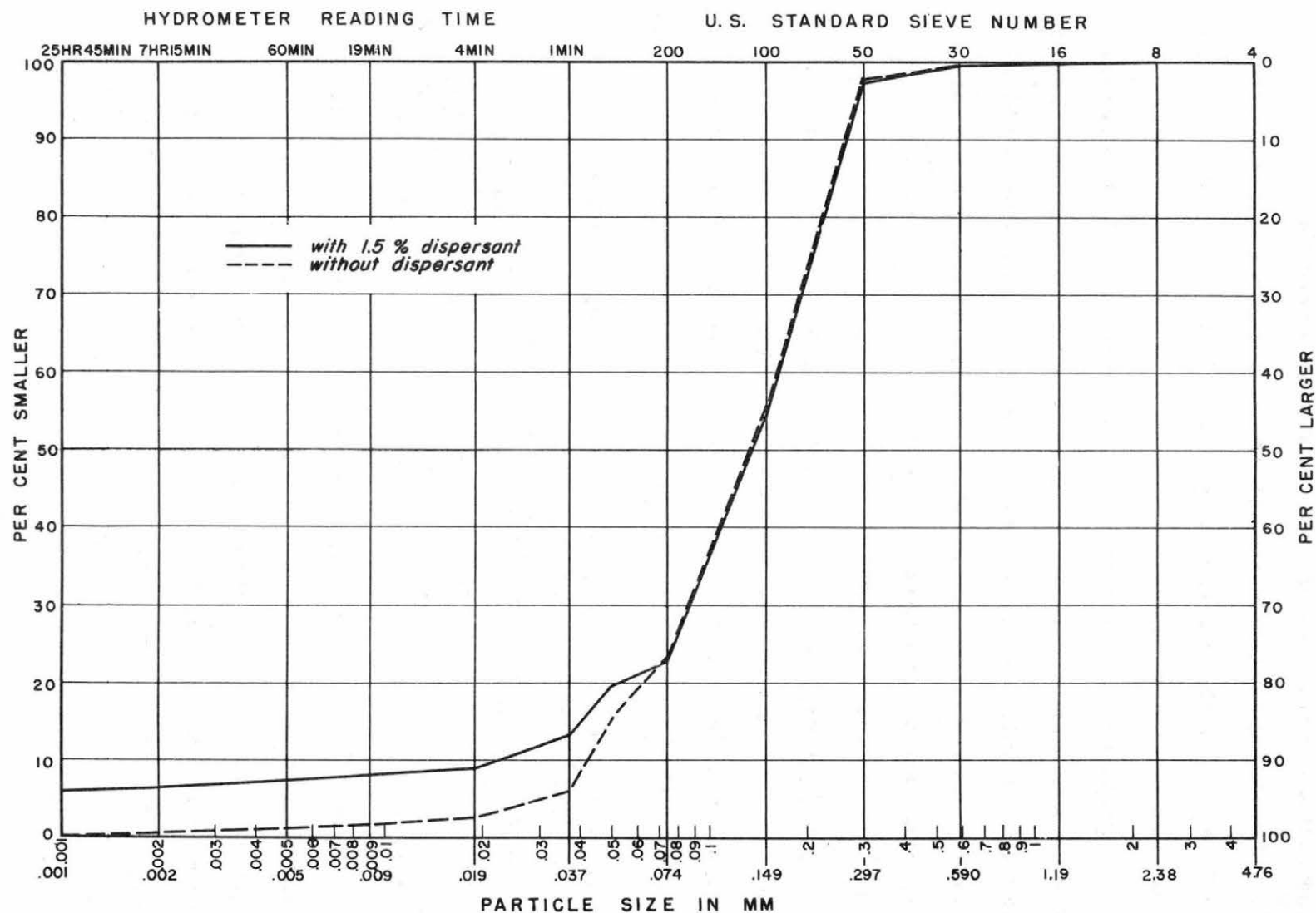


Fig. 28 Particle size-distribution curves of the composite sample used in the 1958 testing. Compare with Figs. 4 and 20,

VIII. MATERIALS FOR TESTING

Described in this chapter are the three materials, soil, water, and sedimenting agents, together with their testing in preparation for the main experiment program. Parts of material testing, pertinent to the evaluation of the results are reported in Chapter X.

Soil

The bed material sample collected from Lateral 1, as reported in the previous chapter, was spread out to dry in a warm room. The temperature was kept at about 40°C. Occasional stirring and scooping prevented serious lump formation and hastened the drying process. After a month had elapsed, the soil was thoroughly mixed in a miniature concrete mixer.

Mechanical analysis -- Particle-size distribution curves of the sample are given in Fig. 28. The effect of dispersing agent (1.5 gm of tetrasodium pyrosulphate in 100 gm of soil) is compared in this figure with that of distilled water.

Saturation moisture content -- The moisture requirement for saturation of the soil was determined. Initially a known weight of soil was loosely packed to a known volume. Then distilled water was allowed to soak through. After the excess of water was removed, the weight of the mixture was obtained. This process was repeated for various densities and the results are shown in Fig. 29. Since the field density, after canal cleaning, averaged 101.2 lb per cu ft or 1.621 gm per cc, the soil columns were to be packed to as close to this density as practicable. The graph indicates a saturation moisture content of 22.3 per cent.

Permeability variation with moisture -- The presence of air in permeability measurements has usually been avoided in the laboratory because of its complexity. Mr. Newman saturated his soil columns completely with water thereby insuring the absence of air. Permeability measurements could thus be obtained with uniformity. However, seepage flow in the field may not be through a saturated soil in all cases.

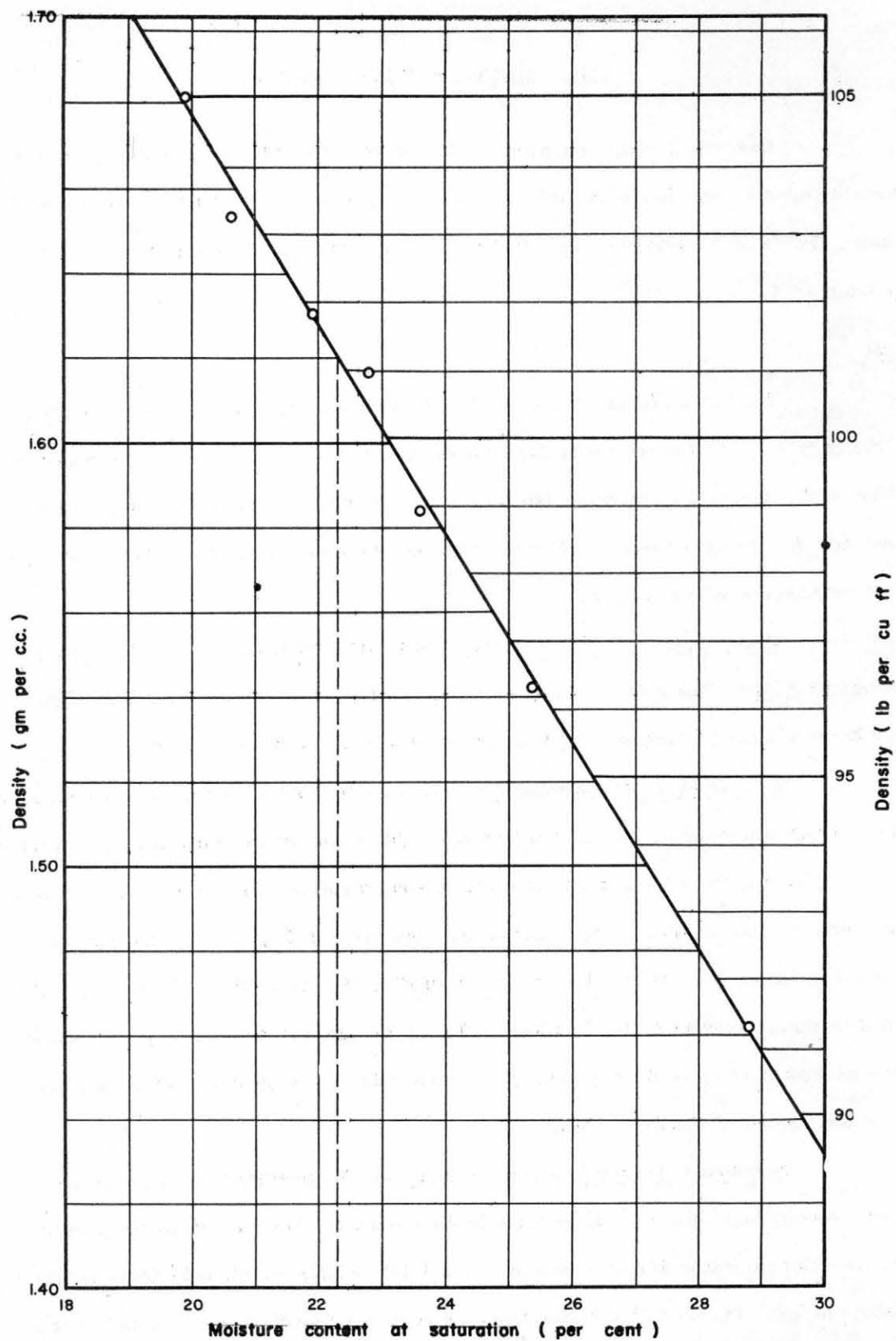


Fig. 29 Variation of saturation moisture content with density of soil.

The fact that the piezometer wells had remained dry led one to suspect that the channel bed of Lateral 1 was only partially saturated with water. Dr. A. T. Corey¹ conducted a test on the Lateral 1 soil sample to determine the effect of partial saturation on water permeability (23). He began with a saturated column of the soil and drained it by degrees, measuring its water permeability at each stage of drainage. The results of this experiment are expressed in relative units: complete saturation and its corresponding permeability being unity and the various degrees of saturation and their corresponding permeability values being fractions thereof. It may be seen from Fig. 30 that the permeability decreases very rapidly with decreasing moisture saturation. At 65 per cent relative saturation the permeability is less than one per cent of that at full saturation. In other words, when the soil contains 14.5 per cent moisture by weight (saturation moisture content taken as 22.3 per cent) the permeability is negligible compared to that at saturation. This behavior serves to explain some of the results obtained in the sediment-sealing experiments, especially when the bentonite suspensions were introduced to partially saturated soil columns.

Permeability variation with density -- In order to find the effect of density on permeability, several columns of soil were packed to various densities. They were then saturated and subjected to flow of water under a constant hydraulic gradient of 2.75. Two series of runs were attempted, but each time the results showed considerable scatter. No systematic variation could be found; and the data were discarded. This failure may be ascribed to two factors: (a) packing to a homogeneous density was not attained, and (b) puddling of the clay present in the soil took place. Although no positive benefits are derived from these attempts, at least we have learned that the results of each run must not be considered as absolute. Each run must be viewed independently in its own history; any comparison between runs must be qualified. For further discussion, see Chapter XII under Packing.

¹ Research Engineer, School of Civil Engineering, Colorado State University.

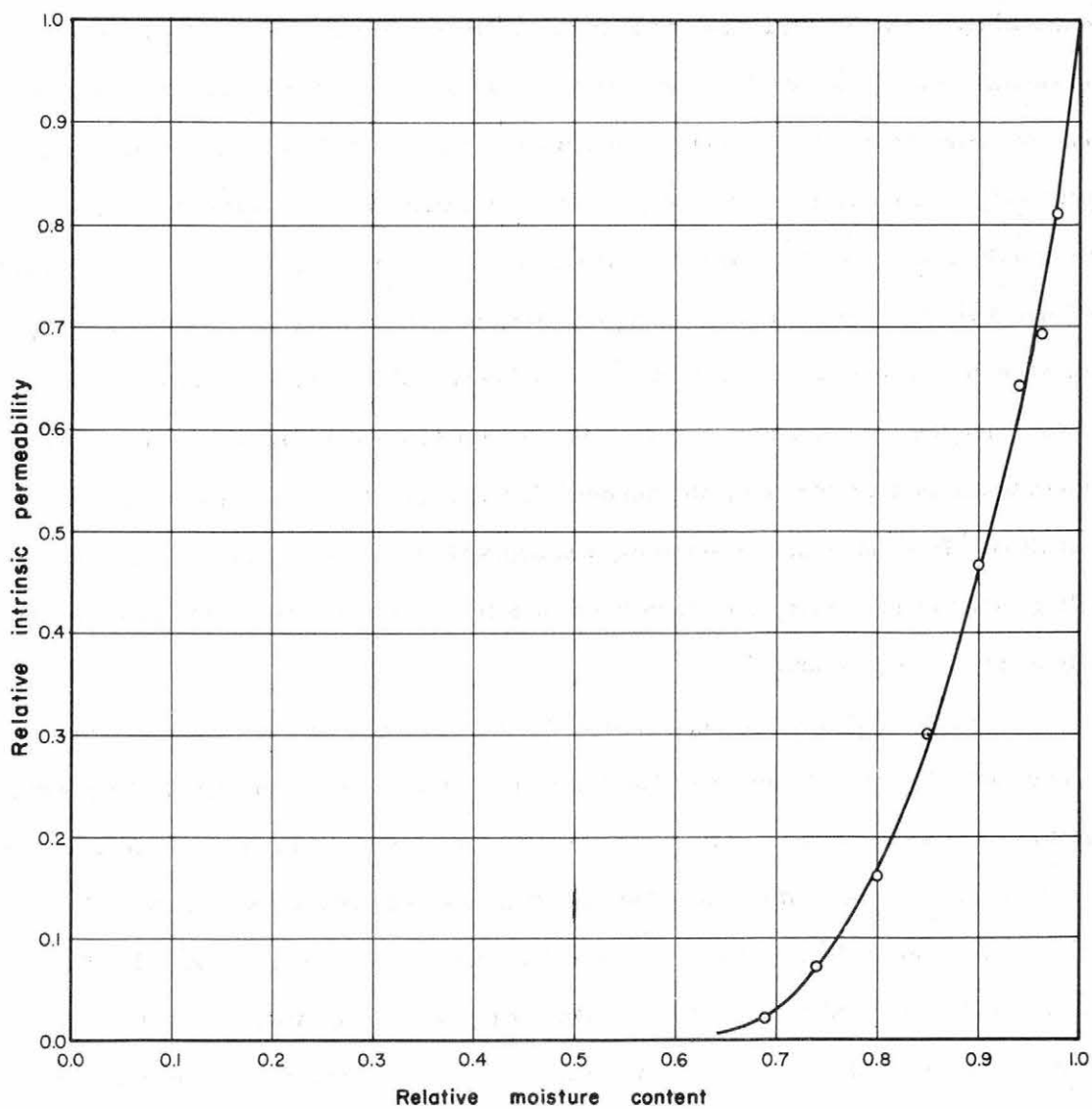


Fig. 30 Relation between relative intrinsic permeability and relative moisture content. The data were taken while the soil was being drained from saturation to dry; a slight variation is expected for the case when the sample undergoes the reverse process (process of imbibition).

Water

The water used in the experiments was artificially manufactured from distilled water. Its composition was fashioned after that of an actual sample taken from Lateral 1 at the time of installation (24). Only the chemical contents were duplicated, as tabulated below. The resultant water would have the same chemical make-up as listed in Table 7 in Chapter III.

TABLE 12 -- CHEMICALS USED IN THE MANUFACTURE OF SYNTHETIC CANAL WATER

ITEM (Reagent grade)	QUANTITY (gm per liter)
$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (dissolved first)	0.40
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	0.44
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	0.11
NaHCO_3	0.28
NaCl	0.06
KCl	0.01

The total hardness of the artificial water was tested by versenate titration each time a new supply was manufactured. The immediate result was always exactly as desired (412 ppm), varying between 405 and 420 ppm as CaCO_3 . However, a gradual increase was noted as testing progressed. Toward the end of the 58-1 series the hardness exceeded 600 ppm. This increase was due to the calcium impurities previously deposited at the bottom of the storage bottles, but this cause was discovered only after the 58-1 series had been completed. Thorough cleaning of the bottles each time before filling enabled the hardness to remain constant.

Sedimenting Agents

Agents used in the program were supplied by the Bureau of Reclamation from the samples obtained during the sedimenting operation in the field. For description of the Baroid bentonite and tetrasodium pyrophosphate, the reader is referred to Chapter III.

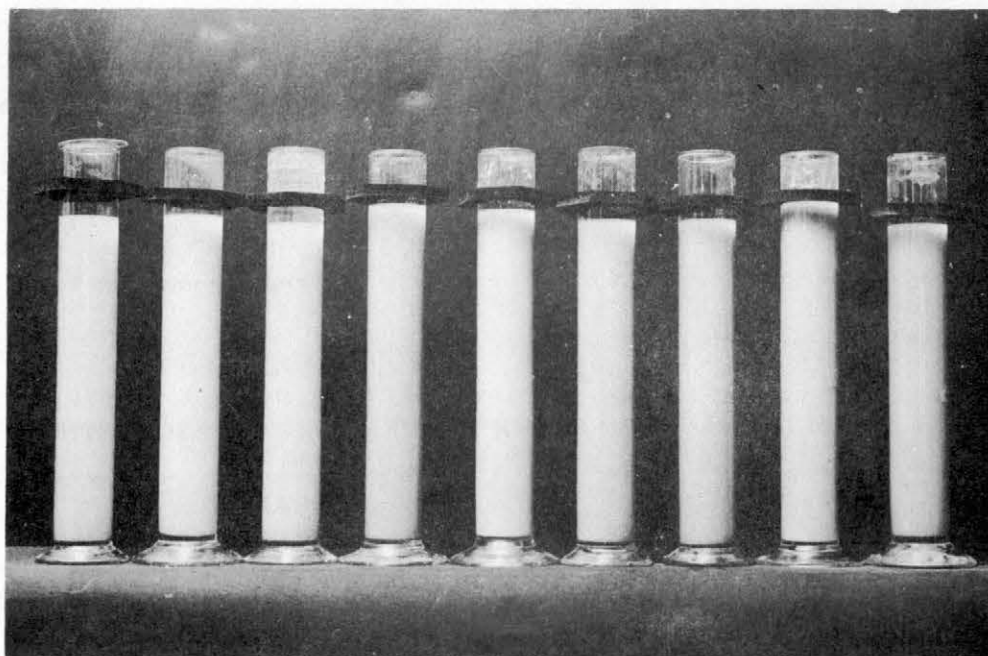


Fig. 31 View of the cylinders at the beginning of the flocculation and dispersion test. CSU photo.

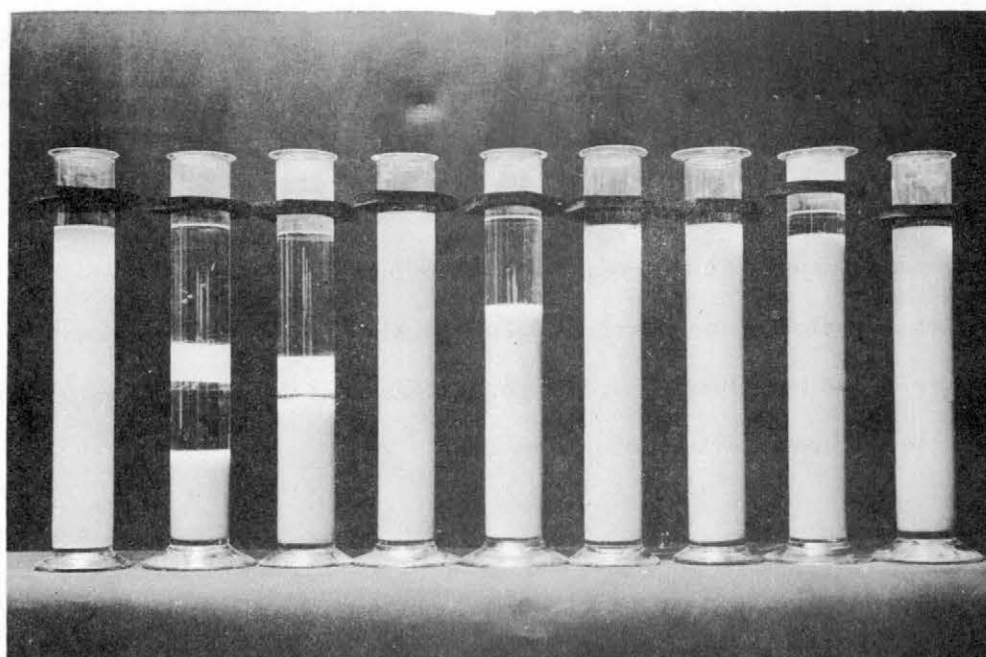


Fig. 32 View of the same cylinders at the end of 72 hours. From left to right: 0.5% bentonite in distilled water; in hard water; in hard water with 7% dispersant; 1.0% bentonite in distilled water; in hard water; in hard water with 7% dispersant; 1.5% bentonite in distilled water; in hard water; in hard water with 7% dispersant. CSU photo.

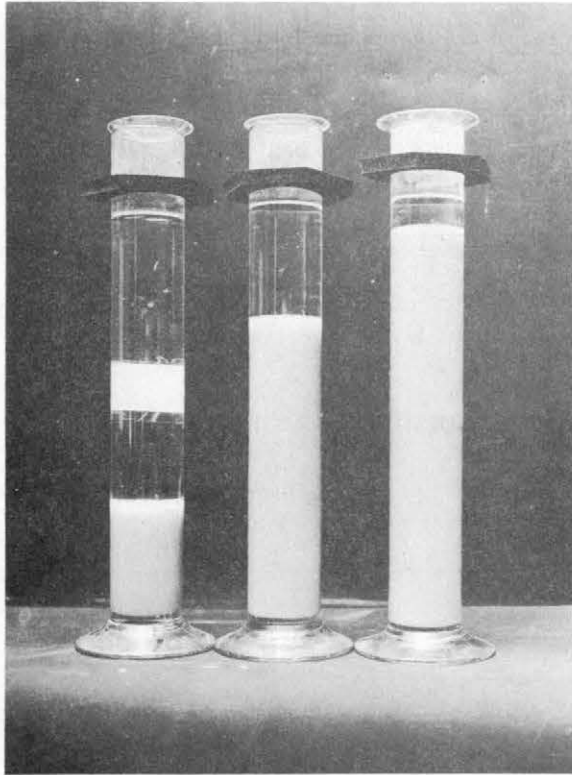


Fig. 33 Close-up view of three cylinders from Fig. 32, showing the softening ability of the bentonite itself. Left to right: 0.5% bentonite, 1.0% bentonite, and 1.5% bentonite all in hard water without dispersant. CSU photo.

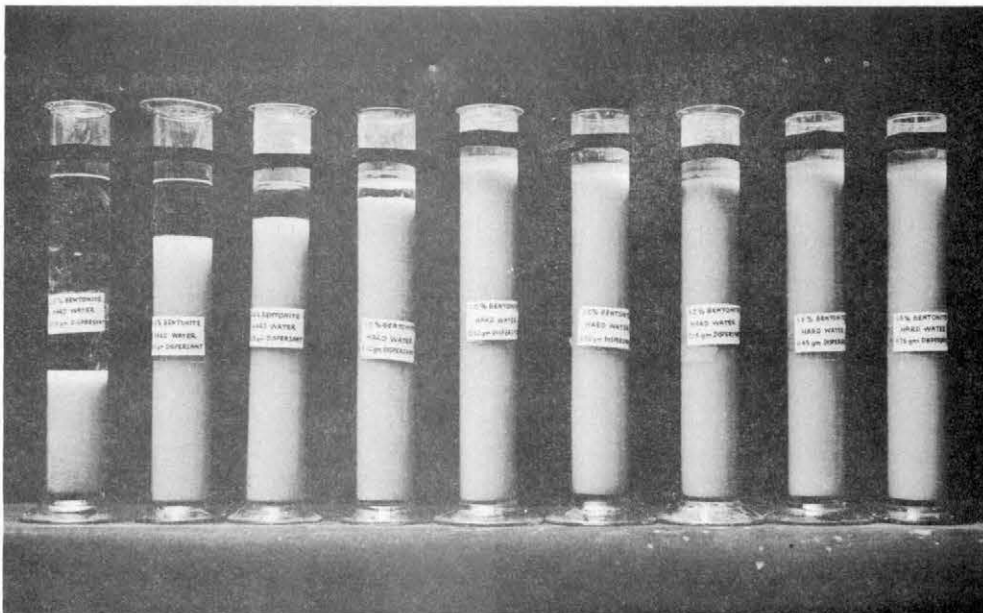


Fig. 34 View of cylinders at the end of 72 hours. From left to right: 0.5% bentonite with 1% dispersant; 3% dispersant; 5% dispersant; 1.0% bentonite with 1% dispersant; 3% dispersant; 5% dispersant; 1.5% bentonite with 1% dispersant; 3% dispersant; 5% dispersant. CSU photo.

A series of flocculation and dispersion tests was made on these materials. Distilled water and the artificial hard water were used to mix the bentonite in liter-cylinders at various concentrations and with various amounts of dispersing agent. In each case a thicker slurry was mixed in a high speed rotary mixer and then diluted to the desired concentration. The cylinders were allowed to stand for three days; and the behavior of each was noted everyday. In Table 13 is a list of the tests made.

TABLE 13 -- TESTING OF FLOCCULATION AND DISPERSION OF VARIOUS BENTONITE MIXES

BENTONITE	DISTILLED WATER (1000 ml)			HARD WATER (1000 ml)		
	0.5%	1.0%	1.5%	0.5%	1.0%	1.5%
	5 gm	10 gm	15 gm	5 gm	10 gm	15 gm
Dispersant						
0%	0 gm	0 gm	0 gm	0 gm	0 gm	0 gm
1%				.05 gm	.10 gm	.15 gm
3%				.15 gm	.30 gm	.45 gm
5%				.25 gm	.50 gm	.75 gm
7%				.35 gm	.70 gm	1.05 gm

Figs. 31 to 34 show the results of these tests. For bentonite suspensions of 0.5 per cent, even 7 per cent dispersant could not maintain deflocculation for three days in the artificial hard water. For bentonite suspensions of 1.0 per cent, 5 per cent dispersant was sufficient; and this was to be used in the experiments required dispersed bentonite suspensions. It may be noted that these results are consistent with those obtained at the Bureau laboratories (see Chapter II, page 10).

IX. EXPERIMENT PROCEDURE

In the 1958 laboratory program two series of runs were made: 58-1 with flocculated bentonite treatment and 58-2 with dispersed bentonite treatment. The first series was intended to reproduce the conditions during the actual installation when the sedimenting mix had a flocculating tendency. The mix followed the same proportions as used in the field, i.e., 70 sacks of dispersant to 4812 sacks of bentonite or 1.46 per cent. The second series was intended to find out how the results would differ with a dispersed mix, and 5 per cent dispersant by weight of bentonite was used, as mentioned in the previous chapter. In both cases a nominal one per cent mix was used, i.e., the air-dry weight of bentonite being 1 per cent.

Apparatus

The permeameters were made of plexiglass with an inside diameter of 6.3 cm (2.5 in.). This dimension differed slightly with individual sets. For computation of data, each permeameter was carefully measured with calipers in four directions at both ends. The average of the eight readings was used to calculate its cross-sectional area. The headwater elevation was maintained constant by a Mariette siphon and the tailwater elevation was fixed at the bottom level of the soil column. The difference in elevation between the headwater and the tailwater was about 120 cm (47 in.). The length of the soil column was about 43 cm (17 in.), and this leaves a water depth of 76 cm (2.5 ft) above the soil surface, which is the estimated average in the canal. The over-all hydraulic gradient was therefore 2.79. However, these dimensions varied slightly with each run, and generally the over-all hydraulic gradient was calculated to be approximately 2.75.

The design of the permeameter and its assembly are shown in Fig. 35. The joints were sealed by water-proof grease and plastic tape. Two sheets of thin fiber glass were used at the bottom of the soil column; these acted as a filter and allowed water to flow through freely.

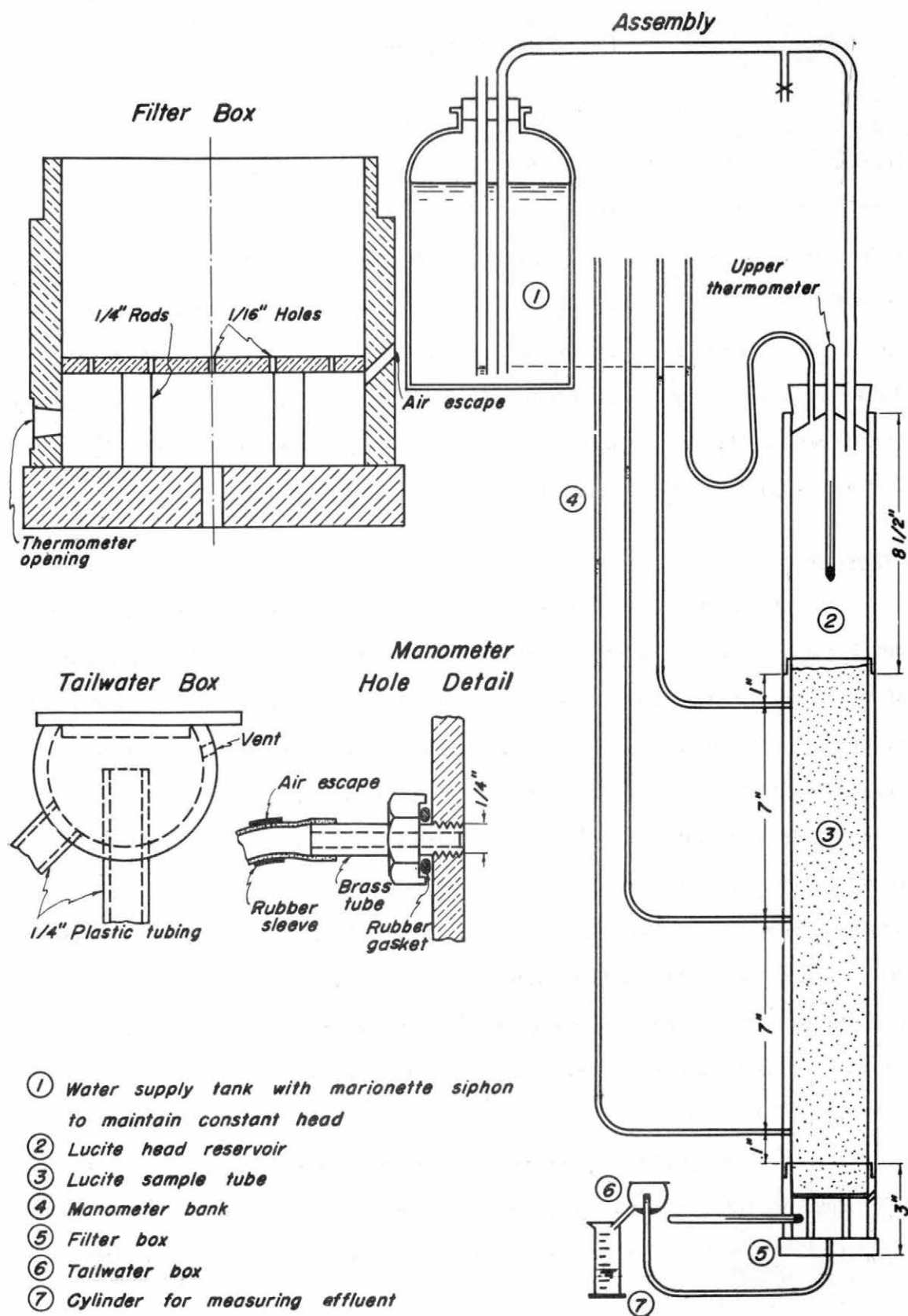


Fig. 35 Design and assembly of the permeameter system.

Schedule

Within each series of tests the runs were divided into a "dry" group and a "wet" group. In the "dry" group the sedimenting treatment was applied to the soil at the same moisture content as when it was packed. In the "wet" group the pre-sedimenting permeability was determined by actual measurement. This necessarily increased the original moisture content. Since the amount of this increase was indeterminable the results obtained from the "wet" runs were difficult to interpret. In the 58-2 series, all the "wet" runs were eliminated except the saturated case. The test schedule is presented in the following table.

TABLE 14 -- TESTS IN THE 1958 PROGRAM

SERIES 58-1 (Treatment with flocculated bentonite suspensions)							
In-Place Moisture	Saturated		18 per cent		12 per cent		6 per cent
	Wet	Dry	Wet	Dry	Wet	Dry	Wet Dry
Run	1A		2A	2K	3A	3K	4A 4K
	1B		2B	2L	3B	3L	4B 4L
	1C						4C

SERIES 58-2 (Treatment with dispersed bentonite suspensions)			
In-Place Moisture	Saturated		8 per cent
	Wet		Dry
Run	1A		4K
	1B		4L
	1C		4M
			4N

Note: The runs are numbered in descending order of in-place moisture content. The letters appended to the run numbers simply denote duplicate runs: A, B, . . . for wet runs, K, L, . . . for dry runs. The runs designated by C and M were for microscopic examination, others for chemical evaluation.

Loading

Each column contained 2200 gm of air-dry soil. After the soil was weighed, it was stored in a plastic bag and the desired amount of water was added for a definite moisture content. This bag was then sealed and allowed to stand for several days until the moisture was evenly distributed within the soil. Packing consisted of dropping the prepared soil into the permeameter by increments, and tamping with a steel rod. When

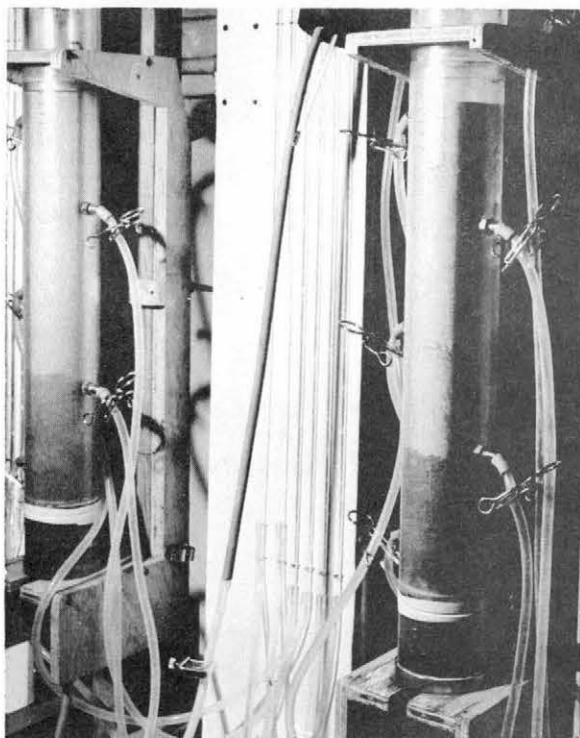


Fig. 36 View of the soaking process to saturate the soil columns. Note the evenness of the wet-front also the almost equal speed of imbibition. CSU photo.

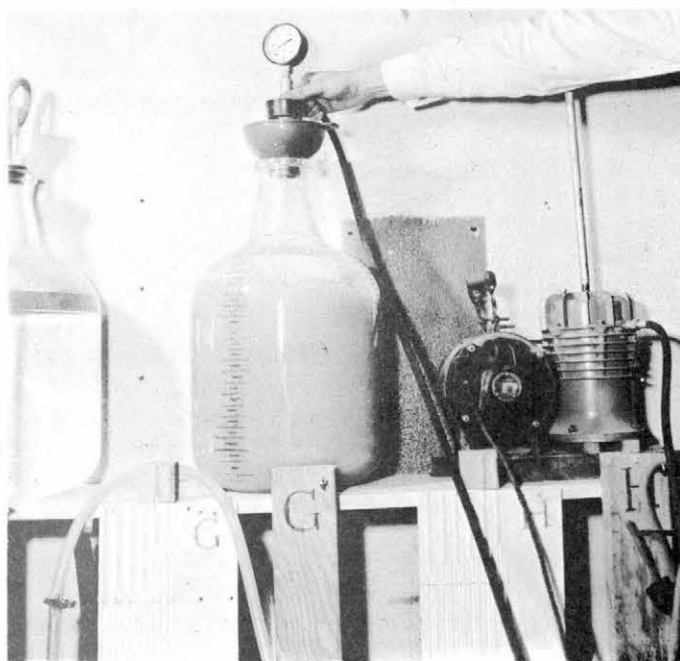


Fig. 37 View of the jetting operation during the preparation of bentonite suspensions. Air jets under a pressure of 10 lb per sq in. help to dilute the 6% slurry to a 1% concentration. CSU photo.

all the soil was dropped the surface was smoothed with the aid of a plunger (see the Appendix for the design of the plunger). Mild tapping on the outside of the cylinder reduced the level of the column to a predetermined mark so that the over-all density was 1.62 gm per c.c. The packing was assumed to be sufficiently uniform and this can be confirmed by witnessing the uniformity of flow of the wetting front when water was introduced (Fig. 36).

In the case of saturated runs, the soil was packed dry and a small stream of water was entered from beneath the column. The very slow process of imbibition was used in order to drive all the air out of the soil. When the soil column had been soaked sufficiently water was introduced to the top, and the flow process was reversed. In all other cases the introduction of either water or bentonite suspensions was from the top, gradually until the headwater level reached 2.5 ft.

Sedimenting Treatment

The mixing of bentonite was first done with a high speed rotary mixer to make a 6 per cent slurry, which was then diluted to one per cent concentration with a blower-type mixer. These seemed to be a reasonable simile to the actual field procedure. Fig. 37 shows the mixing in progress. The design of the mixer is included in the Appendix.

The bentonite suspensions were allowed to stand for 24 hours before being introduced to the soil columns. The sedimenting treatment lasted about 48 hours in each case. At the end of this period, the suspensions were siphoned out, and the filter cake deposited on the surface was removed with a spatula.

Measurement of Percolation

Soon after the entire head of 76 cm was applied to a column, the manometers were set to work; all air bubbles were expelled from the tubes. The effluent was collected into graduated cylinders. Readings were taken frequently. Each reading was usually of 20-minute duration and most readings were taken at 8-hour intervals. During each reading the effluent was measured, the temperatures above and below the columns

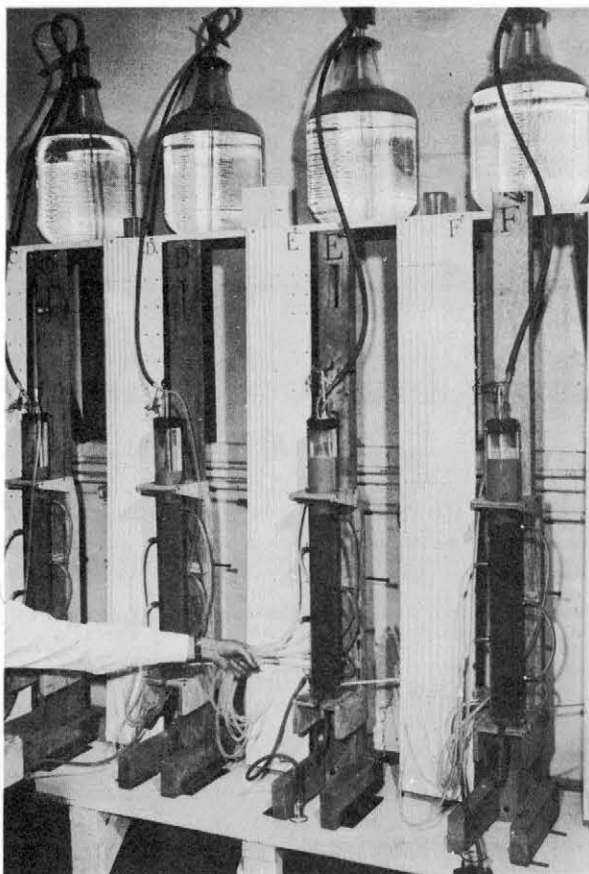
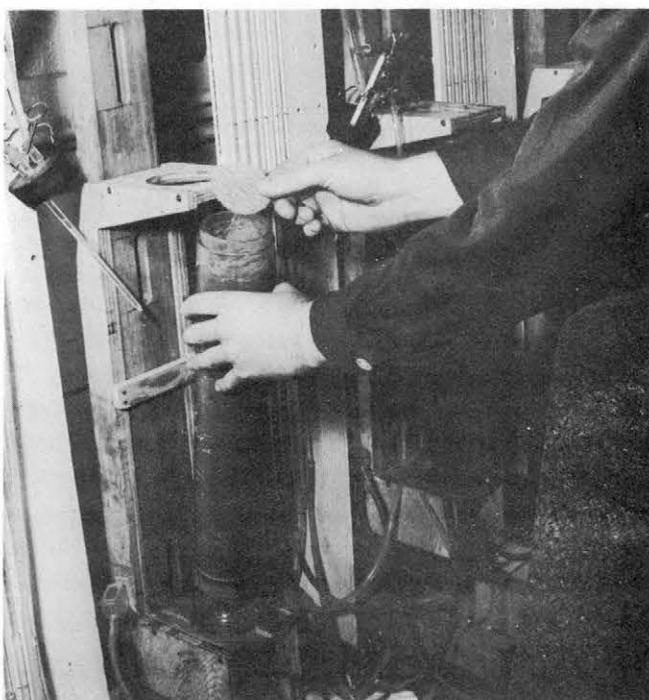


Fig. 38 View of permeameter assemblies during a treatment with flocculated bentonite suspensions. A typical surface seal is evident in permeameter E, reflected by the excessive difference in readings between its first and second manometers. CSU photo.

Fig. 39 A sample being protected by a layer of glass fiber before being sealed for shipment to petrographic laboratories for microscopic examination. CSU photo.



were recorded, changes in soil column lengths were noted, and the manometer readings were taken with a ruler that was marked to yield directly the hydraulic gradient between manometer tappings. Between readings the effluent was collected into large graduated cylinders unless the percolation rate was too high to be handled conveniently. Fig. 38 shows a typical reading in progress.

Sampling for Post-treatment Evaluation

The samples were prepared in two groups. Runs designated by the letters C and M were used for microscopic examination, the others were used in a series of chemical analysis.

Preparation for petrographic examination -- The water above the soil column was removed by siphoning, and the upper portion of the permeameter was disjoined. Two thin sheets of fiber glass (the same material used at the bottom of the permeameter before loading) were placed on top of the soil column. A parafin seal was poured in to water-proof the top end. The manometer taps were plugged with brass screws. The thermometer at the bottom was removed. The filter box was completely filled with water and a cork was placed in the thermometer opening. Later an aluminum cap was substituted for the parafin seal. This cap consisted of two blocks of aluminum with a thick layer of rubber between them. When the cap was put in place, a wing nut could be tightened to bring the aluminum blocks closer so that the rubber would be squeezed to expand laterally, gripping against the inside wall of the cylinder. Samples packed in this way were transferred to the Bureau of Reclamation Denver Laboratories for petrographic examination.

Preparation for chemical analysis -- After the water above the column and the upper portion of the permeameter were removed, the cylinder containing the soil was weighed. The soil column was then slipped out with the help of a plunger (described in the Appendix), care being taken to disturb the soil structure as little as possible. This process was done by stages so that slices of sample could be obtained and stored in paper boxes (Fig. 41). The samples were all 2 cm thick, taken at the following levels:

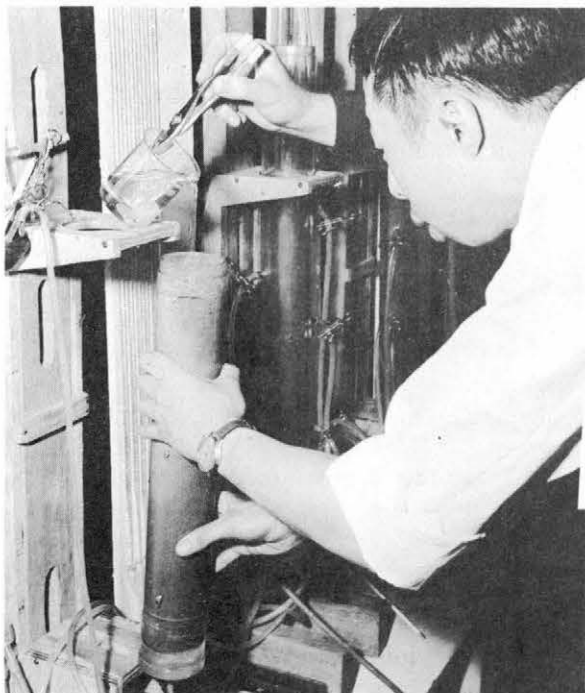


Fig. 40 Pouring parafin over the sample after the glass fiber layer is in place. Note the brass plugs used to seal the manometer taps. CSU photo.

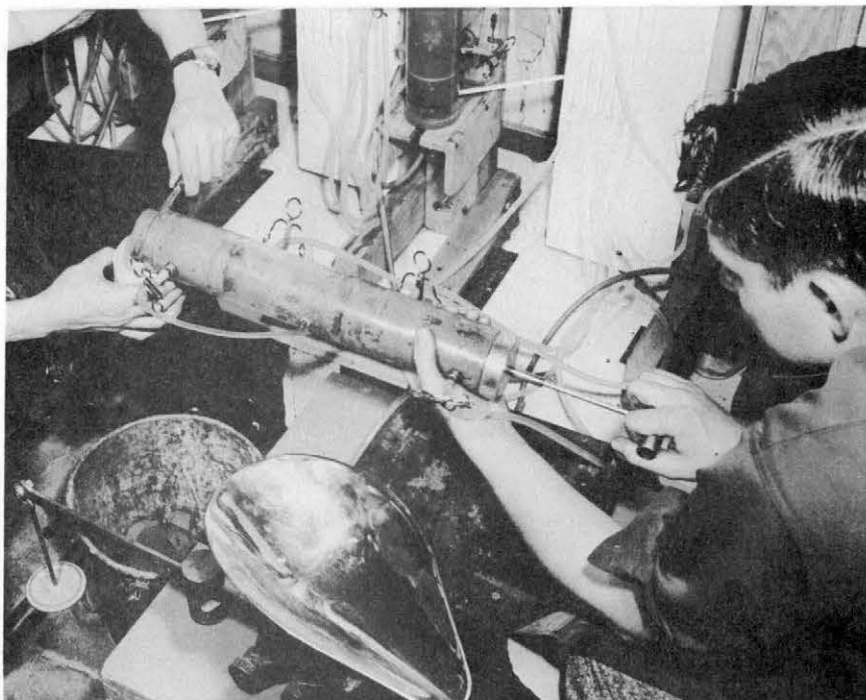


Fig. 41 A column is being sampled after a run. The plunger is being used to push the column through the permeameter. The balance is for determination of the final moisture content. CSU photo.

Top 2 cm

2 - 4 cm

6 - 8 cm

12 - 14 cm

22 - 24 cm

Bottom 2 cm

Samples prepared in this way were transferred to the Department of Soils of the University for evaluation by chemical analysis. The permeameter was then washed, cleaned, and weighed. From the weighing the amount of water ultimately present in the soil could be calculated. Unfortunately no balance having simultaneously the required capacity and accuracy was available; therefore the results could not be used for absolute comparison.

X. EVALUATION TESTS

On completion of the runs, two methods of analyzing the soil columns were used: a chemical testing and a microscopic examination. The chemical testing was performed in the Soils Department of the University under the direction of Professor R. S. Whitney; the microscopic examination in the Petrographic Laboratory of the Bureau of Reclamation by Mr. S. Rubenstein.

Chemical Analysis

Methods used in this analysis are those recommended by the U. S. Department of Agriculture (19). The following is a list of determinations made and their corresponding method numbers as designated in Ref. 19.

- a. Electrical Conductivity, No. 4a
- b. Sodium, No. 10a
- c. Exchangeable Cations, No. 18
- d. Cation Exchange Capacity, No. 19
- e. Exchangeable Sodium Percentage, No. 20a

Since it was important to obtain analytical information for different levels along the soil columns, results from thick samples would be inexplicit. It was therefore deemed necessary to slice the columns into samples no thicker than 2 cm. These samples did not contain sufficient soil for saturated paste to be used for extracts. A slight modification had to be adopted. The moisture content at saturation was determined to be 21.0 per cent. This figure was multiplied by 1.5 to obtain 31.5 per cent. An amount of water equivalent to 31.5 per cent of the weight of the soil was added to each sample, and the resultant mixture was used for testing. Since there was abundant pre-run samples, both methods -- saturated extract and diluted extract -- were used on them to confirm the validity of this modification. It was found that the two results differed only in the second decimal.

Samples were covered tightly with pliofilm and allowed to stand for 4 to 16 hours. They were then thoroughly mixed and immediately filtered by means of Buchner funnels. From 6 to 12 ml of extract was usually obtained, which was briefly centrifuged for clarification. Partial results are tabulated in Table 15 (see the Appendix for complete results).

TABLE 15 -- DETERMINATION OF PENETRATION BY CHEMICAL ANALYSIS

SOIL SAMPLE RUN	DEPTH ¹ (cm)	CATION EXCHANGE CAPACITY (meq/100 gm soil)	EXCHANGEABLE SODIUM PERCENTAGE (%)
Series 58-1 (Flocculated Bentonite Treatment)			
A, B, C	Pre-run	6.9	1.17
K, L	Pre-run	6.6	0.91
1A	Top 2	7.8	0.55
	2-4	8.0	0.95
	4-6	8.2	0.88
	12-14	8.0	0.76
	22-24	7.4	0.80
	Bottom 2	7.6	0.89
1B	Top 2	8.9	0.80
	2-4	8.7	0.82
	6-8	8.0	0.76
	12-14	8.2	0.70
	22-24	7.9	0.63
	Bottom 2	7.6	0.74
2A	Top 2	6.4	3.60
	2-4	7.0	3.68
	6-8	7.2	4.24
	12-14	7.2	3.56
	22-24	7.6	2.79
	Bottom 2	7.5	1.89
2B	Top 2	7.6	3.44
	2-4	8.0	3.08
	6-8	8.8	3.22
	12-14	7.6	3.72
	22-24	7.7	2.99
	Bottom 2	7.2	2.54
2K	Top 2	7.1	0.82
	2-4	7.1	1.10
	6-8	7.1	1.27
	12-14	7.4	1.53
	22-24	8.1	1.51
	Bottom 2	7.8	1.46

¹ Bottom 2 cm was at approximately 41-43 cm depth.

TABLE 15 -- DETERMINATION OF PENETRATION BY CHEMICAL ANALYSIS
Continued

SOIL SAMPLE RUN	DEPTH (cm)	CATION EXCHANGE CAPACITY (meq/100 gm soil)	EXCHANGEABLE SODIUM PERCENTAGE (%)
Series 58-1 (Flocculated Bentonite Treatment) -- Continued			
2L	Top 2	8.8	2.26
	2-4	9.0	2.05
	6-8	8.2	2.00
	12-14	7.9	1.86
	22-24	7.4	1.92
	Bottom 2	7.1	2.27
3A	Top 2	7.9	2.67
	2-4	8.3	3.04
	6-8	7.9	2.97
	12-14	7.8	1.47
	22-24	7.2	3.00
	Bottom 2	7.1	3.35
3B	Top 2	8.6	3.20
	2-4	8.2	3.30
	6-8	8.1	3.20
	12-14	8.0	3.29
	22-24	8.0	3.62
	Bottom 2	7.4	2.40
3K	Top 2	9.4	2.66
	2-4	9.8	2.55
	6-8	8.8	2.67
	12-14	8.6	3.00
	22-24	8.4	3.33
	Bottom 2	9.8	2.06
3L	Top 2	7.6	1.55
	2-4	7.2	1.94
	6-8	7.0	2.30
	12-14	7.3	1.79
	22-24	7.2	2.01
	Bottom 2	7.6	1.71
4A	Top 2	8.6	0.92
	2-4	8.2	0.78*
	6-8	8.2	1.93
	12-14	8.2	2.73
	22-24	8.2	1.86
	Bottom 2	8.2	1.76
4B	Top 2	8.8	1.01
	2-4	8.7	1.37
	6-8	8.2	0.93
	12-14	8.4	0.82
	22-24	8.8	1.53
	Bottom 2	8.2	1.62

* Probably low

TABLE 15 -- DETERMINATION OF PENETRATION BY CHEMICAL ANALYSIS
Continued

SOIL SAMPLE RUN	DEPTH (cm)	CATION EXCHANGE CAPACITY (meq/100 gm soil)	EXCHANGEABLE SODIUM PERCENTAGE (%)
Series 58-1 (Flocculated Bentonite Treatment) -- Continued			
4K	Top 2	8.0	2.02
	2-4	7.8	2.06
	6-8	7.5	1.80
	12-14	8.1	1.85
	22-24	8.8	1.92
	Bottom 2	8.3	1.89
4L	Top 2	8.2	2.18
	2-4	7.6	2.16
	6-8	7.1	1.90
	10-12	7.1	1.84
	16-18	7.2	1.80
	26-28	7.4	1.92
	Bottom 2	7.0	1.78
Series 58-2 (Dispersed Bentonite Treatment)			
1, 4	Pre-run	7.2	1.92
1A	Top 2	9.2	4.12
	2-4	9.2	3.60
	6-8	8.4	3.70
	12-14	8.6	3.48
	22-24	8.6	3.41
	Bottom 2	8.2	3.23
1B	Top 2	8.3	3.25
	2-4	7.5	3.15
	6-8	7.5	3.72
	12-14	7.2	3.54
	22-24	7.5	3.53
	Bottom 2	7.7	3.52
4K	Top 2	7.6	3.87
	2-4	7.0	3.80
	6-8	7.0	3.28
	12-14	7.2	3.17
	22-24	6.8	3.13
	Bottom 2	6.8	3.24
4L	Top 2	7.5	3.31
	2-4	7.1	3.20
	6-8	6.8	3.35
	12-14	7.0	3.21
	22-24	7.1	3.15
	Bottom 2	7.0	3.26
4N	Top 2	8.0	14.20
	2-4	7.5	7.68
	6-8	7.4	3.27
	12-14	7.5	2.01
	22-24	7.7	1.95
	Bottom 2	7.3	2.11

It may be seen that the penetration of bentonite, or, more accurately, the net resultant increase in clay, as reflected by the increase in cation exchange capacity was not impressive in any run. The change in exchangeable sodium percentage, however, was notable. In Run 4N of Series 58-2 the samples had been taken immediately after removal of the filter cake without the usual post-treatment run of hard water, hence the concentration of sodium near the top of the column. Further discussion of these results will appear in the next chapter, in which each run will be considered separately.

Microscopic Examination

The permeameter tubes containing the soil columns were sawed into 1 or 2-in. sections at various levels. These sections were then impregnated with a water-soluble wax having a melting point of 55°C. When the wax was set the specimens were ground to thin slices and made into slides for microscopic examination. Since there was no need for much heating to drive out the moisture before waxing, the original texture and structure of the samples remained largely unchanged through this process.

The general appearance of the sand surface is shown in Fig. 42. The material consisted of fairly uniform fine sand and silt, as found in the mechanical analysis (Fig. 28). The void spaces ranged up to the size of the large grains. Figs. 43 and 44 are microphotographs from Run 1C, Series 58-1, and Run 1C, Series 58-2, respectively. Both were horizontal sections taken within an inch of the top surface. Very little clay in the voids was discovered.

A study of the formation of the filter cake was made by sedimenting bentonite suspensions of one per cent concentration on a sand surface. It was found, by x-ray defraction, that the clay particles tended to orient themselves to lie parallel to the surface. One may envisage a bridging action across the void openings created by these plate-like montmorillonite particles. This possibility can explain the phenomenon of surface sealing without clay penetration. The appearance of the filter cake is shown in Fig. 45, which demonstrates that no visible penetration into the dune sand occurred in this system.

A detailed report on the above work, written by Mr. Sam Rubenstein of the Bureau of Reclamation, is included in the Appendix.



Fig. 42 Enlarged view of the surface of a tested soil column --
Magnification 12x. USBR Photo.



Fig. 43 Microphotograph of a thin horizontal section in the top inch of the soil column of Series 58-1, Run 1C -- Magnification 150x. USBR Photo.

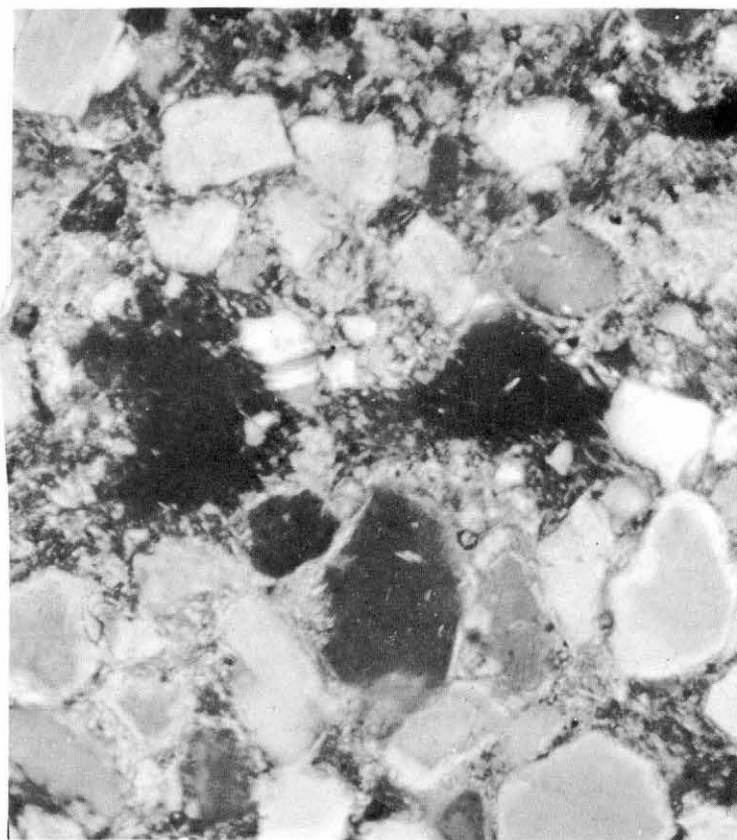


Fig. 44 Microphotograph of a thin horizontal section in the top inch of the soil column of Series 58-2, Run 1C -- Magnification 150x. USBR Photo.

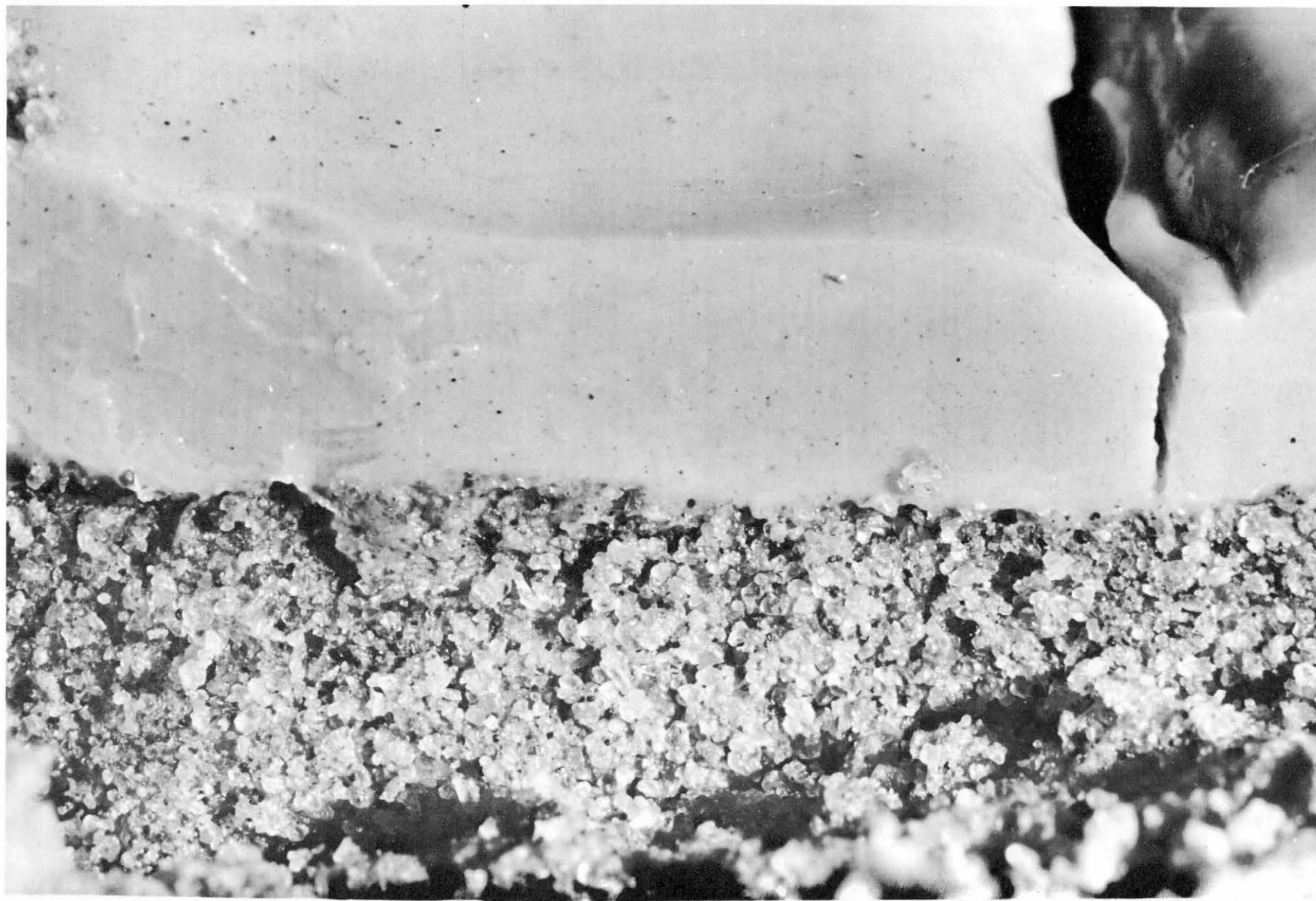


Fig. 45 Enlarged sectional view of a sedimented bentonite cake on the soil surface -- Magnification 17x . USBR Photo

XI. RESULTS

The results of the 1958 laboratory program are presented in detail in this chapter. It is necessary to consider the runs individually because the conditions under which all runs were made did not completely coincide notwithstanding the care exercised toward that end. Comparison of results from different runs will be found in the next chapter, which also contains a comprehensive discussion of the Lateral 1 undertaking as a whole.

Basis for Calculations

Although, for absolute comparison, the most appropriate term available to express soil status in regard to hydraulic flow is the intrinsic permeability (25), this term is not used in the present analysis of results. In its stead, the percolation rate (in cu ft per sq ft per day) is calculated. The underlying aim of these tests is to eliminate or reduce seepage, and the results must be transformed into terms applicable in the field. Most field measurements are based on this percolation rate, which concerns the actual loss of water quantitatively. In order to compute the percolation rates from laboratory data and render them comparable to each other, the discharge was corrected for temperature and over-all hydraulic gradient. The standard temperature was set at 20°C for a dynamic viscosity of 0.01005 poise (26), and the standard over-all hydraulic gradient was 2.75. The actual temperatures ranged from 17° to 25° and the actual over-all applied hydraulic gradient ranged from 2.71 to 2.85.

Series 58-1

This series was treated with flocculated bentonite suspensions with the concentration ranging from 0.9 to 1.0 per cent. Several values were used for initial moisture content: Run 1, saturated; Run 2, 18 per cent; Run 3, 12 per cent; and Run 4, 6 per cent. Two procedures were followed: the sedimenting treatment was introduced after an initial water permeability was determined for Runs A, B, and C; and the sedimenting treatment was introduced without the permeability determination for Runs K and L.

Run 1 -- Three tests were made in Run 1: A, B, and C (Figs. 46-48). The soil was packed in an air-dry state. Synthetic hard water was allowed to soak through the columns from below very gradually so that practically all the air would be driven out. This did not occur as can be seen from the increase in flow rate during the initial phase. The increase abated in approximately three days and the percolation rate became steady. Run A showed a maximum rate far lower than the other two runs for no apparent reason. The maximum relative seal was obtained in Run B -- the percolation rate was reduced by 90 per cent, to 1.5 cu ft per sq ft per day. A slight increase in clay and a decrease in sodium were found in Runs A and B. The soil column for Run C was examined microscopically and found to have a very small amount of penetration.

Run 2 -- Four tests were made in Run 2: A and B with an initial hard water phase; and K and L without the initial permeability determination (Figs. 49 to 52). The columns were loaded with sand containing 18 per cent moisture by weight. The initial permeability was very low. This may have been due to the moist packing. It was impossible to determine the extent of the sealing effect in any of the runs. Suffice it to say that the goal of 0.1 cu ft per sq ft per day was attained albeit the cause unknown. In Runs B and K, the soil columns were not even saturated when disassembled, therefore the air present in the soil could have contributed substantially toward the sealing. All the runs showed very slight increases in clay, while the sodium increases were considerable, especially in the "wet" runs.

Run 3 -- Four tests were made in Run 3: A and B with an initial hard water phase; and K and L without the initial permeability determination (Figs. 53 to 56). The columns were loaded with sand containing 12 per cent moisture by weight. The flocculated bentonite suspensions were applied for 48 hours. In Runs A and B, the initial percolation rate of about 0.4 cu ft per sq ft per day was reduced to about 0.1 cu ft per sq ft per day. In Run K the sealing was presumably equally effective. Run L showed almost no sealing. Some increase in clay and considerable increase in sodium could be detected in Runs A, B, and K; while Run L showed very little increase in either clay or sodium. The cause for this phenomenon can be traced to the removal

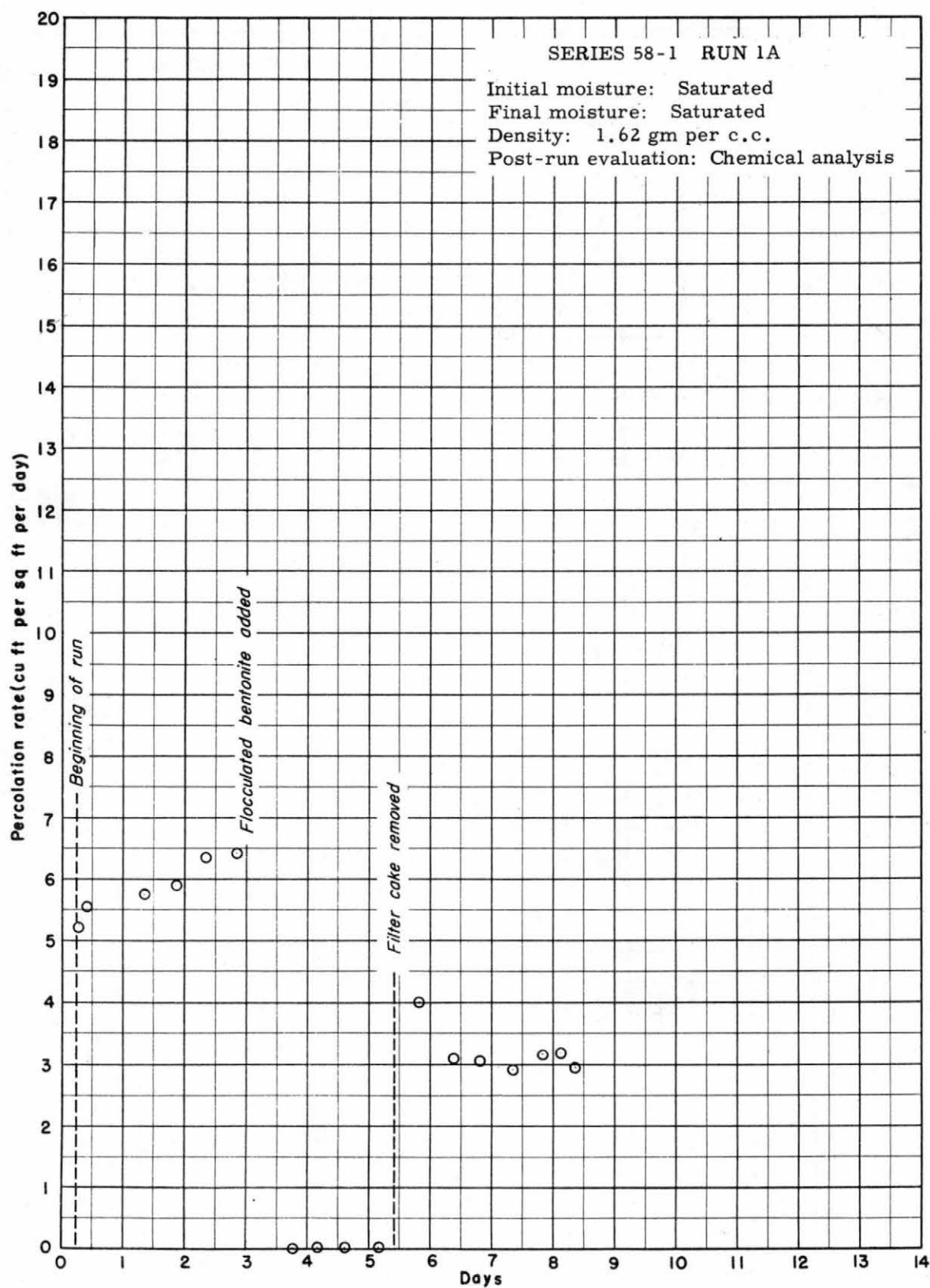


Fig. 46 Graphical representation of the history of percolation rate for 1A, Series 58-1.

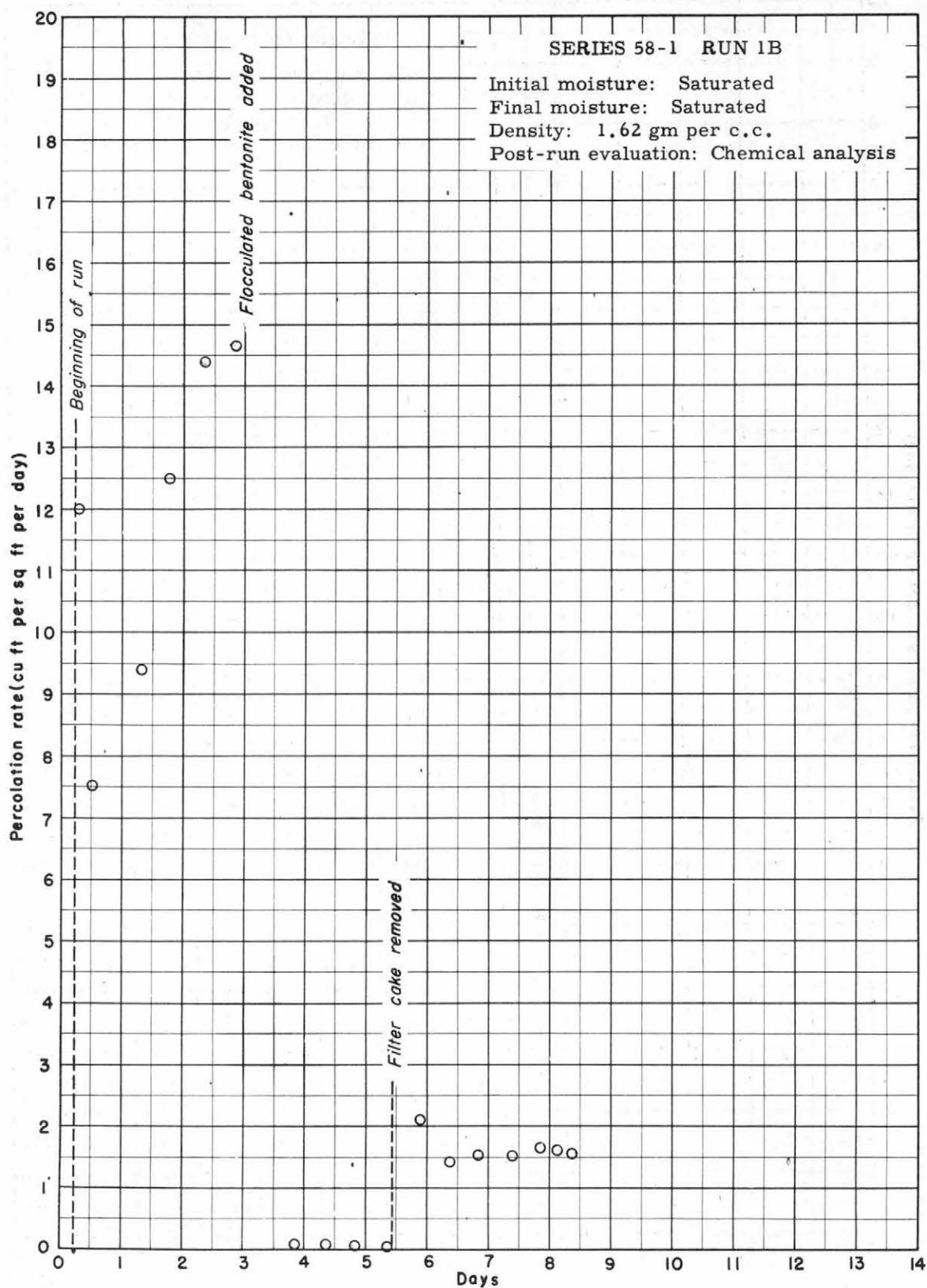


Fig. 47 Graphical representation of the history of percolation rate for 1B, Series 58-1.

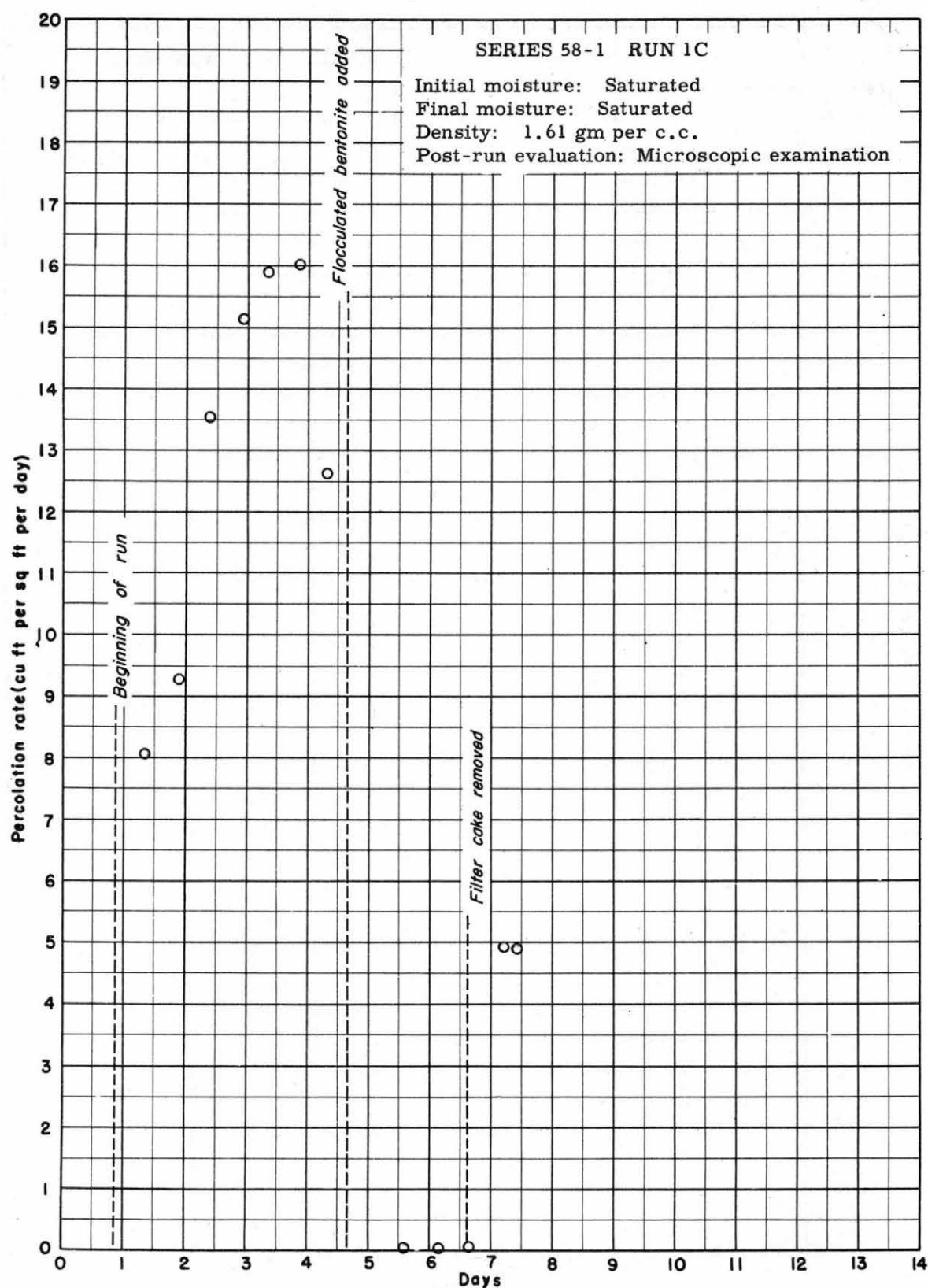


Fig. 48 Graphical representation of the history of percolation rate for 1C, Series 58-1.

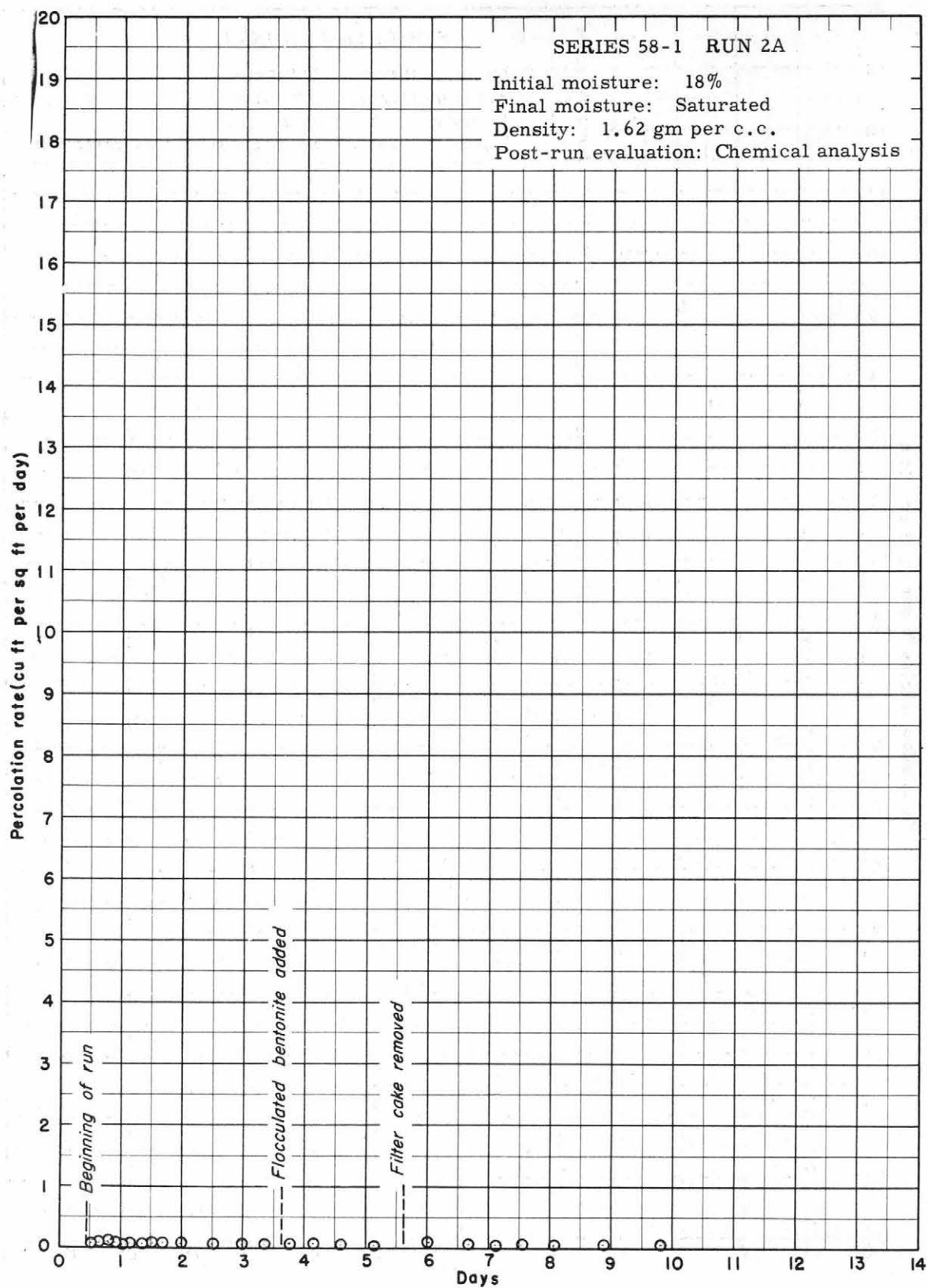


Fig. 49 Graphical representation of the history of percolation rate for 2A, Series 58-1.

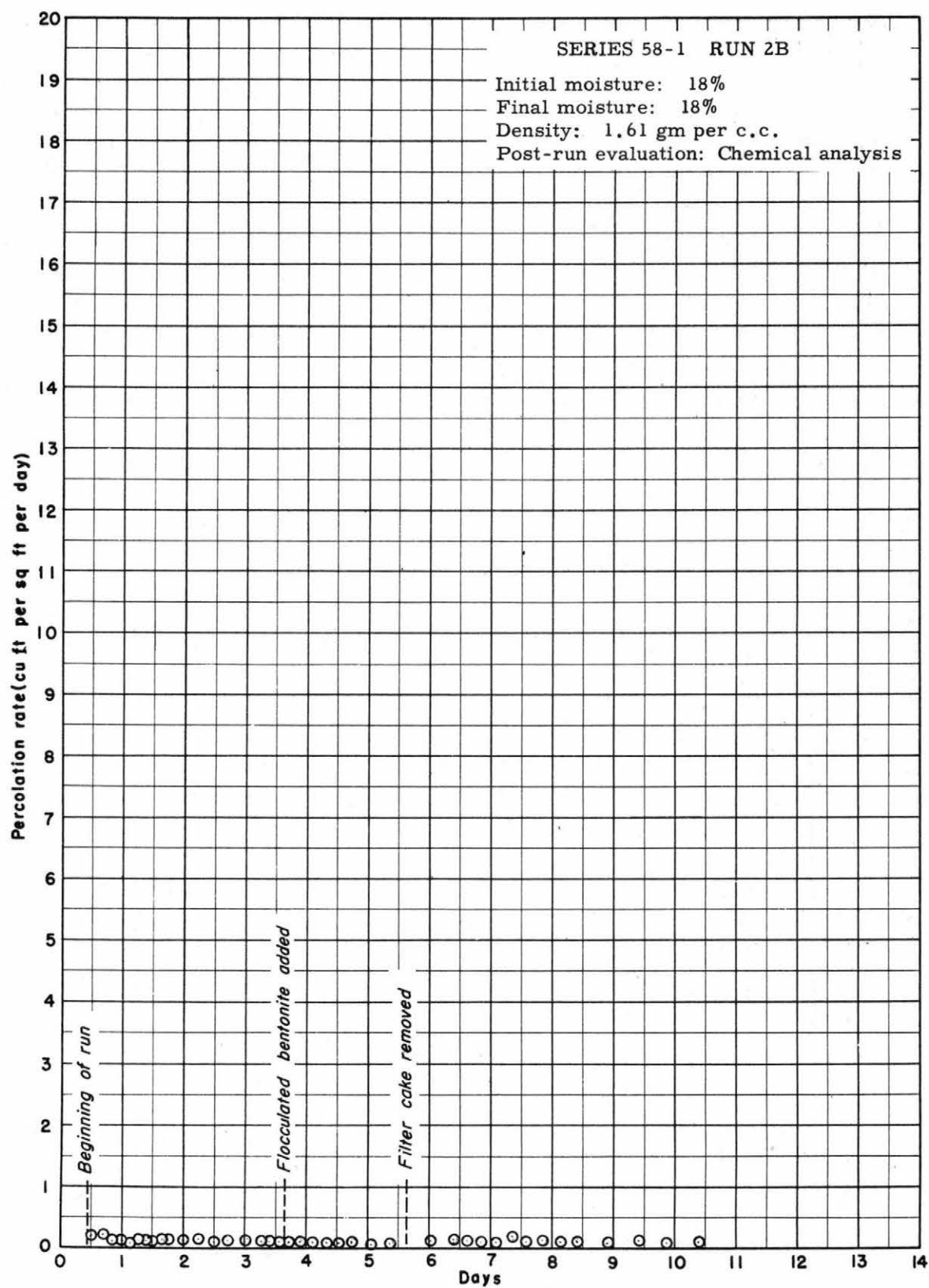


Fig. 50' Graphical representation of the history of percolation rate for 2B, Series 58-1.

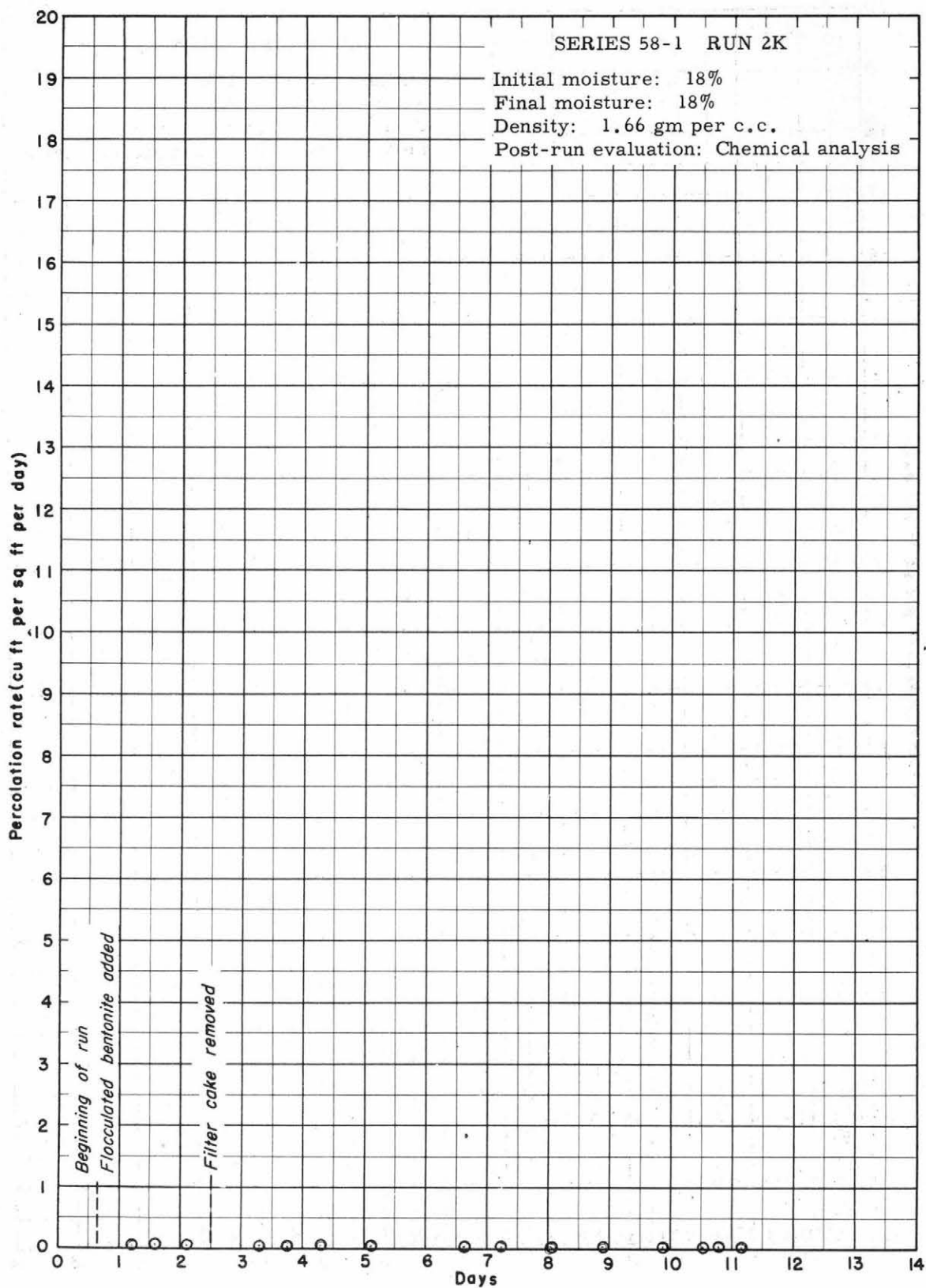


Fig. 51 Graphical representation of the history of percolation rate for 2K, Series 58-1.

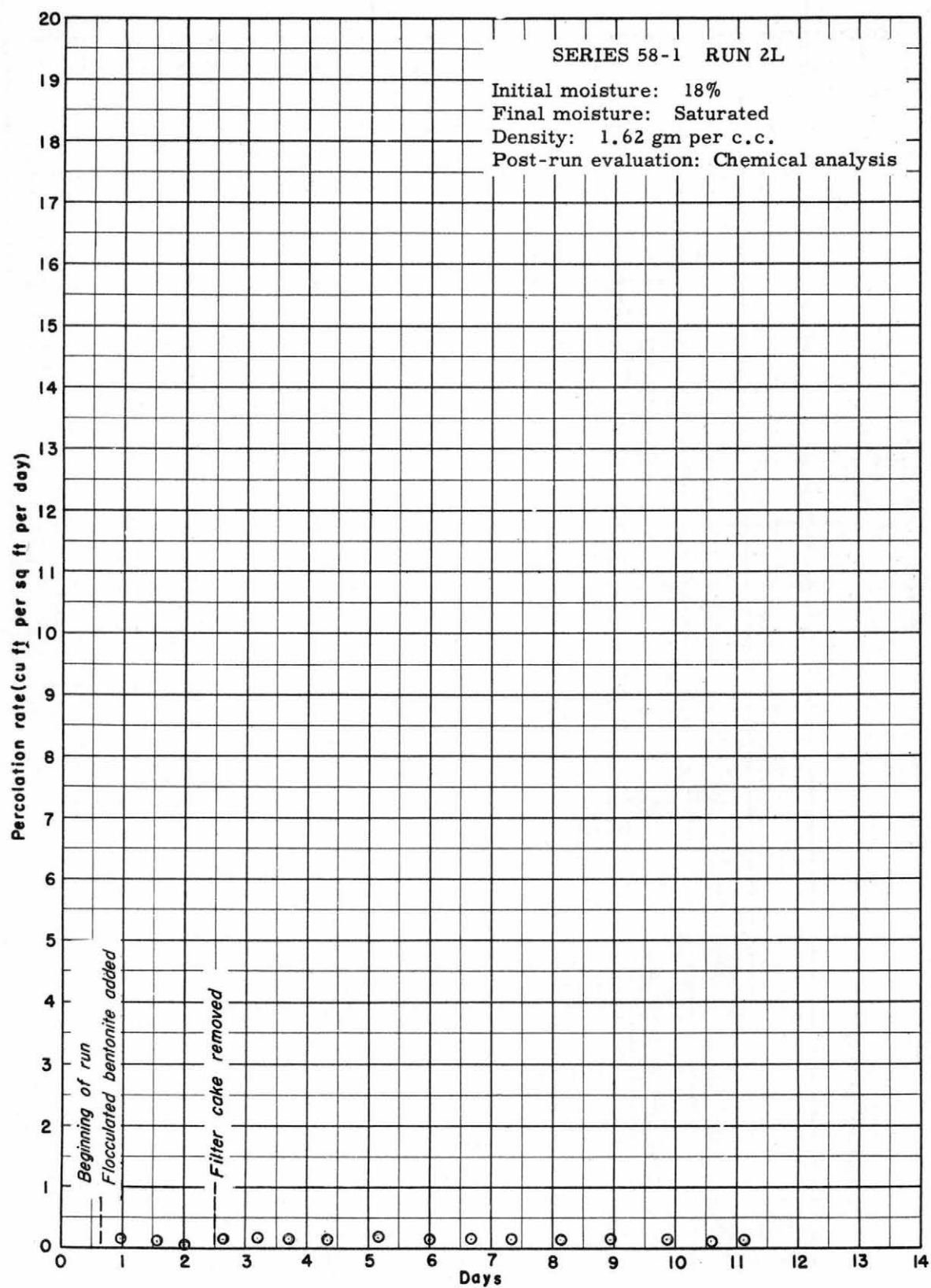


Fig. 52 Graphical representation of the history of percolation rate for 2L, Series 58-1.

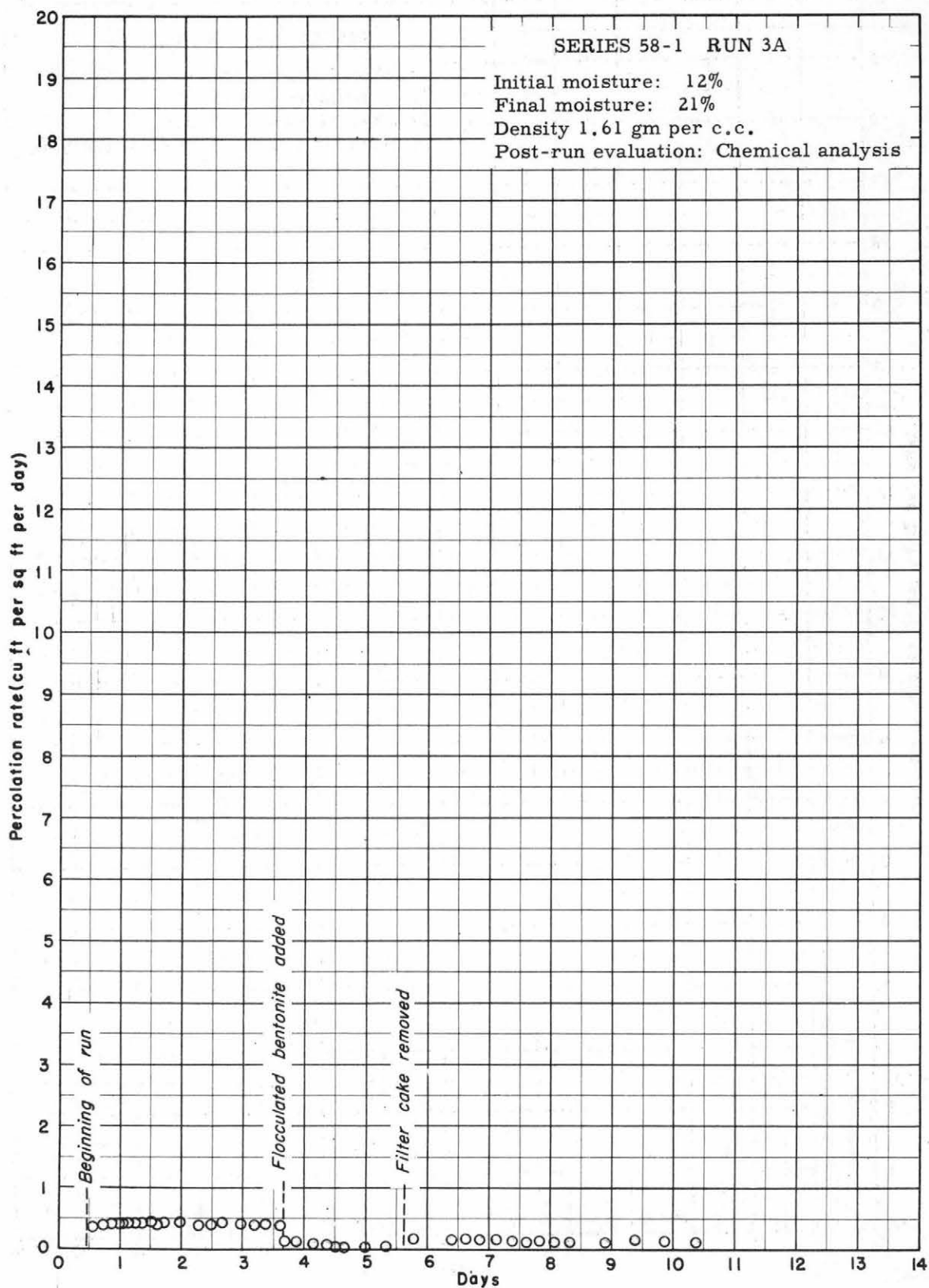


Fig. 53 Graphical representation of the history of percolation rate for 3A, Series 58-1.

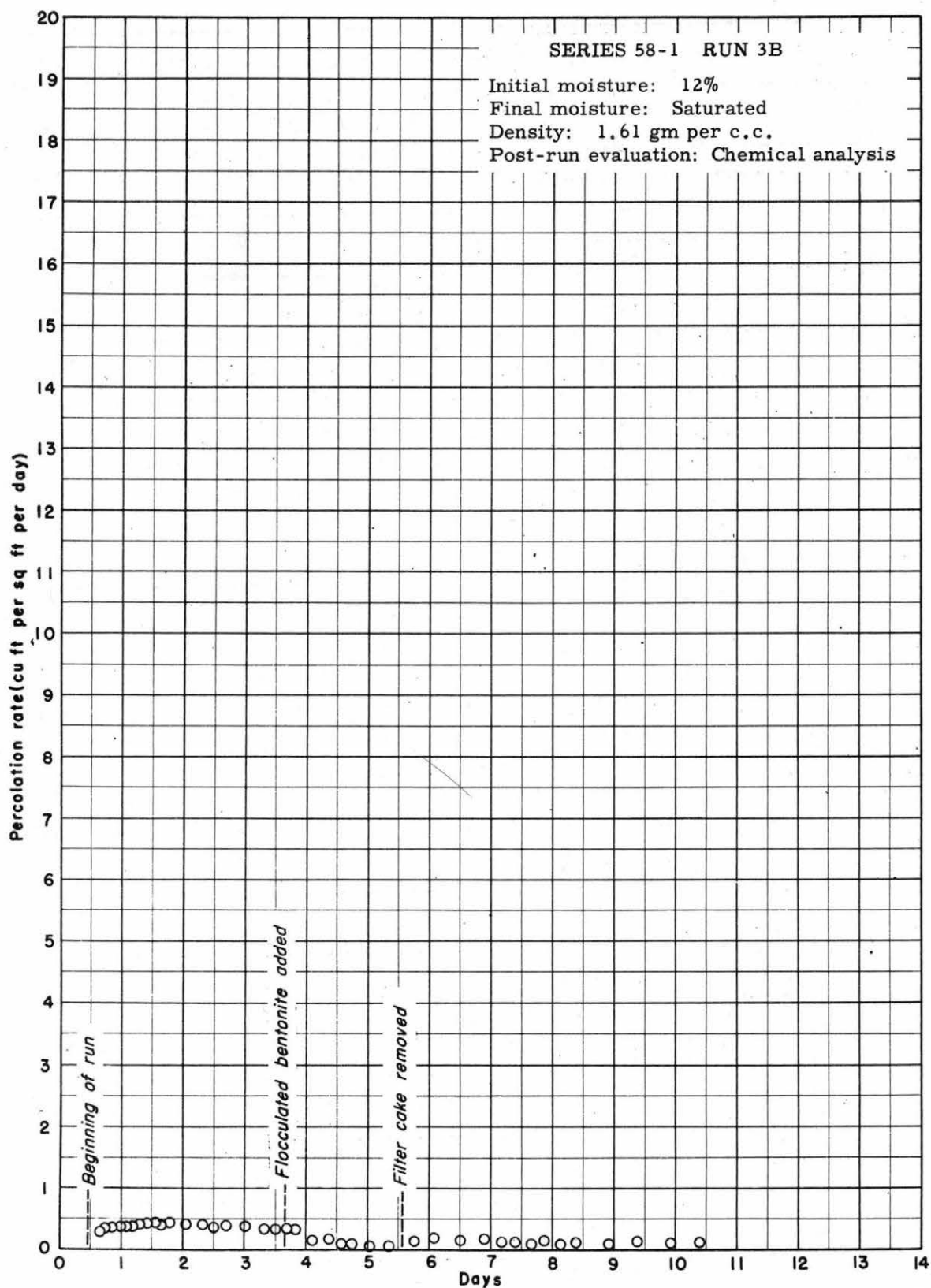


Fig. 54 Graphical representation of the history of percolation rate for 3B, Series 58-1.

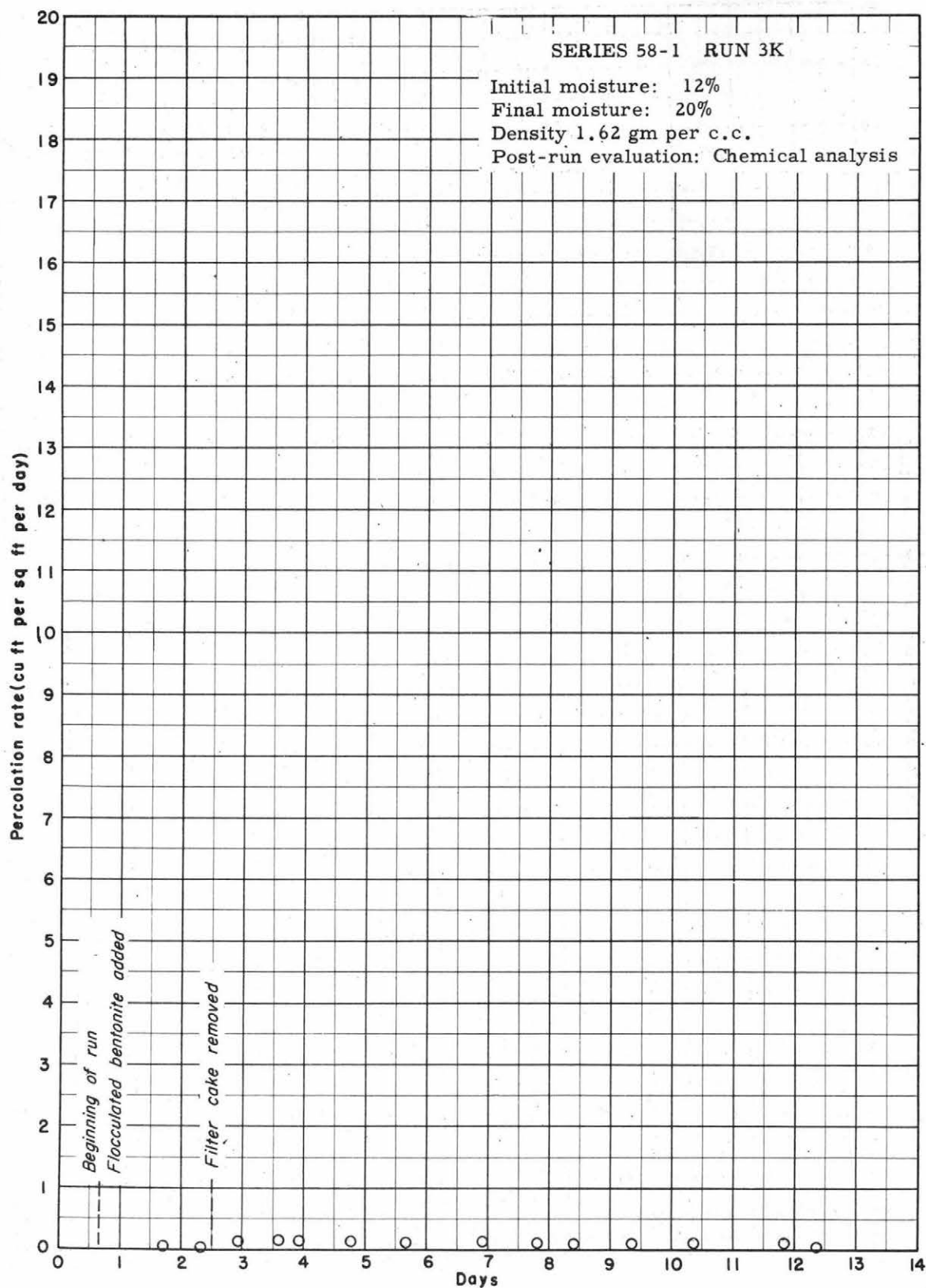


Fig. 55 Graphical representation of the history of percolation rate for 3K, Series 58-1.

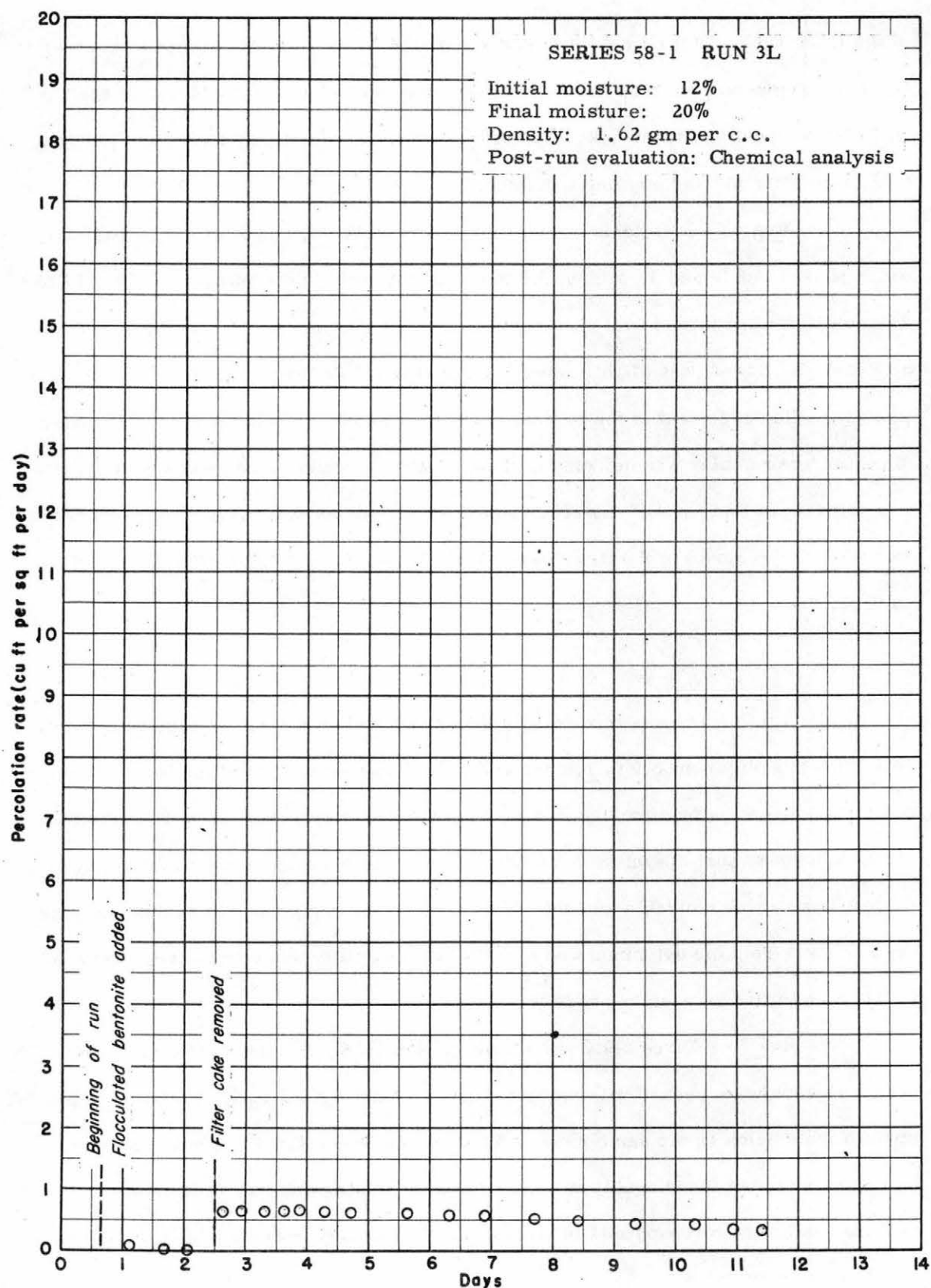


Fig. 56 Graphical representation of the history of percolation rate for 3L, Series 58-1.

of the filter cake. In the first three cases only the filter cake was scraped off with very little soil removed, whereas in the last case an appreciable amount of soil at the top was removed with the filter cake. It follows that much of the clay and sodium migration took place after the sedimenting treatment.

Run 4 -- Five tests were made in Run 4: A, B, and C with an initial hard water phase; and K and L without the initial permeability determination (Figs. 57 to 61). The columns were loaded with sand containing 6 per cent moisture by weight. The overall density in Run A was slightly low, but this was not reflected in the initial percolation rate. No agreement in the initial permeability was found among the "wet" runs. More increase in clay was detected in Runs A and B, while more increase in sodium was detected in Runs K and L. The reason for this is not apparent. The percolation rate after the removal of the filter cake in no case decreased to below 0.1 cu ft per sq ft per day.

Series 58-2

This series was treated with dispersed bentonite suspensions, with the concentration ranging from 0.9 to 1.0 per cent. Two values were used for initial moisture content: Run 1 at saturation; and Run 4 at 8 per cent. Experience from the previous series had shown that the initial hard water phase would increase the initial moisture content to an undeterminable amount. To avoid further complexity in evaluation work created therefrom, the determination of initial permeability was eliminated. Therefore, in Run 4 no initial hard water phase was used.

Run 1 -- Three tests were made in Run 1: A, B, and C (Figs. 62-64). The permeameters were packed with air-dry sand. Synthetic hard water was allowed to soak through from below in the same manner as in Series 58-1, Run 1. The initial percolation rates were not found equal, nor were the final sealing effects. It is interesting to note that each test corresponded in values to a similar test in Series 58-1, as shown in the following tabulation.

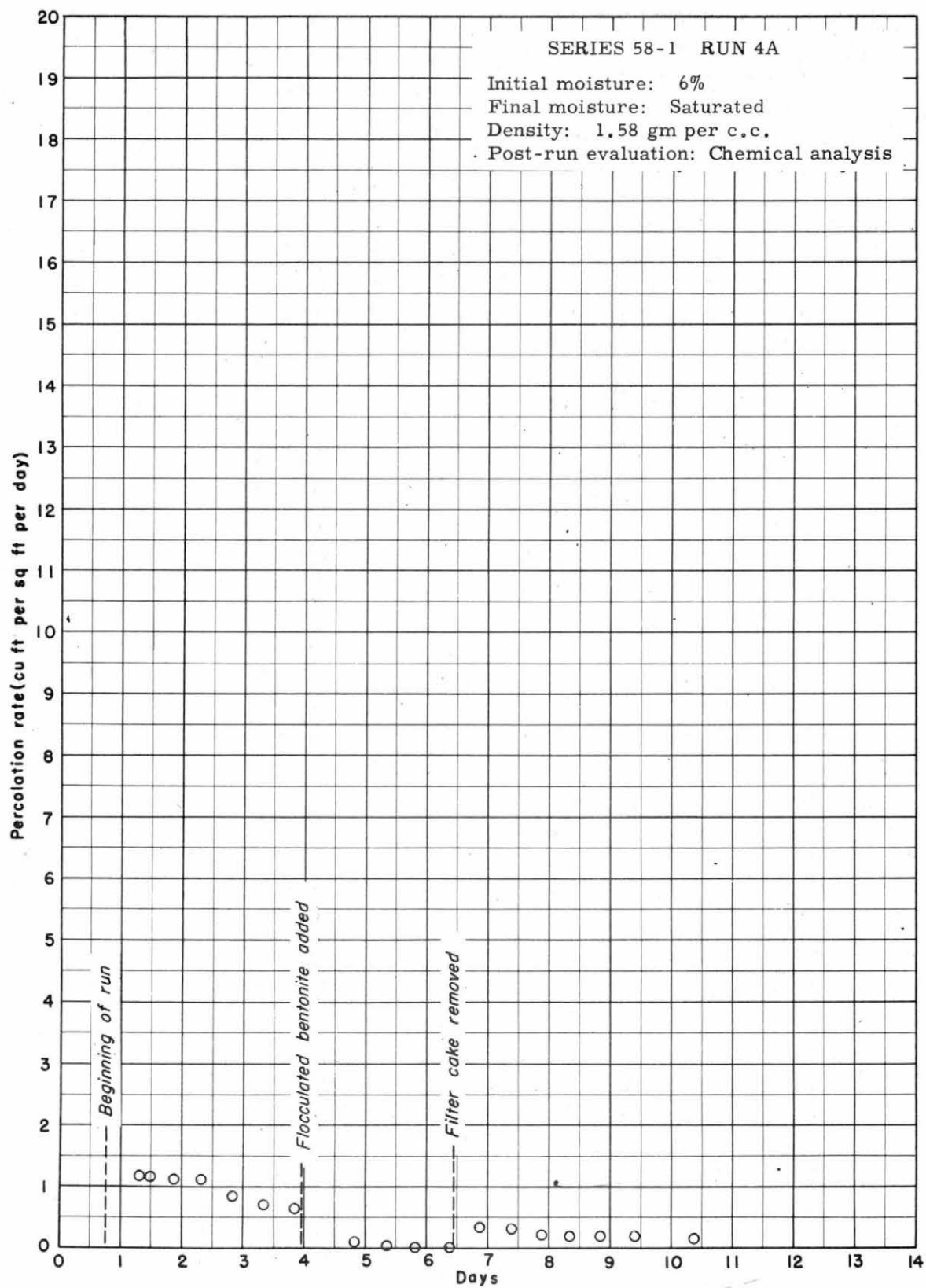


Fig. 57 Graphical representation of the history of percolation rate for 4A, Series 58-1.

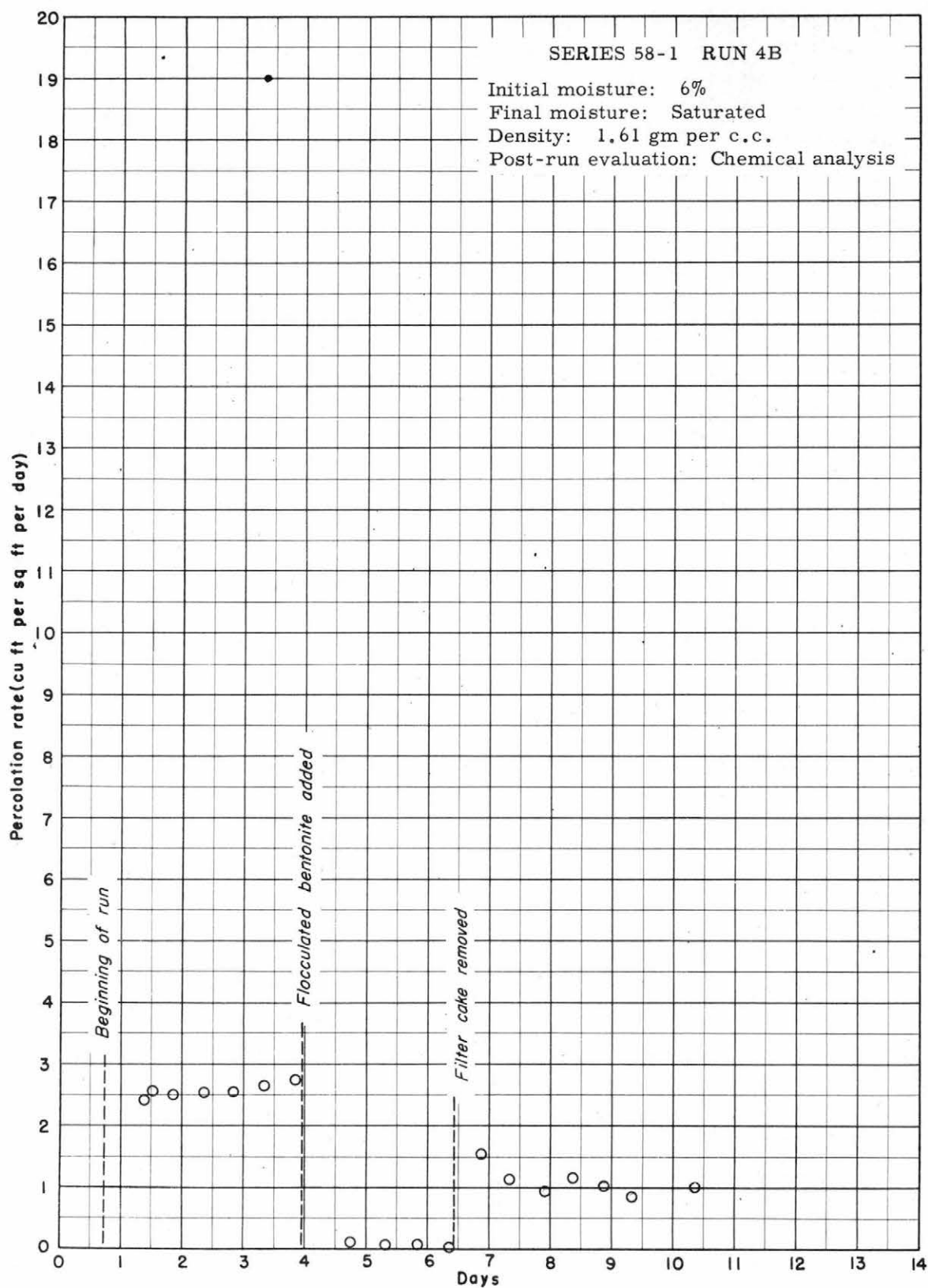


Fig. 58 Graphical representation of the history of percolation rate for 4B, Series 58-1.

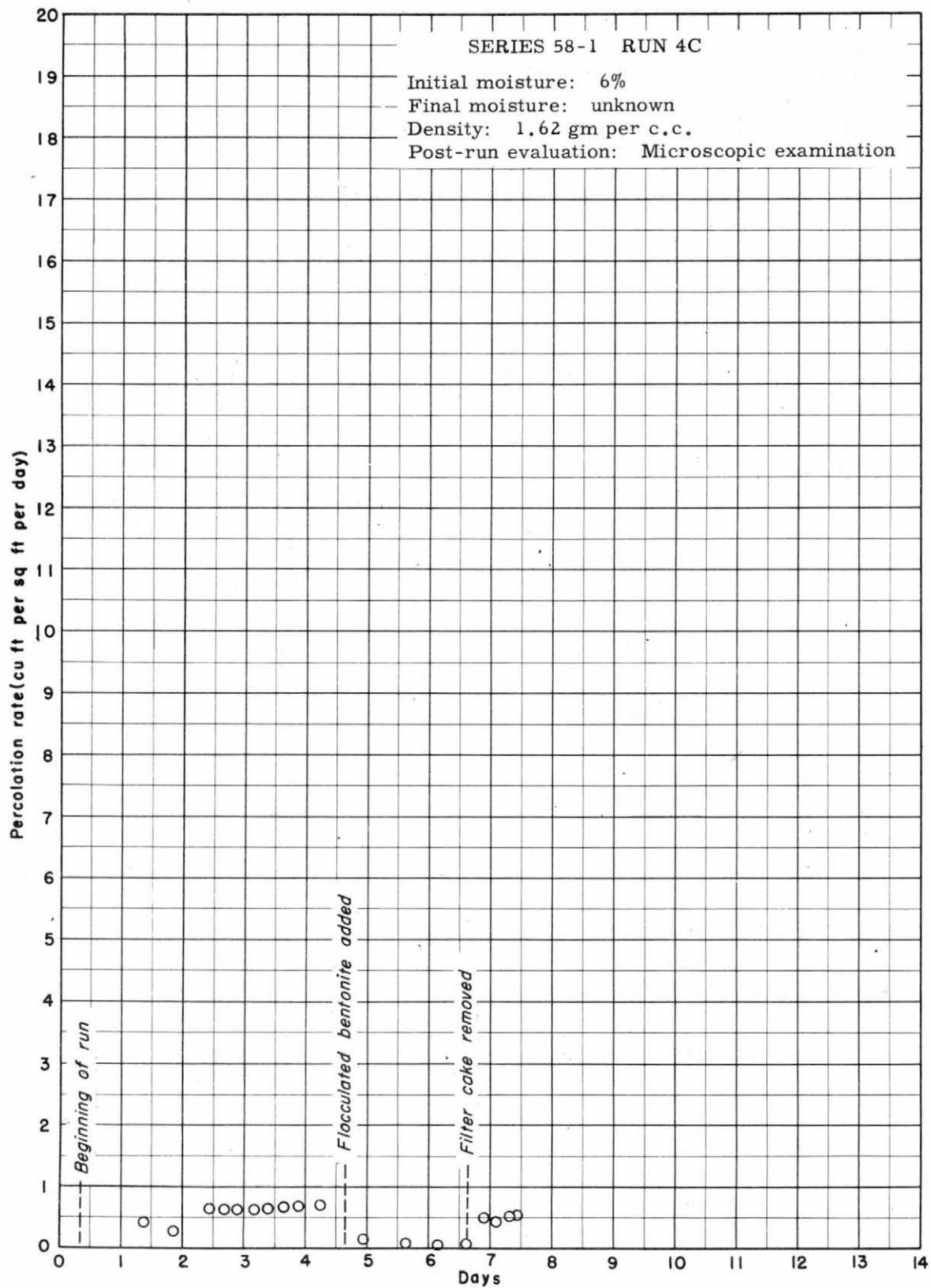


Fig. 59 Graphical representation of the history of percolation rate for 4C, Series 58-1.

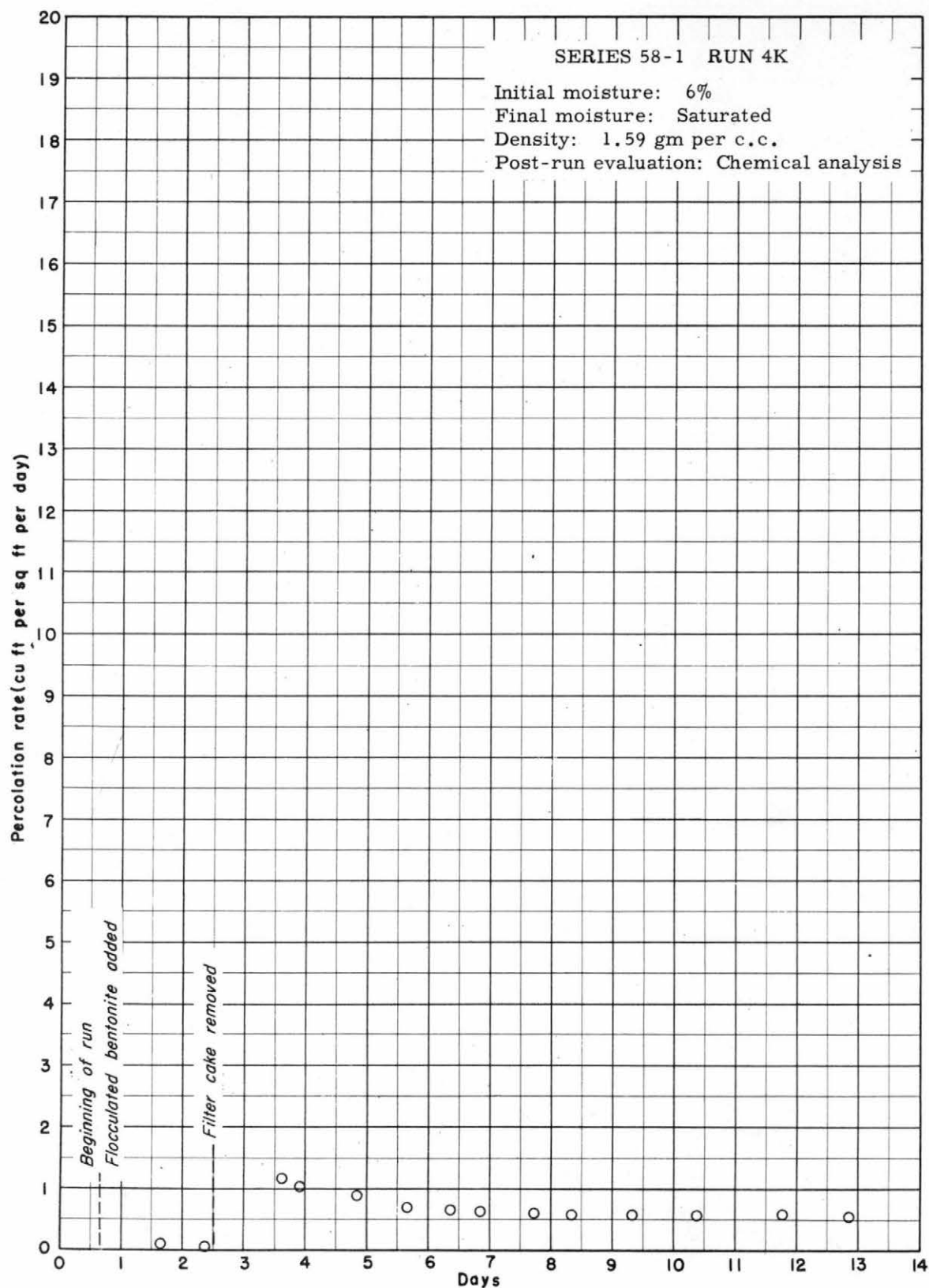


Fig. 60 Graphical representation of the history of percolation rate for 4K, Series 58-1.

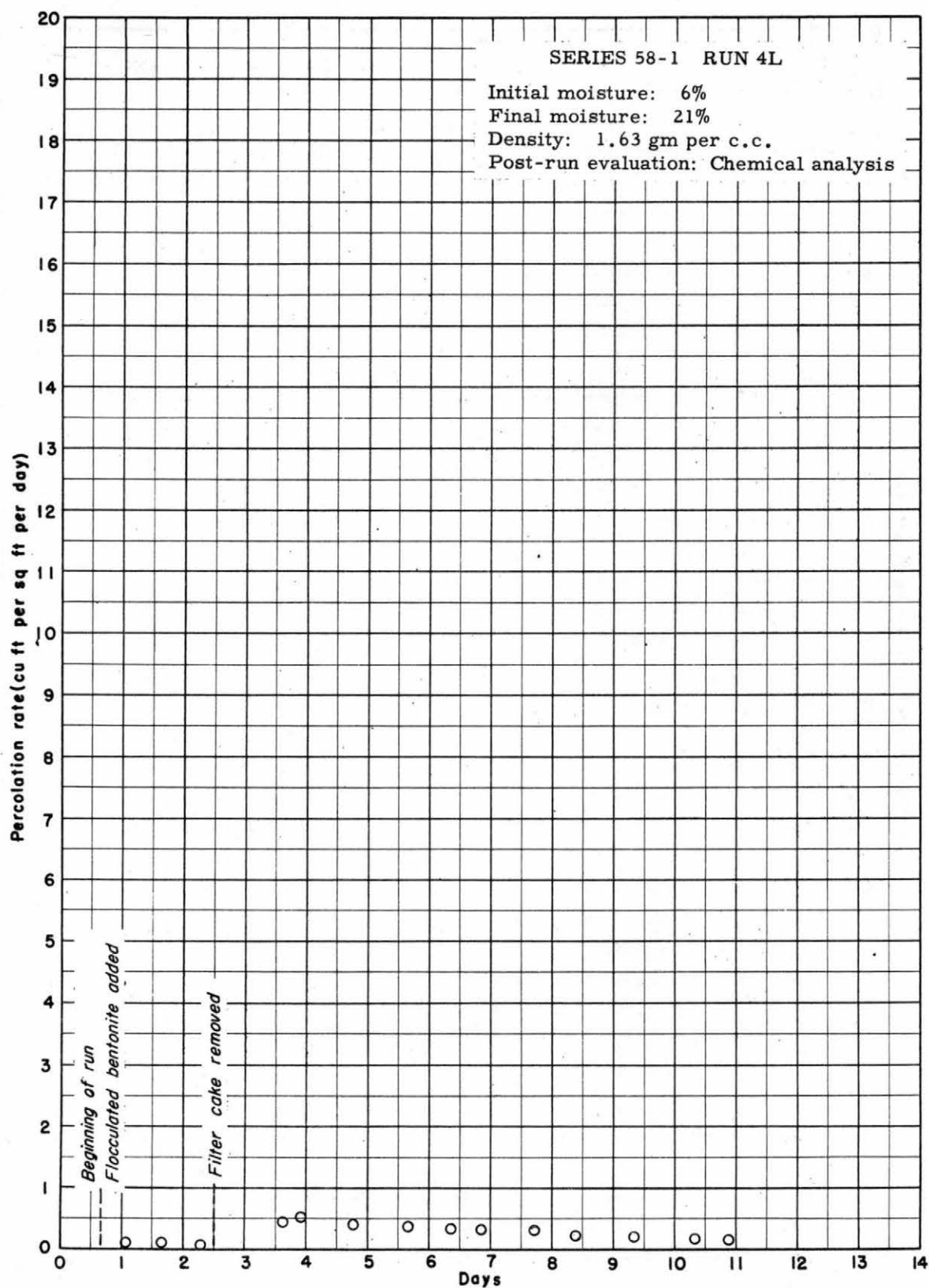


Fig. 61 Graphical representation of the history of percolation rate for 4L, Series 58-1.

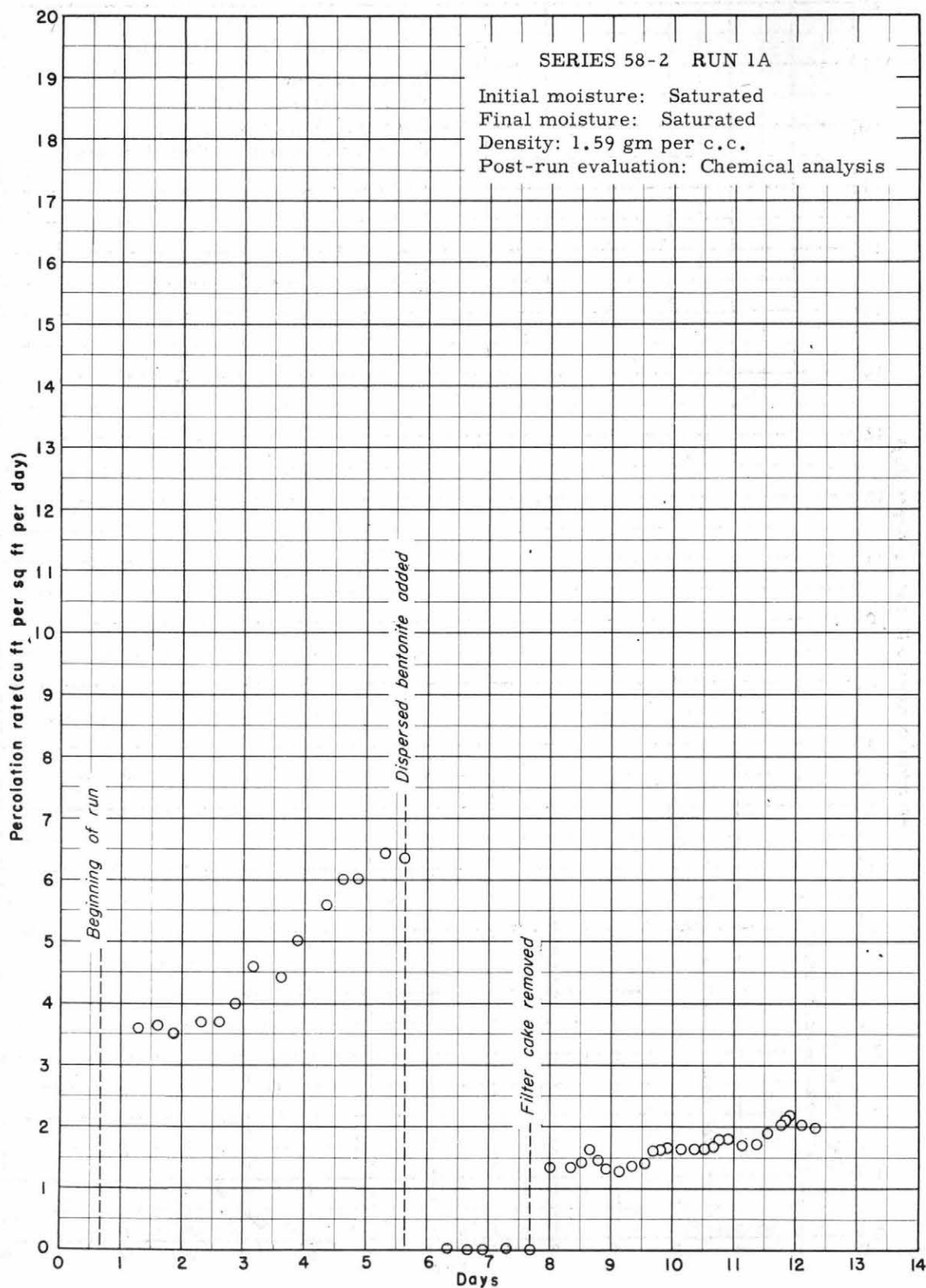


Fig. 62 Graphical representation of the history of percolation rate for 1A, Series 58-2.

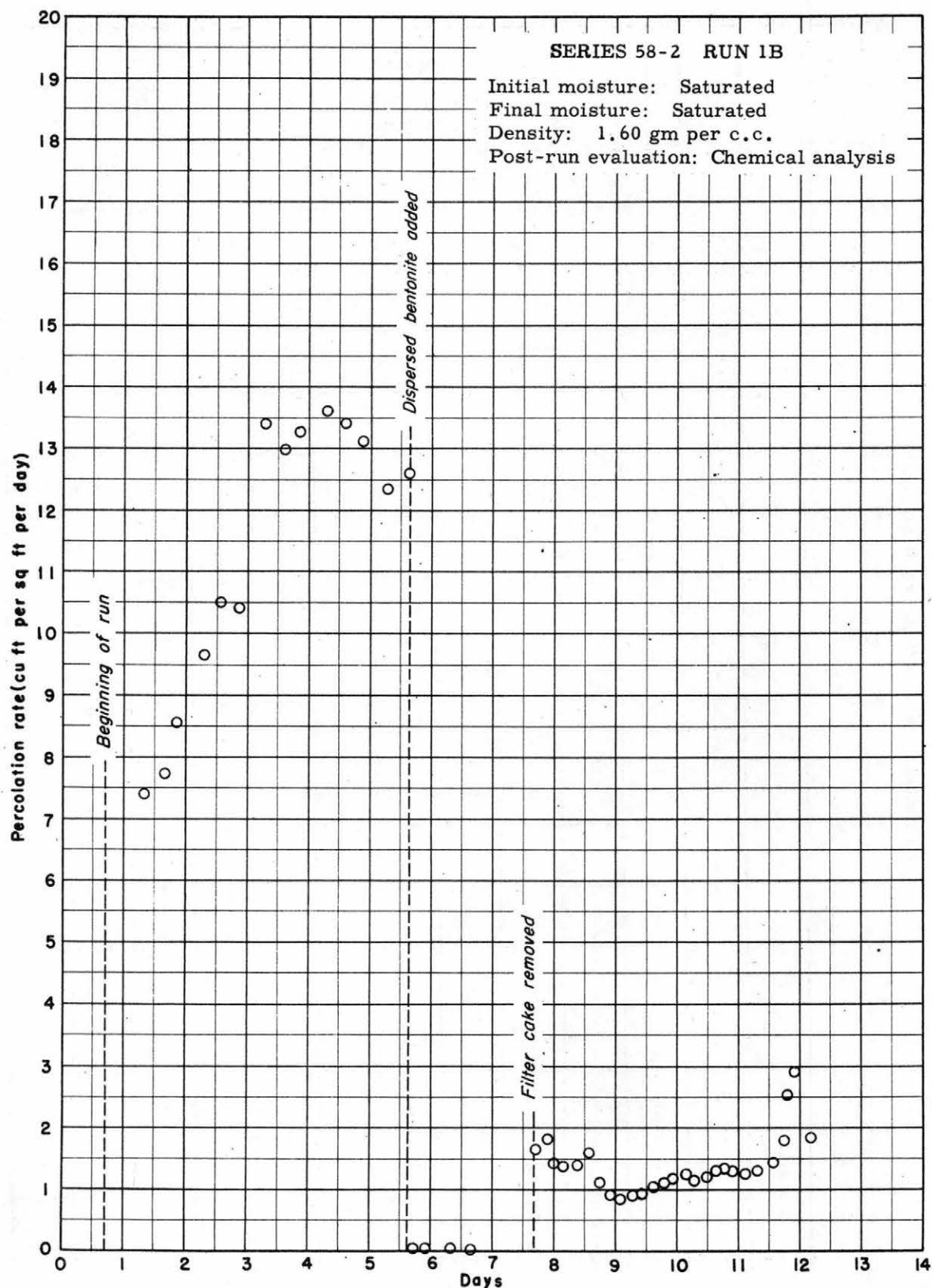


Fig. 63 Graphical representation of the history of percolation rate for 1B, Series 58-2.

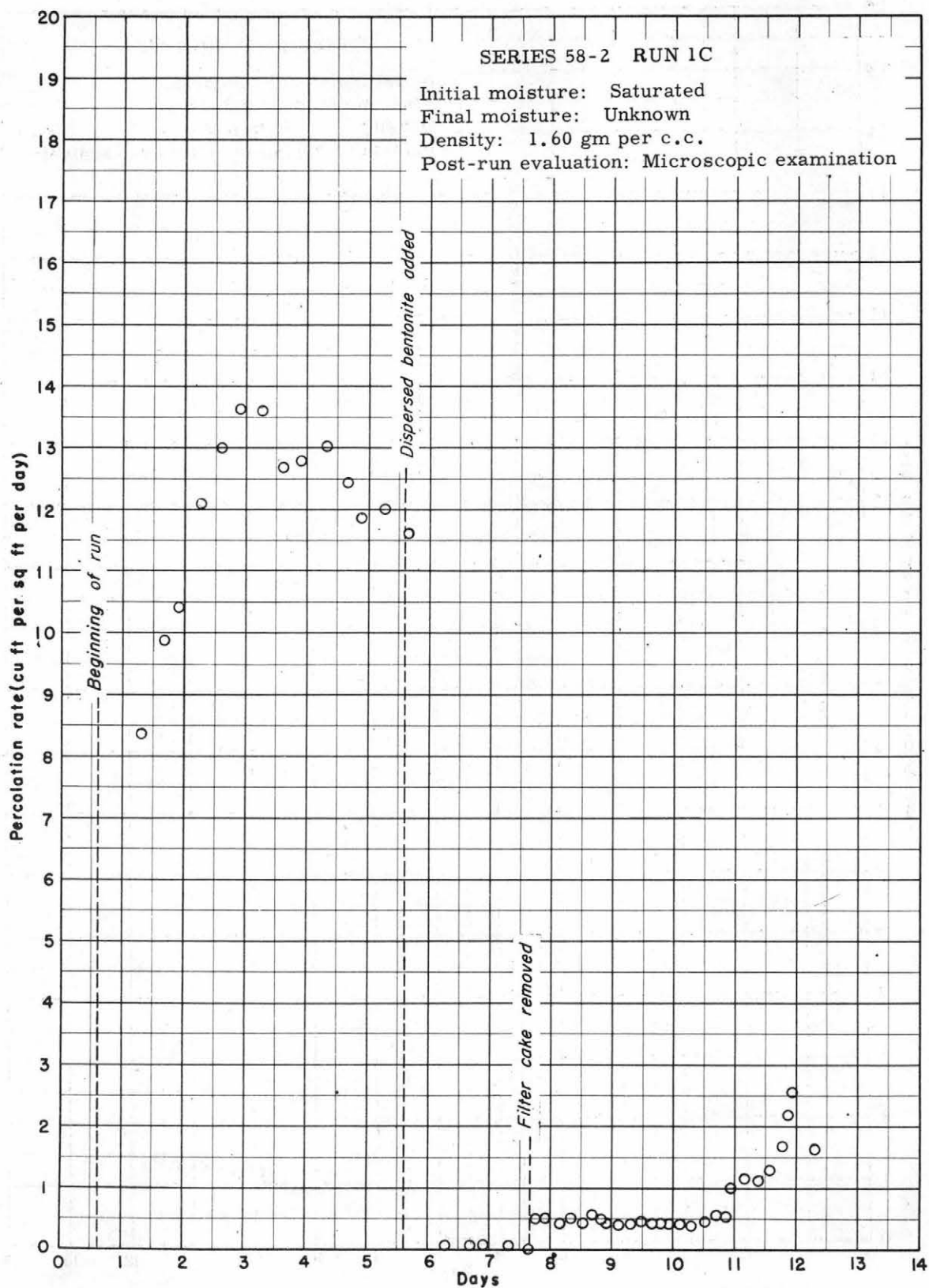


Fig. 64 Graphical representation of the history of percolation rate for 1C, Series 58-2.

TABLE 16 -- COMPARISON OF THE SATURATED RUNS BETWEEN FLOCCULATED AND DISPERSED BENTONITE TREATMENTS

TEST	PERCOLATION RATE (cu ft per sq ft per day)			
	Maximum before sedimenting		72 hrs after removal of cake	
	Series 58-1	Series 58-2	Series 58-1	Series 58-2
Run 1A	6.4	6.4	3.0	1.7
Run 1B	14.7	13.6	1.6	1.3
Run 1C	16.0	13.7	4.9*	0.5*

* The post-treatment percolation rates are compared at 19 hours after the removal of the filter cake because the soil column of Series 58-1 was packed for microscopic examination at that time.

It may be seen that in each case more reduction in percolation was brought about by the dispersed bentonite treatment (Series 58-2). However, as indicated by Figs. 62 to 64, this sealing effect began to wane approximately 90 hours after the removal of the filter cake. The cause for this weakening is not apparent. Whether the corresponding runs in Series 1 would have shown a similar tendency, had they been continued longer, is a matter for conjecture.

Both Runs A and B showed a slight increase in clay and considerable increase in sodium.

Run 4 -- Four tests were made in Run 4: K, L, M, and N (Figs. 65-68). The columns were loaded with sand containing 8 per cent moisture by weight. No initial hard water phase was used, therefore no initial permeability is known. Run N was disassembled for chemical analysis immediately after the cake was removed, therefore the sealing effect for it is not determined. In general, no agreement in the sealing effect was found. At the time of sampling, Run K was saturated, Run L had a moisture content of 21 per cent; it is therefore logical that the ultimate percolation rate in Run K was higher than that of Run L. The final moisture contents in the other two columns are not known, hence no comparison is possible. The sealing effects in Runs K, L, and M were moderate. Chemical analysis showed that there was only a slight increase in clay in Runs K and L, but substantial increase in sodium. Run N presented an interesting case since the condition of the soil column immediately after

sedimenting treatment was disclosed by chemical analysis. The increase in clay along the entire column was essentially the same as in the other runs, but the increase in sodium was concentrated in the top four centimeters, especially the upper two centimeters.

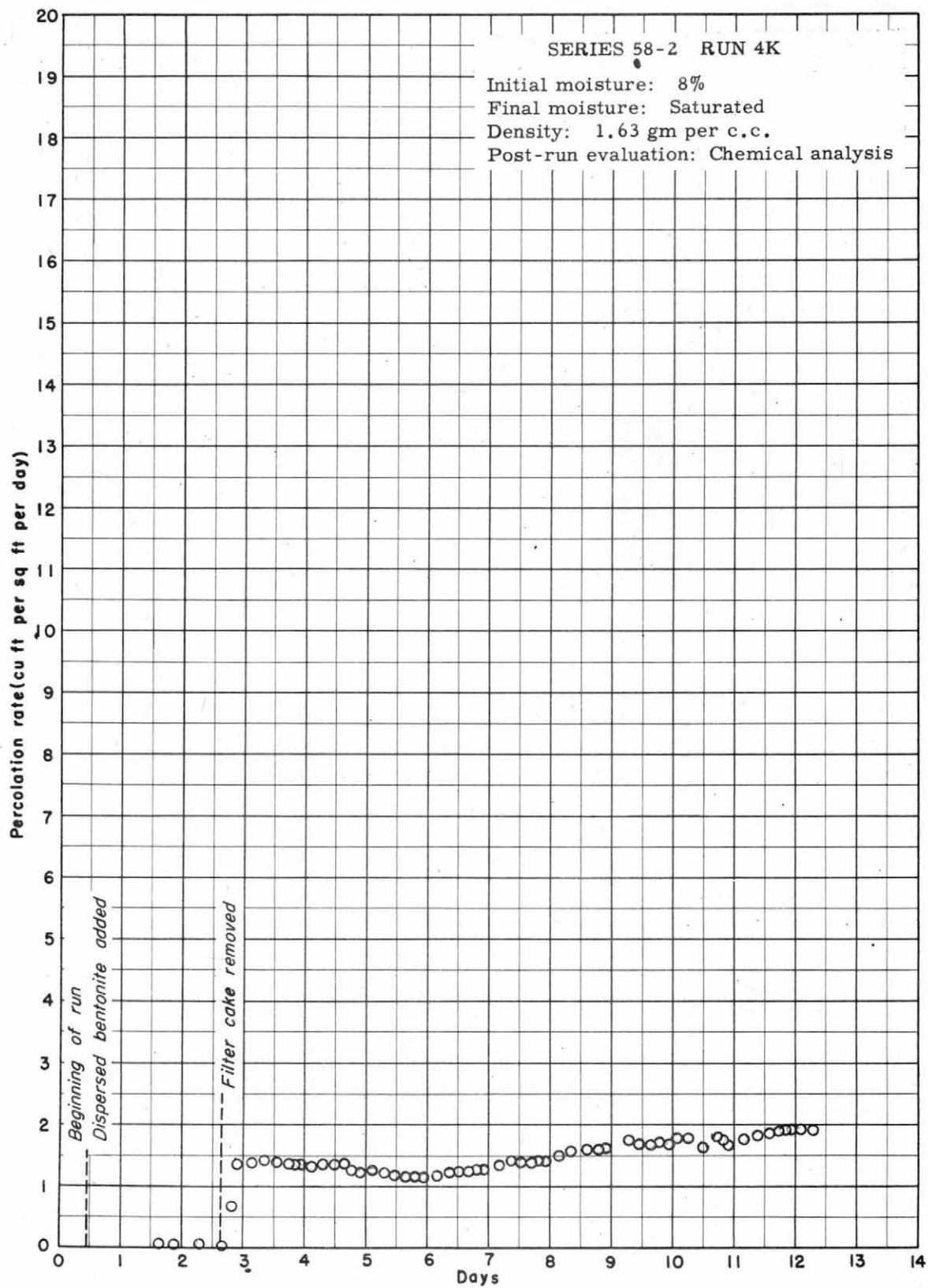


Fig. 65 Graphical representation of the history of percolation rate for 4K, Series 58-2.

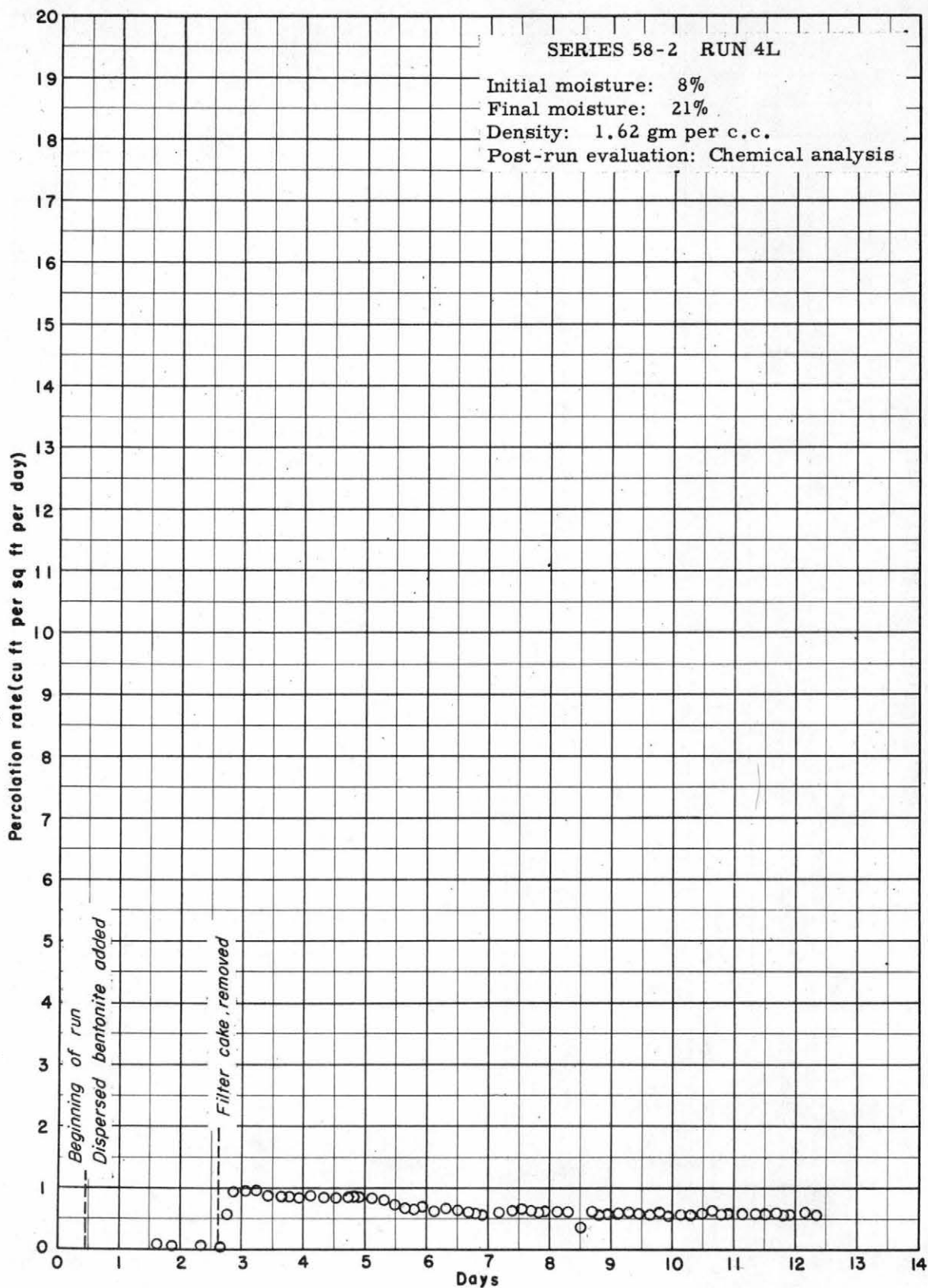


Fig. 66 Graphical representation of the history of percolation rate for 4L, Series 58-2.

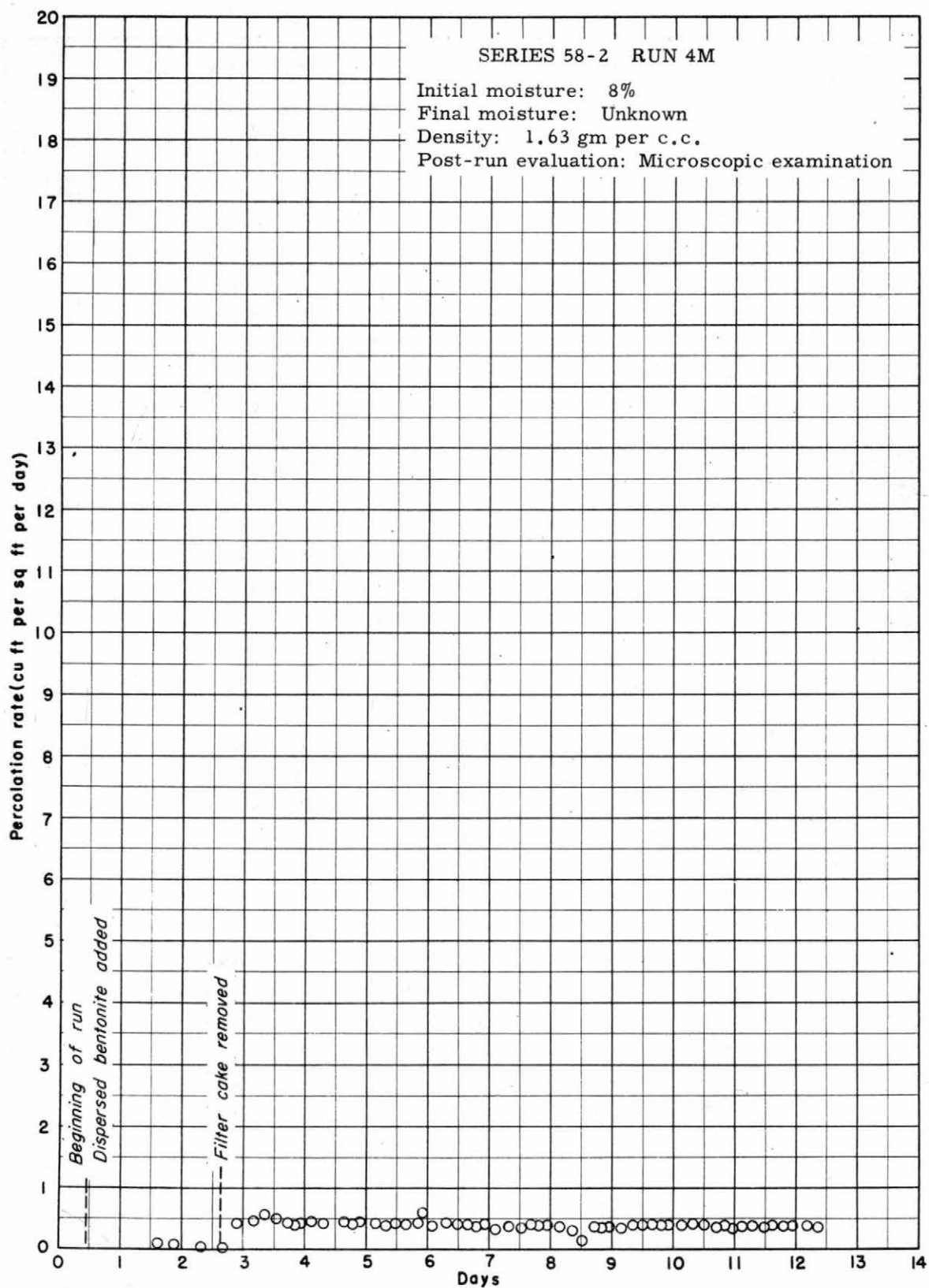


Fig. 67 Graphical representation of the history of percolation rate for 4M, Series 58-2.

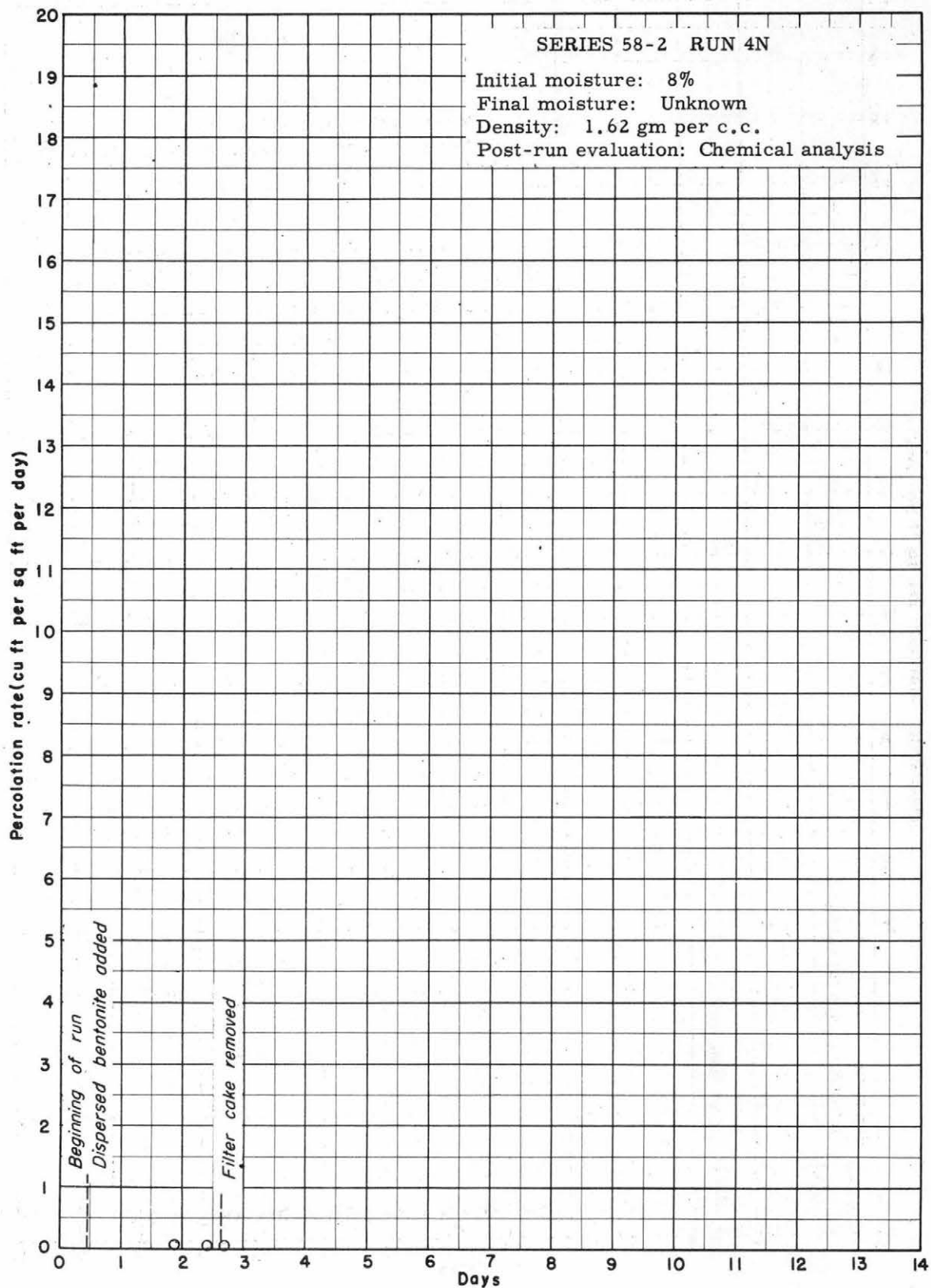


Fig. 68 Graphical representation of the history of percolation rate for 4N, Series 58-2.

XII. DISCUSSION AND CONCLUSIONS

The completion of the 1958 series of laboratory testing brings a logical pause for retrospection to the study of the sediment-sealing attempt at Lateral 1. This test series is characterized by the effort made toward duplicating the conditions found in the field. Interpretation of the test results would not be intelligible without a discourse on the various aspects of these conditions.

Soil

The mixing of the composite sample used in the experiments may be considered successful. Table 17 shows a comparison of the cation exchange capacity between the composite sample and the samples collected from the field before the lateral was cleaned.

TABLE 17 -- COMPARISON BETWEEN COMPOSITE SOIL SAMPLE AND FIELD SOIL SAMPLES

SAMPLE	DEPTH (in.)	TEST SERIES	CATION EXCHANGE CAPACITY (meq per 100 gm soil)
Sta 95+75	0 - 6	Original field sample	8.2
	6 - 12	" " "	8.8
Sta 112+46	0 - 6	" " "	8.1
	6 - 12	" " "	5.4
Sta 163+00	0 - 6	" " "	5.8
	6 - 13	" " "	5.6
Sta 255+44	0 - 6	" " "	6.9
	6 - 12	" " "	4.0
Composite Sample		58-1 Runs A and B	6.9
		Runs K and L	6.6
		58-2	7.2

The values given by the composite sample are well within the range of variation given by the field samples. However, these values are somewhat higher than those obtained before the sediment-sealing installation (given in Table 2) and do not altogether agree with those obtained after the installation (given in Table 6). If the higher values are reliable, then it may be said that the sediment-sealing operation had, if not reduced seepage, at least increased the clay content in the soil. This may be

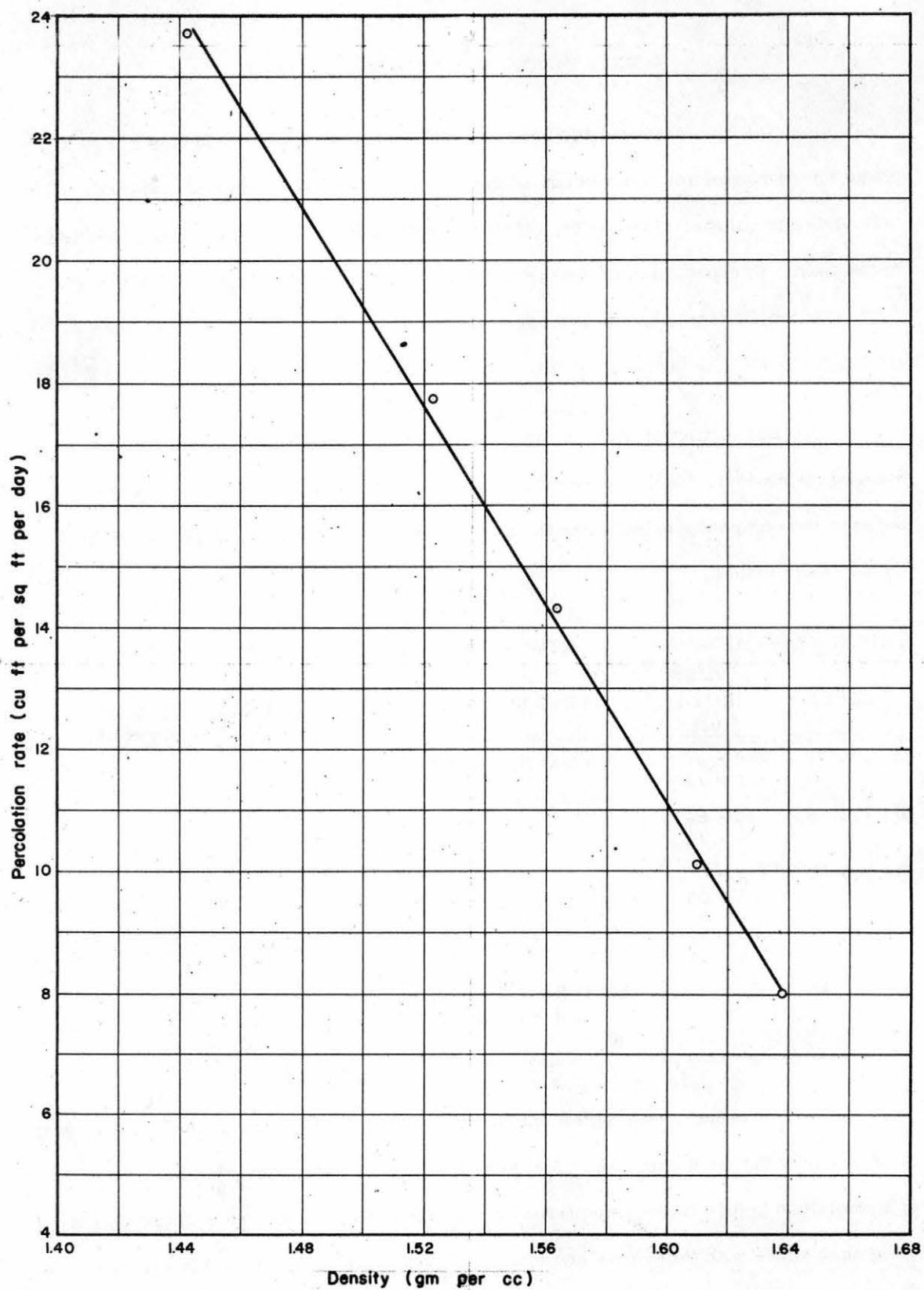


Fig. 69 Variation of percolation rate with bulk soil density.

confirmed by the fact that lumps and curls of the bentonite cake were discovered buried in the channel bed at the time of the 1957 inspection trip (described in Chapter VII). With the scattered cake mixed together in the composite sample (which was collected after the canal had been cleaned and re-shaped) the clay content would logically exceed that of the earlier samples. At any rate the bed material was not available in the original pre-installation state. The 1958 series of testing experimented on only the soil that had undergone the bentonite treatment in the field. Information regarding the behavior of the original soil must necessarily be derived from the earlier experiments.

Packing

Although the columns were packed to an over-all density of 1.62 gm per cc, the initial moisture content at the time of loading varied from run to run. As mentioned in Chapter VIII, the variation of percolation rate with density showed considerable scatter. This was true when the soil was packed with moisture. A direct relationship was found when the soil was packed in an air-dry state, as shown in Fig. 69. The results from the initial permeability determination in the saturated runs (Run 1) of both Series 58-1 and Series 58-2 did not bear out this relationship. The reasons for the deviation may be traced to uneven packing, incomplete saturation, and, above all, boundary leakage. The last factor, though serious when existent, was not prevalent in all runs, and it could be detected when the bentonite suspensions began to by-pass the soil column (Figs. 70 and 71). Since Mr. Newman experimented with columns packed similarly, his results should be comparable to those obtained from the saturated runs. The values given in Table 8 when compared with those given in Table 16 show much higher initial percolation rates, which is another indication of the increase in clay content after the sediment-sealing operation.

When the soil was packed with an initial moisture the percolation rate was reduced considerably, even after the column became saturated, despite the same over-all density of 1.62 gm per cc. The mechanical operation of tamping the soil while it was wet must have brought about some structural arrangement similar to that of compacted earth. Consequently, the results of all the runs using initially wet material

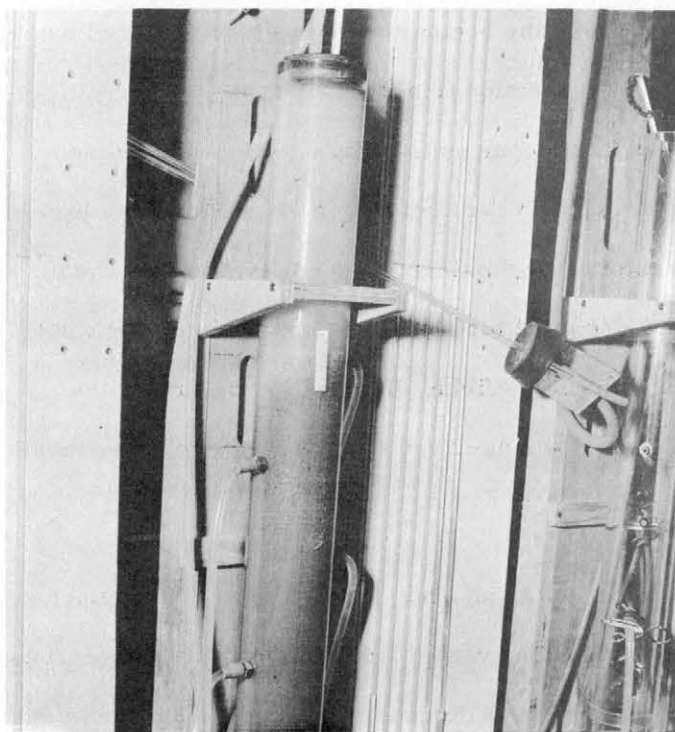
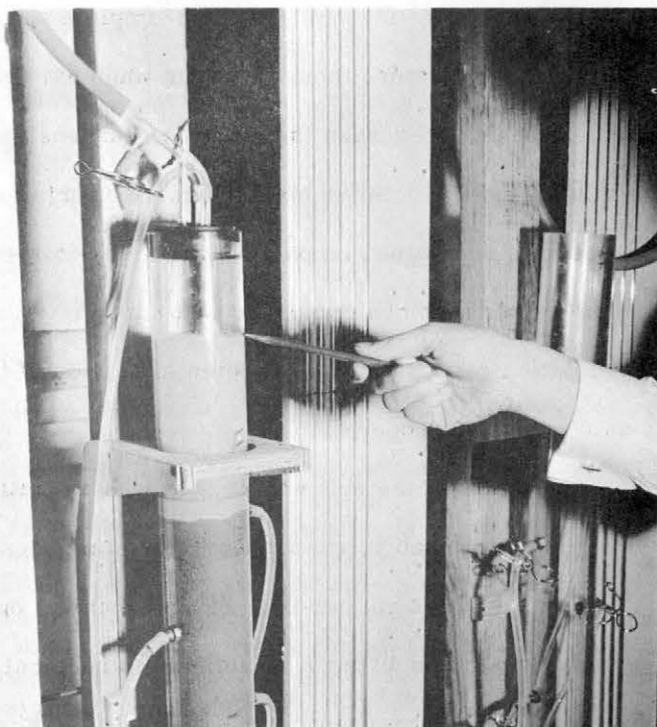


Fig. 70 View of a case of boundary leak during a run with dispersed bentonite treatment. CSU photo.

Fig. 71 View of a typical run without boundary leak. Note the clear break between the flocculated bentonite and the water above it. CSU photo.



cannot be evaluated on an equal basis with those using air-dry material. The fact that the over-all density remained unchanged gives rise to the speculation that some method of stirring the soil, under water, such as harrowing, without conspicuously compacting the soil, may reduce the seepage rate substantially.

Presence of Air

That the permeability of the bed material reacted sensitively to the amount of air present has been dealt with in Chapter VIII (Fig. 30). It should be noted that the lower intrinsic permeability does not result in lower seepage loss because water is lost in bringing the unsaturated soil up to saturation in addition to permeating through the unsaturated layer. Thus, measurement of effluent in the laboratory could not furnish information in regard to the water loss. A system devised to measure the inflow would be necessary in order to determine the water lost into the soil.

The difference in penetration of bentonite between saturated and unsaturated soil columns seems slight. In general, it may be said that the saturated columns promoted a trifle more penetration. This is judged from the ultimate results; were the penetration measured on the basis of per unit weight of effluent perhaps the unsaturated columns would give higher values. This point, however, is irrelevant because in any case, as it will be discussed presently, the penetration was inadequate for the pre-established goal.

Penetration

According to the microscopic examination, dispersed bentonite did not penetrate beyond the top inch of the soil columns, and flocculated bentonite penetrated even less. The cation exchange capacity determinations, which may be a more sensitive test, showed traces of penetration through entire columns, but the quantity was far too small to bring about any beneficial sealing effect. The increase in exchangeable sodium percentage, on the other hand, was quite pronounced in many runs. It may also be closely correlated with the sealing effect; the few runs in which a decrease in exchangeable sodium percentage was detected showed high ultimate percolation rate. From the

example of Run 4N, Series 58-2, it may be deduced that the migration of sodium had not taken place until after the filter cake was removed. It is not known whether more bentonite would have penetrated the soil or whether the migration of sodium would have occurred if the filter cake had been allowed to remain undisturbed. Inasmuch as the sealing became nugatory immediately after the removal of the filter cake, it is futile to speculate on these details. The amount of clay penetration required for a worthwhile seal must be disproportionately higher than what is possible by the mere forces of gravitation and capillarity. The sealing effect brought about by the sodium increase must necessarily be temporary, for it obviously cannot endure any prolonged flow of calcium water.

Hydraulic Gradient

The over-all applied hydraulic gradient was set at 2.75. All the data from other sources used in comparison have been converted to this basis. This value is arbitrary: an incidental result from setting the headwater level at 30 in. above the soil surface (an average depth in the lateral) and the tailwater level at the bottom of the soil column. Naturally the internal hydraulic gradient, as measured by the manometer readings, fluctuated from time to time, from level to level. Wherever a seal occurred it could be expected that the local hydraulic gradient would rise. The behavior of the hydraulic gradient across a certain section in relation to its permeability should present an interesting study, and the data collected from the 1958 series of experiments should provide sufficient material for analysis of this particular soil. However, such an endeavor would be beyond the scope of the present project.

The intrinsic permeability is theoretically expressed by:

$$K' = \frac{Q\eta}{A\rho g i}$$

where Q is the percolation in unit time; η , the dynamic viscosity of the percolate; A , the cross-sectional area of the passage; ρ , the density of the percolate; g ,

gravitational acceleration; and i , the hydraulic gradient. It follows that

$$\frac{\partial i}{\partial K'} = \frac{-Q\eta}{A\rho g K'^2}$$

Thus, when the permeability K' decreases the hydraulic gradient increases at a rapid rate, which is partially off-set by the decrease in the discharge Q . It may be seen that:

$$\lim_{K' \rightarrow 0} i = \infty^1$$

This tendency inevitably leads to the paradox that the less permeable a soil the more it tends to leak, a decided adverse factor against the aspiration of a perfect sealing. It is clear, therefore, that a reduction in intrinsic permeability would not yield a proportional reduction in the actual loss of water. To regard the measurement in intrinsic permeability as a direct scale of the sealing effect would be erroneous (of which the author was guilty in Ref. 25).

It may be visualized that as the clay particles filled up the voids in the sand it became increasingly difficult for further filling up. This difficulty would be enhanced until a virtual standstill was reached. This point may be the optimum for the sediment-sealing process under the present practice, and which may be far short of the pre-established goal. Consequently, in order to promote more effective sealing, it is necessary to introduce modifications to the process, such as extrinsically forcing clay penetration, and using agents other than clay.

Percolation Rate

The original plan of adjusting the permeameter flow to two rates of percolation, 0.4 and 1.2 cu ft per sq ft per day, did not materialize. It was thought that these

¹ This is not strictly correct because the increase in hydraulic gradient across a finite section being sealed may be divided into two stages: (a) it increases rapidly until it is equal to the over-all available head divided by the thickness of the section; (b) it increases further, accompanied by a de-saturation of the soil below the section being sealed. During the first stage, the limit of infinity holds true only when the available head is unlimited or the thickness of the section is infinitesimal. During the second stage, Darcy's law no longer holds because it is beyond the realm of saturated flow (see Fig. 30).

rates would cover the range encountered in the field. The fact that the rates obtained in the laboratory are usually higher may have a combination of several possible causes. The artificial hydraulic gradient used in the laboratory, if anything, was probably lower than that in the field; additional attempts at field measurement are necessary for an accurate evaluation. Studies are needed similar to the types conducted by Kirkham (27) and by Day (28) but more related to actual field conditions.

Boundary leakage was not usual, and when it occurred the sedimenting process could put an end to it. Improvement in loading and packing is needed to eliminate this irregularity. The presence of air, as discussed previously, may cause immense differences in percolation. However, as time progresses the soil tends to be saturated. A device should be used in future testing to measure the inflow as well as the outflow; also a new procedure must be adopted to avoid the effect of tamping when a soil with an initial moisture is loaded. As for layering, it is probably the greatest factor contributing to the difference in percolation measurements between the laboratory and the field. This factor, in addition, may completely alter the nature of a penetration phenomenon.

The existence of stratification in the channel bed was positively confirmed during the 1957 field inspection trip. No attempt to duplicate this phenomenon was made in the laboratory. It must be emphasized that the application of laboratory data to the field is very seriously limited by this difference. A study of layering and all its implications is urgently needed. This can perhaps be accomplished by extensive sampling in the field and testing undisturbed samples.

Turbulence

Closely related to stratification is turbulence. The permeameter approach to the problem of seepage does not take the stream flow into account. With such a sand bed as in Lateral 1, evasion from flow characteristics would be unrealistic. Flume tests on another project in the University Hydraulics Laboratory revealed that thin lenses of bentonite several inches below the surface could result from sand-dune movement. Detailed account of this behavior is not yet available, but doubtless this

discovery will introduce fresh cogitation on methods to bring about penetration as well as the possible manner of secondary structural arrangement the penetrated bentonite can assume. A series of flume tests may be desirable.

Criteria for Measurements

So far the percolation rate in cu ft per sq ft per day, a unit expressing the over-all loss in absolute quantities, has been computed from the data gathered from both the laboratory and the field. One exception is the inflow-outflow measurements, which have remained in terms of percentage of the total inflow. This is necessary because not only no accurate estimate of the wetted perimeter from day to day is available, but also no other criterion than the actual amount saved from loss can serve as the ultimate economic justification at this site.

To obtain percentage loss figures from permeameter tests in the laboratory is out of the question. To compute the reduction in percolation rate as a percentage of the initial percolation rate would be misleading. For instance, a 50 per cent reduction from an initial rate of 10 to a final rate of 5 cu ft per sq ft per day cannot be extrapolated to mean that had the initial rate been 1.0 the final rate would have become 0.5 cu ft per sq ft per day. The resort to using the absolute values of percolation rate was therefore necessary though not altogether desirable. The goal for sealing, established at 0.1 cu ft per sq ft per day, was purely arbitrary. Needless to say, a reduction in the field from 3.0 to 1.0 cu ft per sq ft per day would justify an installation provided that the total benefit realized, including the value of water saved and the land reclaimed, would be worth more than the cost of installation. Conversely, a reduction from 0.15 to 0.05 cu ft per sq ft per day would not justify an installation if its cost would exceed the prospective benefits.

In the case of Lateral 1, the loss in 1955, before sedimenting, amounted to about 20 per cent of the inflow according to corrected weir measurements (Chapter IV). In 1956, after sedimenting, the total inflow was 7,050.46 acre-ft; the expected loss should have been about 1,400 acre-ft. Actually the loss was measured to be 1,122.84

acre-ft, presumably reduced by the sedimenting operation. A saving of 277 acre-ft for the season may be claimed provided all circumstances are considered equal. Since the total inflow in 1955 was over 8,000 acre-ft, the total daily wetted perimeter could have exceeded that of 1956, in which case, the higher loss percentage would be within reason. Other differences such as temperature, evaporation, and precipitation, would also contribute to the inaccuracy.

At any event, the value of 277 acre-ft of water plus whatever additional saving in the 1957 season could not justify the total expenditure of approximately \$11,800.

Bentonite Requirement

The amount of bentonite used in the laboratory experiments was low. The estimates for all the runs are listed in Table 18.

TABLE 18 -- ESTIMATES OF BENTONITE USED IN THE LABORATORY EXPERIMENTS

SERIES 58-1	BENTONITE USED (lb per sq ft)	SERIES 58-1	BENTONITE USED (lb per sq ft)	SERIES 58-2	BENTONITE USED (lb per sq ft)
Run		Run		Run	
1A	.088	3A	.123	1A	.093
1B	.096	3B	.150	1B	.094
1C	.326	3K	.078	1C	.088
2A	.088	3L	.078	4K	.069
2B	.125	4A	.094	4L	.069
2K	.057	4B	.087	4M	.078
2L	.145	4C	.176	4N	.095
		4K	.065		
		4L	.067		

The average quantity is 0.106 lb per sq ft. By far the major part of this bentonite was removed from the permeameter in the form of filter cake, and only a very minor part penetrated into the soil, while the cake was present the percolation virtually stopped (below 0.1 cu ft per sq ft per day) in all the runs. This leads to two speculations: (a) if the cake can be preserved for a long time without deterioration, will further penetration of the bentonite from the cake into the soil be possible? (b) if the cake can be artificially mixed into the soil will it be preserved as a whole and bring about sealing in depth?

It may be noted that in the field installation, 481,200 lb of bentonite was used to seal 72,778 sq yd, or 0.735 lb per sq ft. Apparently this quantity would have been ample if all of it had been retained and evenly spread in the soil.

Conclusions

The Lateral 1 sediment-sealing installation was a failure as an attempt to save water. However, its evaluation and analysis, together with the laboratory experiments that explored into the various phases of the sealing process in its connection, are in themselves of some didactic value. The conclusions arrived at in the light of the findings up to date are summarized as follows:

- a. Reliable inflow-outflow records covering entire irrigation seasons are needed in order to evaluate properly any sealing attempt on a logical basis.
- b. Effective sealing is produced by the surface filter cake, destruction or removal of which erases the sealing.
- c. Increase in exchangeable sodium ions produces a sealing in Lateral 1 bed material, but is neither adequate nor believed enduring.
- d. No apparent difference exists between the sealing efficiency of a flocculated bentonite filter cake and that of a dispersed bentonite filter cake.¹
- e. The voids in a dune sand of this type cannot be filled by bentonite particles sedimenting under pressure derived from normal canal water depth.
- f. When the bed material of Lateral 1 is moist or wet, moderate tamping, without over-all compaction, can bring about considerable sealing.
- g. For close similitude, it is essential to include soil stratification in the correlation of permeameter study with the prototype. Consequently, tests on undisturbed samples are desirable.

¹ This disregards subsequent drying and wetting cycles (29:132) as well as accumulated action of hard water on the dispersed cake.

- h. Regimes of sand movement, forming ripples, bars, dunes, antidunes, etc., may create situations unobservable in permeameter tests.

XIII. RECOMMENDATIONS

At the beginning of Chapter VI, three questions were asked in regard to the possibility of sediment-sealing, the attainable seepage reduction and its measurement, and the causes of failure of the Lateral 1 installation and the recommended remedies. In the light of the facts so far uncovered, these questions can be answered as follows:

- a. It is not possible in Lateral 1 to obtain enough penetration to reduce the seepage to a very low rate by the simple process of sedimenting clay material such as bentonite. For the filter cake itself must be made to penetrate the soil completely and this requires an additional process of operation. Alternately, it may be possible that other chemicals, as additives to bentonite or more probably as sealing agents themselves, will bring about an effective sealing.
- b. The goal of reducing seepage rate to below 0.1 cu ft per sq ft per day as a standard seems illogical. A relative standard should be adopted to justify any sealing operation. This should be the comparison of the cost of installation with the benefits realized, and in the case of Lateral 1 the benefits being the cost of the total quantity of water saved. To compute this amount of water, accurate records of inflow and outflow measurements for entire seasons, accompanied by complete information on stream stage, temperature, evaporation, and rainfall, should be made available both before and after the sealing installation.
- c. The field installation at Lateral 1 was a failure as measured by the above criterion although the amount of water saved was only an approximate estimate in the absence of detailed records. There is evidence that the filter cake deposited in the canal bed was very effective in stopping seepage. However, it was soon allowed to dry and crack and be washed away. Significant bentonite presence was only in the form

of curled and crumbled cake buried in scattered spots by sand bed movement. The channel should have been completely cleaned to promote better penetration; this had been proposed but only partially carried out at the time of the installation.

As a remedy, it is recommended that a new bentonite sedimenting process be tried. During the ponding stage, some mechanical means such as harrowing should be used to disturb the surface of the channel bed, thereby promoting penetration. It is hoped that such an operation would enable the filter cake to mix with the subsoil and form an impermeable and unerodable stratum, a practice widely experimented in Wyoming for the USDA Agricultural Stabilization and Conservation program. This process may also bring about the sealing effect obtained in the laboratory from tamping wet soil and may disrupt whatever existing layering in the soil structure, which normally obstructs the penetration process.

Before the actual installation, it would be necessary to take two preparatory steps: (a) In the field, bring all measuring devices up to standard tolerance, calibrate them if possible; set up recorders for inflow and outflow, temperature, etc.; sink new piezometers at frequent intervals and perhaps also tensiometers; and keep accurate records for at least one entire irrigation season; (b) In the laboratory, conduct permeameter experiments on undisturbed samples, including a simulated harrowing operation, and also conduct flume tests to study the effects of layering and bed load movement on seepage, especially the phenomenon of burying clay lenses by dune action.

Alternately, other sealing agents should be tested. These should be experimented on in the laboratory first. Chemical products such as "SS-13" manufactured by the Brown Mud Company and "IBMA" by the Monsanto Chemical Company entertain potentialities worth exploring. Such investigations may be best accomplished by establishing a general program in which the Lateral 1 soil, as dune sand, will be included as one of the several types of bed material used in testing the performance of each prospective sealing agent.

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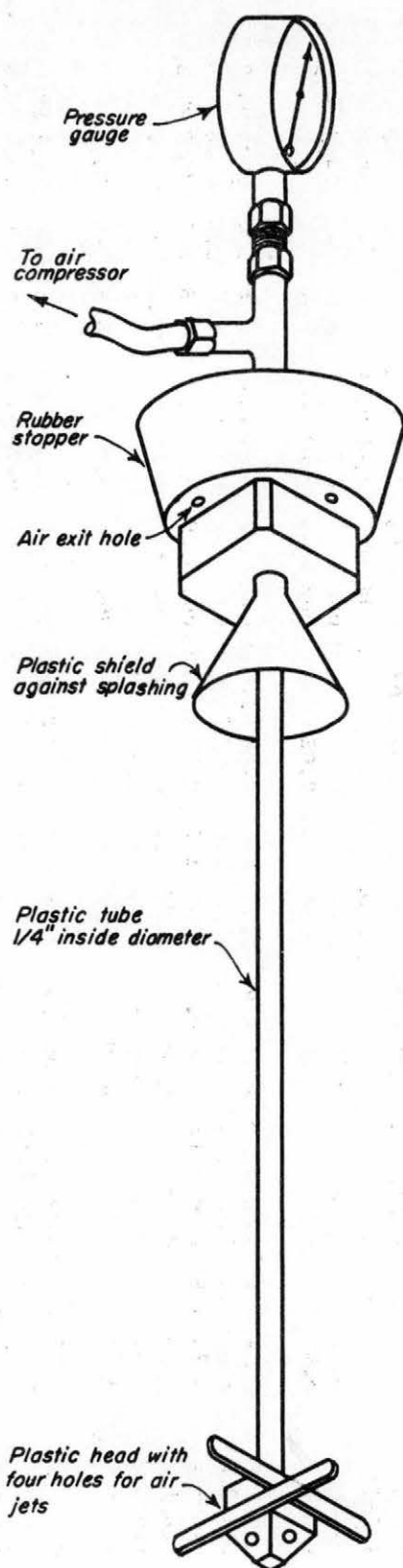
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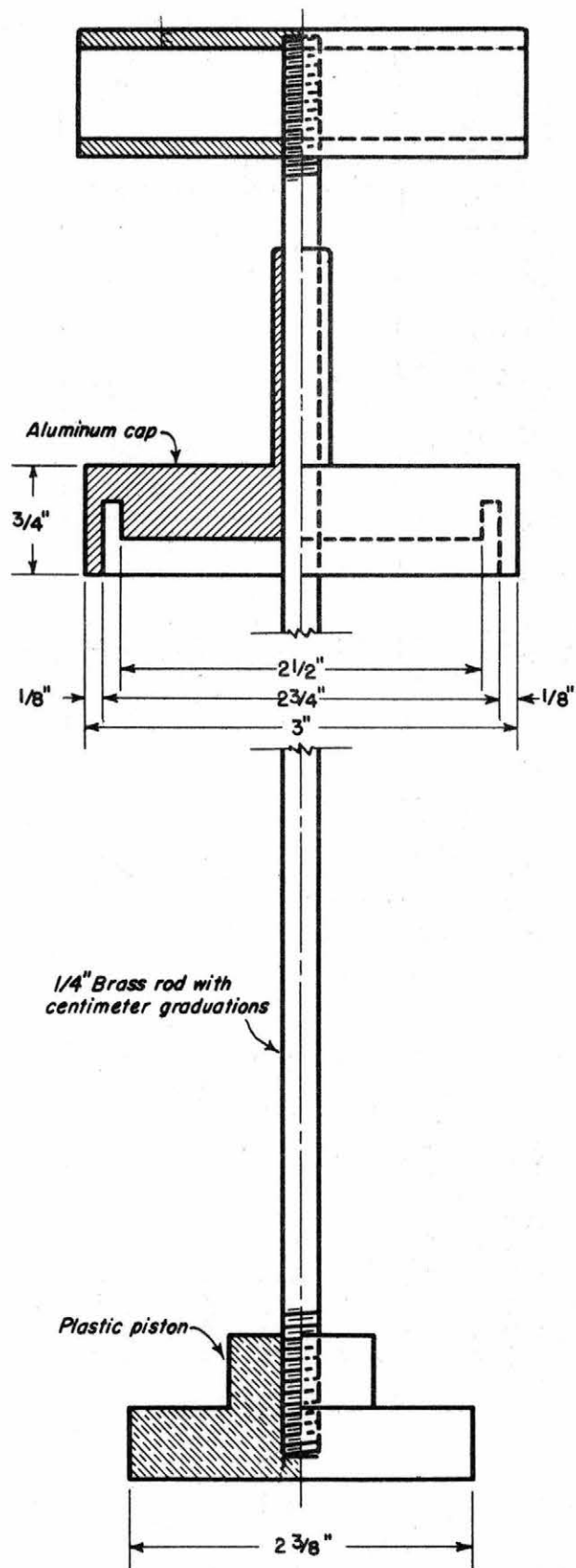
RESULTS OF CHEMICAL ANALYSES OF CANAL BED SOILS BY USBR
Before and After Sediment Lining on
Lateral 1 of Interstate Canal--North Platte Project

STA- TION	DEPTH (ft)	EXCHANGE CAPACITY		EXCHANGEABLE CATIONS						SOLUBLE SALTS				SATURATED PASTE			
				Na		K		Ca+Mg		Na		K		Total	pH		Sat %
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
58+16	0 -0.4	4.85	7.9	0.65	0.16	0.37	0.03	3.83	7.7	0.10	0.09	0.006	0.02	0.19 0.44	7.6	7.6	35.3 38.2
	0.4-0.8	4.25	2.9	0.59	0.11	0.38	0.00	3.28	2.8	0.03	0.04	0.004	0.01	0.11 0.13	7.6	7.8	32.0 28.0
	0.8-1.2	4.30	2.9	0.73	0.12	0.38	0.00	3.19	2.8	0.02	0.03	0.003	0.00	0.09 0.11	7.7	7.8	33.0 26.0
	1.2-1.6	3.40	-	0.60	-	0.38	-	2.42	-	0.02	-	0.004	-	0.08 0.09	7.7	-	29.2 -
	1.6-2.0	3.40	-	0.73	-	0.38	-	2.29	-	0.02	-	0.003	-	0.08 -	8.0	-	29.4 -
	2.0-2.4	3.45	-	0.73	-	0.38	-	2.34	-	0.02	-	0.003	-	0.09 -	7.6	-	32.4 -
204+60	0 -0.4	4.10	2.9	0.60	0.11	0.37	0.00	3.13	2.8	0.02	0.04	0.005	0.01	0.07 0.12	7.6	7.9	29.0 30.0
	0.4-0.8	3.65	2.5	0.48	0.12	0.37	0.00	2.80	2.4	0.02	0.03	0.006	0.00	0.07 0.10	7.7	8.0	27.8 30.0
	0.8-1.2	3.75	1.9	0.60	0.13	0.38	0.05	2.77	1.7	0.02	0.02	0.003	0.00	0.06 0.09	7.8	7.9	30.0 27.5
	1.2-1.6	3.65	-	0.48	-	0.38	-	2.79	-	0.02	-	0.007	-	0.07 -	7.6	-	31.1 -
	1.6-2.0	3.55	-	0.72	-	0.38	-	2.45	-	0.03	-	0.008	-	0.08 -	7.6	-	27.7 -
	2.0-2.4	3.45	-	0.72	-	0.19	-	2.54	-	0.03	-	0.004	-	0.08 -	7.8	-	30.3 -
306-58	0 -0.4	4.85	5.9	0.48	0.12	0.38	0.05	3.99	5.7	0.02	0.03	0.004	0.00	0.08 0.10	7.6	7.8	30.7 38.1
	0.4-0.8	5.55	5.1	0.48	0.11	0.38	0.00	4.69	5.0	0.02	0.04	0.004	0.00	0.09 0.10	7.6	7.7	30.7 30.0
	0.8-1.2	2.95	4.9	0.73	0.11	-	0.00	3.22	4.8	0.02	0.04	0.003	0.01	0.09 0.09	8.2	7.5	29.2 30.0
	1.2-1.6	4.10	-	0.60	-	0.19	-	3.31	-	0.02	-	0.004	-	0.09 -	7.9	-	30.6 -
	1.6-2.0	3.25	-	0.60	-	0.38	-	2.27	-	0.02	-	0.003	-	0.08 -	8.0	-	30.0 -
	2.0-2.4	4.30	-	0.48	-	0.38	-	3.44	-	0.02	-	0.003	-	0.09 -	8.4	-	30.9 -
	Averages for three test sites (0-1.2ft)																
	0 -0.4	4.60	5.6	0.58	0.13	0.37	0.01	3.65	5.4	0.05	0.05	0.005	0.01	0.11 0.22	7.6	7.8	31.7 35.4
	0.4-0.8	4.48	3.5	0.52	0.11	0.38	0.00	3.59	3.4	0.02	0.04	0.005	0.003	0.09 0.11	7.6	7.8	30.2 29.3
	0.8-1.2	3.67	3.2	0.69	0.12	0.38	0.02	3.06	3.1	0.02	0.03	0.003	0.003	0.08 0.10	7.9	7.7	30.7 27.8
	Average	4.25	4.1	0.60	0.12	0.38	0.01	3.43	4.0	0.03	0.04	0.002	0.002	0.09 0.14	7.7	7.8	30.9 30.8

Note: "Pre" denotes pre-installation measurements.
"Post" denotes post-installation measurements.



Design of blower-type mixer for bentonite suspensions



Design of plunger device for smoothing surface and removing soil from permeameters

RESULTS OF CHEMICAL ANALYSIS OF BED MATERIAL SAMPLES COLLECTED IN 1957

SAMPLE		ELECTRICAL CONDUCTIVITY of Extract of 31.5% moisture paste at 25°C	SOLUBLE Na ⁺ meq. Na ⁺ 100 g. soil	TOTAL Na ⁺ (NH ₄ OAc Extractable) meq. Na ⁺ 100 g. soil	EXCHANGEABLE Na ⁺ (Total Soluble) meq. Na ⁺ 100 g. soil	CATION EXCHANGE CAPACITY meq. 100 g. soil	EXCHANGEABLE SODIUM PERCENTAGE
Station	Depth						
95+75	0-6	0.00100	0.024	0.246	0.222	8.2	2.7
	6-12	0.00064	0.041	0.199	0.154	8.8	1.8
112+46	0-6	0.00059	0.054	0.225	0.171	8.1	2.1
	6-12	0.00059	0.038	0.157	0.119	5.4	2.2
163+00	0-6	0.00042	0.030	0.142	0.112	5.8	1.9
	6-13	0.00037	0.053	0.157	0.104	5.6	1.9
255+44	0-6	0.00059	0.039	0.132	0.093	6.9	1.3
	6-12	0.00102	0.042	0.077	0.035	4.0	0.9

RESULTS OF CHEMICAL ANALYSIS OF PERMEAMETER SAMPLES FROM SERIES 58-1

SAMPLE		ELECTRICAL CONDUCTIVITY	SOLUBLE Na ⁺	TOTAL Na ⁺	EXCHANGEABLE Na ⁺	CATION EXCHANGE CAPACITY	EXCHANGEABLE SODIUM PERCENTAGE
Run	Depth in. cm.	of Extract of 31.5% moisture paste at 25°C	meq. Na ⁺ 100 g. soil	(NH ₄ OAc Extractable) meq. Na ⁺ 100 g. soil	(Total Soluble) meq. Na ⁺ 100 g. soil	meq. 100 g. soil	
AB	Pre-run	0.00084	0.076	0.157	0.081	6.9	1.17
KL	Pre-run	0.00064	0.063	0.123	0.060	6.6	0.91
1A	Top 2	0.00047	0.040	0.083	0.043	7.8	0.55
	2-4	0.00052	0.042	0.118	0.076	8.0	0.95
	4-6	0.00048	0.041	0.113	0.072	8.2	0.88
	12-14	0.00048	0.040	0.101	0.061	8.0	0.76
	22-24	0.00043	0.038	0.097	0.059	7.4	0.80
	Bottom 2	0.00051	0.042	0.110	0.068	7.6	0.89
1B	Top 2	0.00048	0.042	0.113	0.071	8.9	0.80
	2-4	0.00050	0.042	0.113	0.071	8.7	0.82
	6-8	0.00042	0.036	0.097	0.061	8.0	0.76
	12-14	0.00042	0.032	0.089	0.057	8.2	0.70
	22-24	0.00048	0.039	0.089	0.050	7.9	0.63
	Bottom 2	0.00049	0.041	0.097	0.056	7.6	0.74
2A	Top 2	0.00120	0.162	0.393	0.231	6.4	3.60
	2-4	0.00101	0.138	0.396	0.258	7.0	3.68
	6-8	0.00097	0.160	0.465	0.305	7.2	4.24
	12-14	0.00091	0.123	0.379	0.256	7.2	3.56
	22-24	0.00082	0.067	0.279	0.212	7.6	2.79
	Bottom 2	0.00087	0.082	0.224	0.142	7.5	1.89
2B	Top 2	0.00113	0.146	0.408	0.262	7.6	3.44
	2-4	0.00109	0.139	0.386	0.247	8.0	3.08
	6-8	0.00092	0.126	0.410	0.284	8.8	3.22
	12-14	0.00106	0.146	0.429	0.283	7.6	3.72
	22-24	0.00100	0.123	0.353	0.230	7.7	2.99
	Bottom 2	0.00101	0.096	0.279	0.183	7.2	2.54
2K	Top 2	0.00080	0.032	0.090	0.058	7.1	0.82
	2-4	0.00074	0.039	0.117	0.078	7.1	1.10
	6-8	0.00064	0.050	0.140	0.090	7.1	1.27

RESULTS OF CHEMICAL ANALYSIS OF PERMEAMETER SAMPLES FROM SERIES 58-1
(Continued)

SAMPLE Run	Depth in. cm.	ELECTRICAL CONDUCTIVITY of Extract of 31.5% moisture paste at 25°C	SOLUBLE Na ⁺	TOTAL Na ⁺ (NH ₄ OAc Extractable)	EXCHANGEABLE Na ⁺ (Total Soluble)	CATION EXCHANGE CAPACITY	EXCHANGEABLE SODIUM PERCENTAGE
			meq. Na ⁺ 100 g. soil	meq. Na ⁺ 100 g. soil	meq. Na ⁺ 100 g. soil	meq. 100 g. soil	
2K	12-14	0.00067	0.064	0.177	0.113	7.4	1.53
	22-24	0.00068	0.069	0.191	0.122	8.1	1.51
	Bottom 2	0.00080	0.077	0.191	0.114	7.8	1.46
2L	Top 2	0.00116	0.148	0.347	0.199	8.8	2.26
	2-4	0.00116	0.148	0.333	0.185	9.0	2.05
	6-8	0.00090	0.109	0.273	0.164	8.2	2.00
	12-14	0.00094	0.121	0.268	0.147	7.9	1.86
	22-24	0.00083	0.101	0.243	0.142	7.4	1.92
	Bottom 2	0.00091	0.115	0.276	0.161	7.1	2.27
3A	Top 2	0.00116	0.142	0.353	0.211	7.9	2.67
	2-4	0.00108	0.134	0.386	0.252	8.3	3.04
	6-8	0.00102	0.129	0.364	0.235	7.9	2.97
	12-14	0.00101	0.128	0.243	0.115	7.8	1.47
	22-24	0.00095	0.137	0.353	0.216	7.2	3.00
	Bottom 2	0.00086	0.112	0.350	0.238	7.1	3.35
3B	Top 2	0.00116	0.140	0.415	0.275	8.6	3.20
	2-4	0.00112	0.139	0.410	0.271	8.2	3.30
	6-8	0.00092	0.113	0.372	0.259	8.1	3.20
	12-14	0.00095	0.123	0.386	0.263	8.0	3.29
	22-24	0.00094	0.132	0.422	0.290	8.0	3.62
	Bottom 2	0.00082	0.113	0.293	0.180	7.4	2.40
3K	Top 2	0.00131	0.180	0.430	0.250	9.4	2.66
	2-4	0.00136	0.190	0.440	0.250	9.8	2.55
	6-8	0.00130	0.180	0.415	0.235	8.8	2.67
	12-14	0.00122	0.176	0.425	0.249	8.6	3.00
	22-24	0.00121	0.194	0.474	0.280	8.4	3.33
	Bottom 2	0.00141	0.287	0.489	0.202	9.8	2.06
3L	Top 2	0.00112	0.145	0.263	0.118	7.6	1.55
	2-4	0.00107	0.132	0.272	0.140	7.2	1.94
	6-8	0.00093	0.115	0.276	0.161	7.0	2.30

RESULTS OF CHEMICAL ANALYSIS OF PERMEAMETER SAMPLES FROM SERIES 58-1
(Continued)

Run	SAMPLE Depth in. cm.	ELECTRICAL CONDUCTIVITY of Extract of 31.5% moisture paste at 25°C	SOLUBLE Na ⁺	TOTAL Na ⁺	EXCHANGEABLE Na ⁺	CATION	EXCHANGEABLE
			meq. Na ⁺ 100 g. soil	(NH ₄ OAc Extractable) meq. Na ⁺ 100 g. soil	(Total Soluble) meq. Na ⁺ 100 g. soil	EXCHANGE CAPACITY meq. 100 g. soil	SODIUM PERCENTAGE
3L	12-14	0.00094	0.115	0.246	0.131	7.3	1.79
	22-24	0.00089	0.109	0.254	0.145	7.2	2.01
	Bottom 2	0.00101	0.121	0.251	0.130	7.6	1.71
4A	Top 2	0.00044	0.044	0.123	0.079	8.6	0.92
	2-4	0.00045	0.054*	0.118	0.064*	8.2	0.78*
	6-8	0.00052	0.079	0.237	0.158	8.2	1.93
	12-14	0.00051	0.082	0.306	0.224	8.2	2.73
	22-24	0.00055	0.098	0.251	0.153	8.2	1.86
	Bottom 2	0.00045	0.069	0.213	0.144	8.2	1.76
4B	Top 2	0.00057	0.054	0.143	0.089	8.8	1.01
	2-4	0.00057	0.064	0.183	0.119	8.7	1.37
	6-8	0.00050	0.042	0.118	0.076	8.2	0.93
	12-14	0.00047	0.041	0.110	0.069	8.4	0.82
	22-24	0.00045	0.042	0.177	0.135	8.8	1.53
	Bottom 2	0.00051	0.058	0.191	0.133	8.2	1.62
4K	Top 2	0.00126	0.168	0.330	0.162	8.0	2.02
	2-4	0.00107	0.143	0.304	0.161	7.8	2.06
	6-8	0.00091	0.116	0.251	0.135	7.5	1.80
	12-14	0.00106	0.135	0.285	0.150	8.1	1.85
	22-24	0.00098	0.120	0.289	0.169	8.8	1.92
	Bottom 2	0.00089	0.106	0.263	0.157	8.3	1.89
4L	Top 2	0.00123	0.164	0.343	0.179	8.2	2.18
	2-4	0.00095	0.129	0.293	0.164	7.6	2.16
	6-8	0.00082	0.102	0.237	0.135	7.1	1.90
	10-12	0.00083	0.102	0.233	0.131	7.1	1.84
	16-18	0.00086	0.107	0.237	0.130	7.2	1.80
	26-28	0.00088	0.104	0.246	0.142	7.4	1.92
	Bottom 2	0.00083	0.093	0.218	0.125	7.0	1.78

* Soluble probably high . . ESP probably low

RESULTS OF CHEMICAL ANALYSIS OF PERMEAMETER SAMPLES FROM SERIES 58-2

Run	SAMPLE Depth in. cm.	ELECTRICAL CONDUCTIVITY of Extract of 31.5% moisture paste at 25°C	SOLUBLE Na ⁺	TOTAL Na ⁺	EXCHANGEABLE Na ⁺	CATION EXCHANGE CAPACITY meq. 100 g. soil	EXCHANGEABLE SODIUM PERCENTAGE
			meq. Na ⁺ 100 g. soil	(NH ₄ OAc Extractable meq. Na ⁺ 100 g. soil	(Total Soluble) meq. Na ⁺ 100 g. soil		
1A	Pre-run	0.000668	0.068	0.206	0.138	7.2	1.92
	Top 2	0.001181	0.167	0.546	0.379	9.2	4.12
	2-4	0.001003	0.135	0.466	0.331	9.2	3.60
	6-8	0.001018	0.135	0.446	0.311	8.4	3.70
	12-14	0.001056	0.137	0.436	0.299	8.6	3.48
	22-24	0.001082	0.153	0.446	0.293	8.6	3.41
1B	Bottom 2	0.001164	0.161	0.426	0.265	8.2	3.23
	Top 2	0.001119	0.156	0.426	0.270	8.3	3.25
	2-4	0.000993	0.140	0.376	0.236	7.5	3.15
	6-8	0.000981	0.142	0.421	0.279	7.5	3.72
	12-14	0.001017	0.146	0.401	0.255	7.2	3.54
	22-24	0.001094	0.156	0.421	0.265	7.5	3.53
4K	Bottom 2	0.000986	0.140	0.411	0.271	7.7	3.52
	Top 2	0.000952	0.157	0.451	0.294	7.6	3.87
	2-4	0.000908	0.135	0.401	0.266	7.0	3.80
	6-8	0.000900	0.126	0.356	0.230	7.0	3.28
	12-14	0.000916	0.128	0.356	0.228	7.2	3.17
	22-24	0.000834	0.118	0.331	0.213	6.8	3.13
4L	Bottom 2	0.000895	0.126	0.346	0.220	6.8	3.24
	Top 2	0.001296	0.173	0.421	0.248	7.5	3.31
	2-4	0.000956	0.159	0.386	0.227	7.1	3.20
	6-8	0.001005	0.148	0.376	0.228	6.8	3.35
	12-14	0.000856	0.131	0.356	0.225	7.0	3.21
	22-24	0.000895	0.142	0.366	0.224	7.1	3.15
4N	Bottom 2	0.000895	0.128	0.356	0.228	7.0	3.26
	Top 2	0.001548	0.479	1.615	1.136	8.0	14.20
	2-4	0.001072	0.279	0.855	0.576	7.5	7.68
	6-8	0.000957	0.139	0.381	0.242	7.4	3.27
	12-14	0.000923	0.102	0.253	0.151	7.5	2.01
	22-24	0.000922	0.082	0.232	0.150	7.7	1.95
	Bottom 2	0.000958	0.099	0.253	0.154	7.3	2.11

UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

PHYSICAL CHARACTERISTICS OF THE
BENTONITE/SOIL INTERFACE--SEDIMENT
SEALING PROJECT
LOWER-COST CANAL LINING PROGRAM
Petrographic Laboratory Report No. Pet-122

DIVISION OF ENGINEERING LABORATORIES



COMMISSIONER'S OFFICE
DENVER, COLORADO

September 2, 1958

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UNITED STATES
DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

Commissioner's Office--Denver
Division of Engineering Laboratories
Chemical Engineering Laboratory Branch
Petrographic Laboratory Section
Denver, Colorado
September 2, 1958

Laboratory Report No. Pet-122
Written by: S. Rubenstein
Checked by: W. Y. Holland
Submitted by: W. U. Garstka

Subject: Physical characteristics of the bentonite/soil interface--
Sediment sealing project--Lower-cost Canal Lining Program

INTRODUCTION

The work described in this report was conducted to supplement the fiscal year 1958 Cooperative Bureau-Colorado State University Sediment Sealing Project. The University assignment was to find the causes of the bentonite surface layer formation during the Lateral 1, North Platte Project installation and to recommend improved methods of sediment sealing. The University chose the permeameter approach to the problem described in their fiscal year 1958 report. As a part of the Bureau Lower-cost Canal Lining Program, the Division of Engineering Laboratories undertook the petrographic work to provide a different approach to the same problem. The two studies were to be coordinated so that tests would be conducted on the same soil specimens and similar clay-water systems. In line with this program, a series of permeability tests with flocculated and dispersed bentonite were to be conducted by the University (1) after which the Bureau would conduct a petrographic examination of the tested samples.

Four of the permeameter tube samples after testing were submitted by Colorado State University to the Bureau Engineering Laboratories. The Petrographic Laboratory was requested to examine the soil structure and the clay-water suspension system. The samples consisted of bed material collected from Lateral 1 site, Torrington, Wyoming, and packed to a density approaching natural conditions in plastic permeameter tubes. The samples marked 58-I, 1C and 4C represent the series of tests with flocculated bentonite and 58-II, 1C and 4M with dispersed bentonite. Sample No. 58-II, 4M contained 8 percent moisture and Sample No. 58-II, 1C was subjected to permeation with water before being treated with bentonite.

(1) Numbers in parentheses refer to Bibliography at end of text.

CONCLUSIONS

The two methods of investigation of the bentonite/soil interface were as follows:

1. Microscopic examination
2. X-ray diffraction analysis

A study of the soil pore space by microscopic methods indicates that the size of the voids (0.02 to 0.12 mm) is sufficient to pass individual platelets (approximately 2 microns) and small aggregated particles of clay.

Determination by X-ray diffraction of the orientation of the bentonite particles at the bentonite/soil interface shows they are parallel to the surface of sedimentation, indicating a possibility of a bridging effect over the void spaces.

Evidence of bentonite penetration was absent in these samples.

METHODS OF STUDY

The orientation of the bentonite particles was determined by X-ray methods. The samples were examined optically with stereoscopic and petrographic microscopes. Clay-staining tests were also performed for identification.

THIN SECTION PREPARATION

Petrographic thin sections taken at depths of 1 inch, 4 inches, 8 inches, and 12 inches (horizontal and vertical section for each point) were prepared from each tube (Table 1). A new method of impregnation of the material for petrographic thin sections was used. This included the use of a high molecular weight polyethylene glycol (Carbowax-6000) (2) which melts at 55° C and is soluble in water in all proportions. The use of this material has the advantage of replacing the soil moisture without changing the structure of the soil.(3)

Slices about one inch thick were first sawed from the tubes at various points (1, 4, 8, and 12 inches from the top). These samples were then placed in the oven with melted Carbowax at 65° C. At the end of 3 days, the water in the soils and the melted Carbowax had formed a uniform mixture by diffusion; the samples were then removed from the Carbowax and allowed to cool. Thin sections of 0.04 mm thickness were then ground by standard methods with the exception that kerosene instead of water was used as both lubricant and cleaner, and the cement used for sticking the sample to the microscope slide did not require heat for application.

TEXTURAL PARAMETERS

The grain size and void spaces were determined with the eyepiece micrometer and microscope. The amount of original clay was estimated during thin section analysis by the point counter method. The observed radii of the grains and voids were corrected in accordance with the theory of thin section analysis.⁽⁴⁾ A chart showing the size and frequency distribution of the voids is shown in Figure 1.

A summary of the petrographic analysis appears in Table 2.

Photomicrographs of thin sections were taken to show the texture and void spaces in the soil (Figures 2, 3, and 4).

X-RAY STUDIES

For X-ray studies, a 1 percent suspension of bentonite and water was first prepared using 6 grams of bentonite and 594 grams of water. The suspension was then separated into two fractions. To one fraction, sufficient dispersant was added to separate the fine-grained clay. The bentonite (Baroid), dispersant (tetrasodium pyrophosphate) and water (prepared synthetically of similar hardness, see Table 2) that were used in the field installation were mixed to produce the bentonite suspension. Both fractions (dispersed and flocculated) were sedimented in water 1 to 2 days on a flat plastic surface. The samples were then evaporated in a 65° C oven, and flakes of each were X-rayed.

The bentonite layer in the permeameter tubes was previously removed in the permeability tests by the University, therefore, to examine the results of the sediment sealing a section of permeameter tube 1 inch from the original surface (Permeameter Tube 58-I-4C) was sedimented with bentonite in a manner similar to that first applied to the tube at Colorado State University. A 1 percent solution of bentonite and canal water with sufficient dispersant added was sedimented on the upper soil surface. The hydraulic gradient of 3 was maintained by a column of water with a self-starting constant head device. The head remained constant except for the period of initial application of the bentonite solution. After a 48-hour sedimenting period, the tube was opened for observation. The bentonite layer was about 1/8 inch thick and rested only on the surface with no penetration visible. A photograph of the clay-soil interface is seen in Figure 5.

OUTLINE OF PROCEDURES

An outline of the procedure for the examination of the soils is as follows:

- I. General description
- II. Petrographic examination
 - A. Preparation of the soils
 - 1. Cutting of cores at 4-inch intervals
 - 2. Impregnation with a water soluble wax
 - 3. Grinding of the petrographic thin sections with kerosene
 - B. Microscopic examination
 - 1. Void and grain size
 - 2. Texture
 - 3. Mineralogy
 - C. Special techniques
 - 1. Clay-staining tests
 - 2. X-ray diffraction analysis
 - 3. Photographs
 - D. Sedimentation
 - 1. Preparation of bentonite, dispersant, and water solution
 - 2. Permeameter tube with constant head device for dispensing bentonite solution

The samples in general are similar and therefore will be discussed together.

PETROGRAPHIC EXAMINATION

Laboratory Nos. P-6496A, B, C, E, 6508A, B, D, E, G (58-II, 1C and 4M)

The soils are composed of tan, friable, poorly graded, fine-grained sand and silt. The shape of the grains in thin section varies from spherical to flat, mainly having a sphericity of approximately 0.6.(5) Most of the grains have subrounded to rounded corners which show the effect of transportation by water. The soils are loosely packed; either point-to-point contact of the grains or water film between the grains is the general case. The size of the particles ranges from 0.04 to 0.54 mm, the median range is 0.05 to 0.17 mm (average size 0.18 mm). The voids differ from the grains in both size and frequency. They range in size from submicroscopic to 0.46 mm in diameter. The median range is from 0.02 to 0.12 mm (average size 0.16 mm) (Figure 1). The percentage of voids present ranges from 13 to 30 percent. The major mineral component is quartz with minor amounts of potash and plagioclase feldspar, amphiboles, pyroxenes, clay, and iron oxide. Only trace amounts of sparsely distributed original clay are present in the form of aggregates in the void spaces or to a lesser extent as coating on the quartz grains.

Laboratory Samples No. P-6472, 6480, 6481 (58-I, 1C and 4C)

The soils are similar in appearance and texture to those described above. The mineral composition is also similar with only insignificant amounts of clay present.

A comparison of the methods of thin section preparation shows that for the samples prepared with Carbowax, in general, the voids are slightly more frequent and larger than those occurring in the samples prepared with a plastic resin (R-313).(6)

Orientation of Bentonite Platelets

The X-ray diffraction pattern of the specially sedimented bentonite on a plastic slide shows a concentration of energy of the 14 A line due to the high degree of orientation of the bentonite. The pattern of the 14 A line appears as two crescent-shaped arcs instead of a circular line. The intensification of the pattern is due to the preferred orientation of the clay along the basal plane parallel to the surface of sedimentation.

RESULTS AND DISCUSSION

The size and percentages of the void spaces of the samples (mean size 0.02 to 0.12 mm and 13 to 30 percent) are sufficient to pass individual platelets (approximately 2 microns) and small aggregated particles of bentonite. However, in all the samples, only trace amounts of bentonite were visible immediately below the surface, indicating causes other than particle size exist for the inability of the bentonite to penetrate the soils. The photograph taken of the bentonite sedimented soil shows conclusively the lack of penetration of bentonite into the soil (Figure 5).

The X-ray diffraction analysis indicates that the bentonite platelets at the clay-soil interface are oriented parallel to the surface of sedimentation. This orientation of the particles may form laminae which have a bridging effect over the void spaces and in time forms a surface seal on the soil. This is the most likely explanation obtained from this study for the formation of the bentonite surface layer which forms a bentonite sediment lining.

The results of the petrographic examination indicate that the new technique of thin section preparation is more favorable than the previous method (plastic resin R-313) in preserving the original pore space without changing the volume. In general, a comparison of the samples from 58-I, 1C prepared from Carbowax and R-313 showed slightly larger void spaces in the thin sections made with Carbowax.

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Special thanks are also due to Mr. R. T. Shen, Research Engineer, Colorado State University, for his assistance in supplying the samples.

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Table 1

PETROGRAPHIC SAMPLE DESIGNATION					
Laboratory:	:	:	:	:	
Sample No.:	Depth:	Series:	Run:		Notes
P-6480	: 0-1"	: 58-1	: 1C	: Saturated	} Flocculated
P-6481	:	:	:	:	
P-6472	: 0-1"	: 58-1	: 4C	: 6 percent moisture	
P-6496A	: 0-1"	: 58-2	: 1C	: Saturated	} Dispersed
B	:	:	:	:	
C	: 4"	:	:	:	
D	:	:	:	:	
E	: 8"	:	:	:	
F	:	:	:	:	
G	: 12"	:	:	:	
H	:	:	:	:	
P-6408A	: 0-1"	: 58-2	: 4M	: 8 percent moisture	
B	:	:	:	:	
C	: 4"	:	:	:	
D	:	:	:	:	
E	: 8"	:	:	:	
F	:	:	:	:	
G	: 12"	:	:	:	
H	:	:	:	:	

Table 2

CHEMICALS USED IN THE MANUFACTURE
OF CANAL WATER

Item (Reagent grade)	:	Quantity (gm per liter)
	:	
$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ (dissolved first)	:	0.40
	:	
$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$	:	0.44
	:	
$\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	:	0.11
	:	
NaHCO_3	:	0.28,
	:	
NaCl	:	0.60
	:	
KCl	:	0.10
	:	

Table 3

SUMMARY OF PETROGRAPHIC CHARACTERISTICS OF THE SOILS

Sample No.	Series	Depth (inches)	Texture		Mineralogy		Stain test	Remarks
	Run		Grain size*	Void size*		%		
P-6480	58-I 1C	0-1"	:0.04-0.54 mm :Av 0.18 mm	:0.02-0.46 mm :Av 0.17 mm	:Major			
					: Quartz		: Negative	: Flocculated
					: Wax			
					: Minor			
					: Feldspar			
					: Chert			
					: Amphibole			
					: Iron oxides			
: Clay								
P-6472	58-I 4C	0-1"	:0.04-0.54 mm :Av 0.18 mm	:0.02-0.46 mm :Av 0.17 mm	:Major			
					: Quartz	: 66.4	: Trace	: Flocculated
					: Wax	: 30.0		
					: Minor			
					: Chert	: 1.2		
					: Amphibole	: 0.8		
					: Clay	: 0.7		
					: Feldspar	: 0.6		
: Iron oxide	: 0.3							
P-6496A	58-II 1C	0-1"	:0.04-0.54 mm :Av 0.18 mm	:0.02-0.46 mm :Av 0.17 mm	:Major			
					: Quartz	: 83.0	: Trace	: Dispersed
					: Wax	: 13.2		
					: Minor			
					: Iron oxides	: 1.45		
					: Amphibole	: 1.35		
					: Chert	: 0.45		
					: Feldspar	: 0.18		
: Clay	: Trace							
P-6496B	58-II 1C	0-1"	:0.04-0.54 mm :Av 0.18 mm	:0.02-0.46 mm :Av 0.17 mm	:Major			
					: Quartz		: Trace	: Dispersed
					: Wax			

Table 3--Continued

Sample No.	Series	Depth (inches)	Texture		Mineralogy		Stain test	Remarks
	Run		Grain size*	Void size*		%		
P-6496B					Minor			
					Iron oxides			
					Amphiboles			
					Chert			
					Feldspar			
					Clay			
P-6496C	58-II 1C	4"			Major			
				0.02-0.46 mm	Quartz		Negative	Dispersed
				Av 0.17 mm	Wax			
					Minor			
					Feldspar			
					Chert			
					Iron oxide			
					Amphibole			
P-6496E	58-II 1C	8"			Major			
				0.02-0.46 mm	Quartz		Negative	Dispersed
				Av 0.17 mm	Wax			
					Minor			
					Feldspar			
					Chert			
					Iron oxide			
					Amphibole			

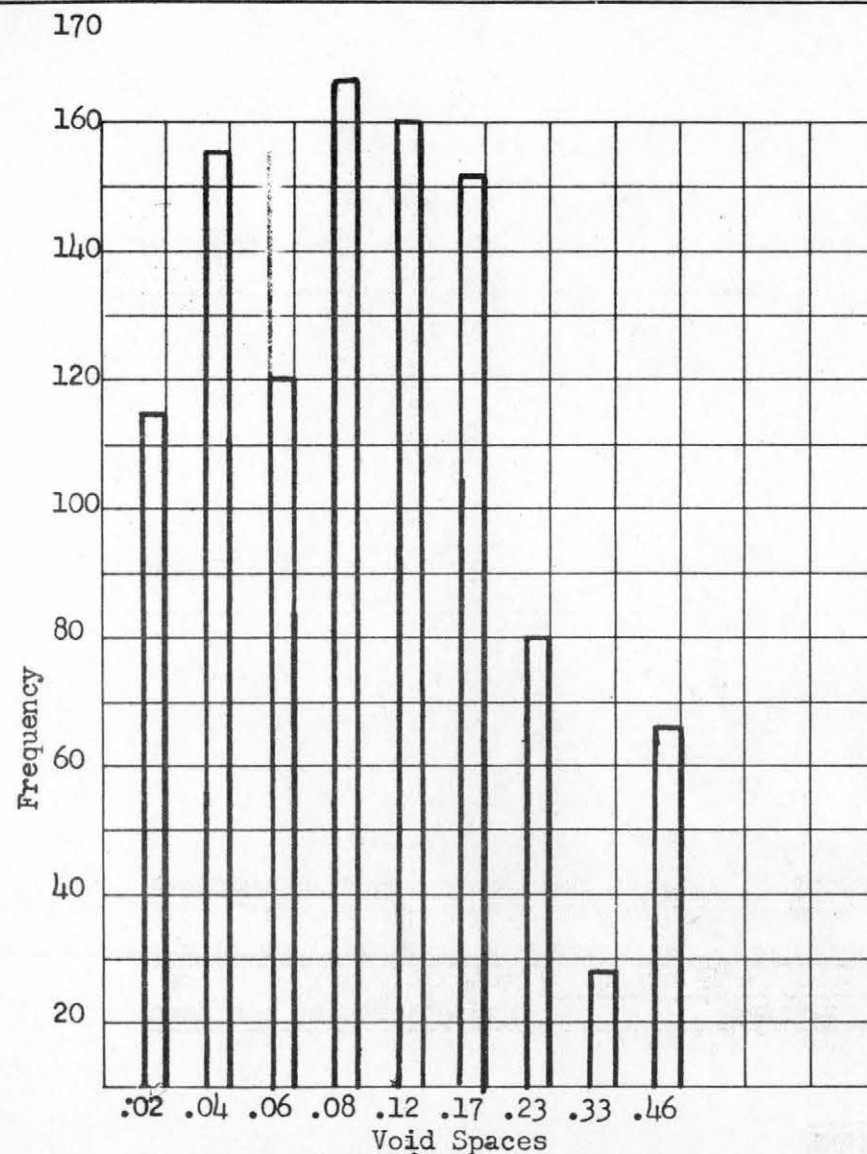
Table 3--Continued

Sample No.	Series	Depth (inches)	Texture		Mineralogy		Stain test	Remarks
	Run		Grain size*	Void size*		%		
P-6496G	58-II 1C	12"		0.02-0.46 mm Av 0.17 mm	Major Quartz Wax		Negative	Dispersed
					Minor Feldspar Chert Iron oxide Amphibole			
P-6508A	58-II 4M	0-1"	0.04-0.54 mm Av 0.18 mm	0.02-0.46 mm Av 0.17 mm	Major Quartz Wax	70.3 22.2	Trace	Dispersed
					Minor Feldspar Iron oxide Chert Clay Amphibole	2.4 2.2 1.3 1.2 0.4		
P-6508B	58-II 4M	0-1"	0.04-0.54 mm Av 0.18 mm	0.02-0.46 mm Av 0.17 mm	Major Quartz Wax		Trace	Dispersed
					Minor Feldspar Iron oxide Clay Amphibole			

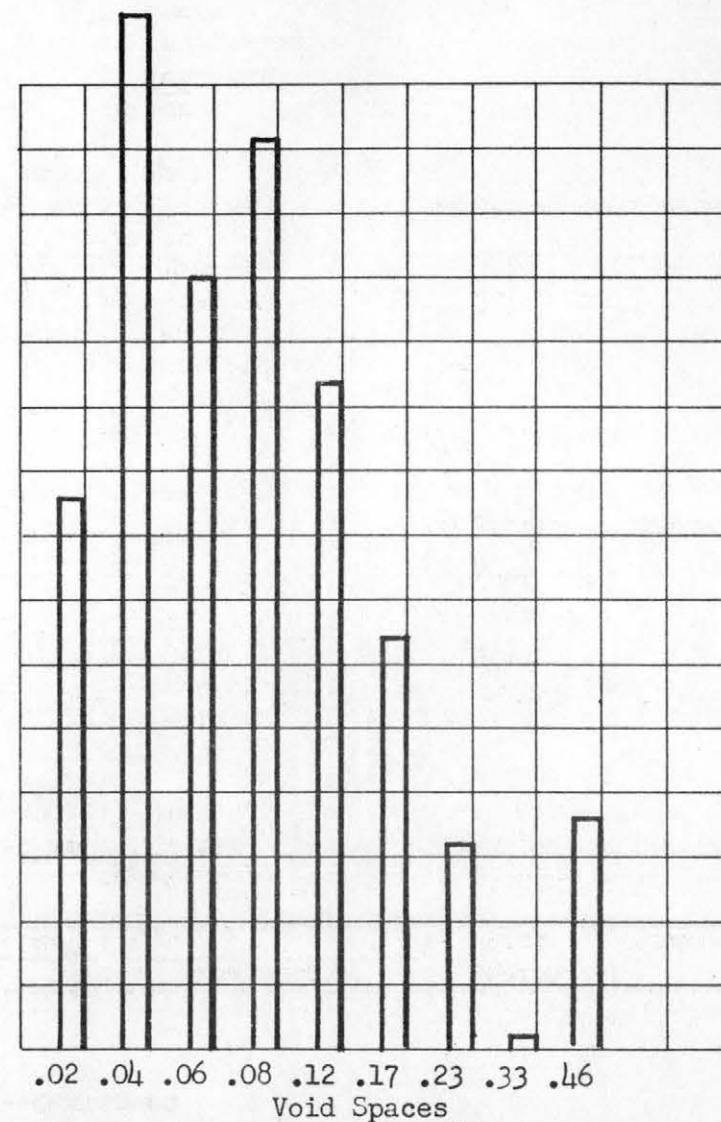
Table 3--Continued

Sample No.	Series	Depth (inches)	Texture	Mineralogy	Stain test	Remarks
	Run		Grain size* : Void size*	%		
P-6508D	58-II 4M	4"	:0.02-0.46 mm :Av 0.17 mm	Major Quartz Wax Minor Feldspar Iron oxide Chert Clay Amphibole	:Negative	:Dispersed
P-6508E	58-II 4M	8"	:0.02-0.46 mm :Av 0.17 mm	Major Quartz Wax Minor Feldspar Iron oxides Chert Clay Amphibole	:Negative	:Dispersed
P-6508G	58-II 4M	12"	:0.02-0.46 mm :Av 0.17 mm	Major Quartz Wax Minor Feldspar Iron oxides Chert Clay Amphibole	:Negative	:Dispersed

LAB. SAMPLE NO. _____ DRAWN BY _____ CHECKED BY _____ DATE _____



Tube 3-58 II-1C



Tube 4-58 II-4M

Fig. 1-Distribution of voids in permeameter tube samples.

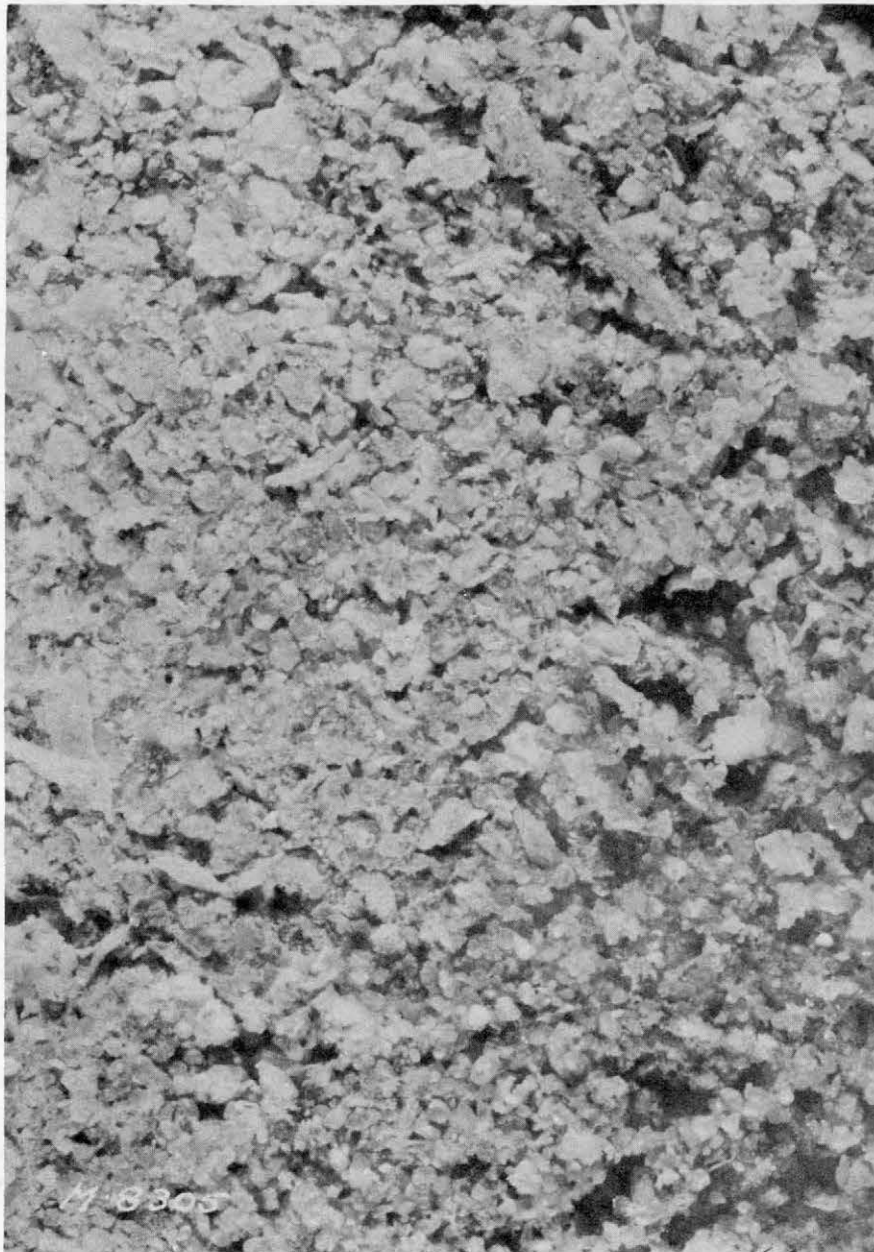


Fig. 2 - Photomicrograph of surface of packed permeameter sample 53I-1c composed of fine sand and silt showing texture (void spaces and fine grain size).

Magnification 12x

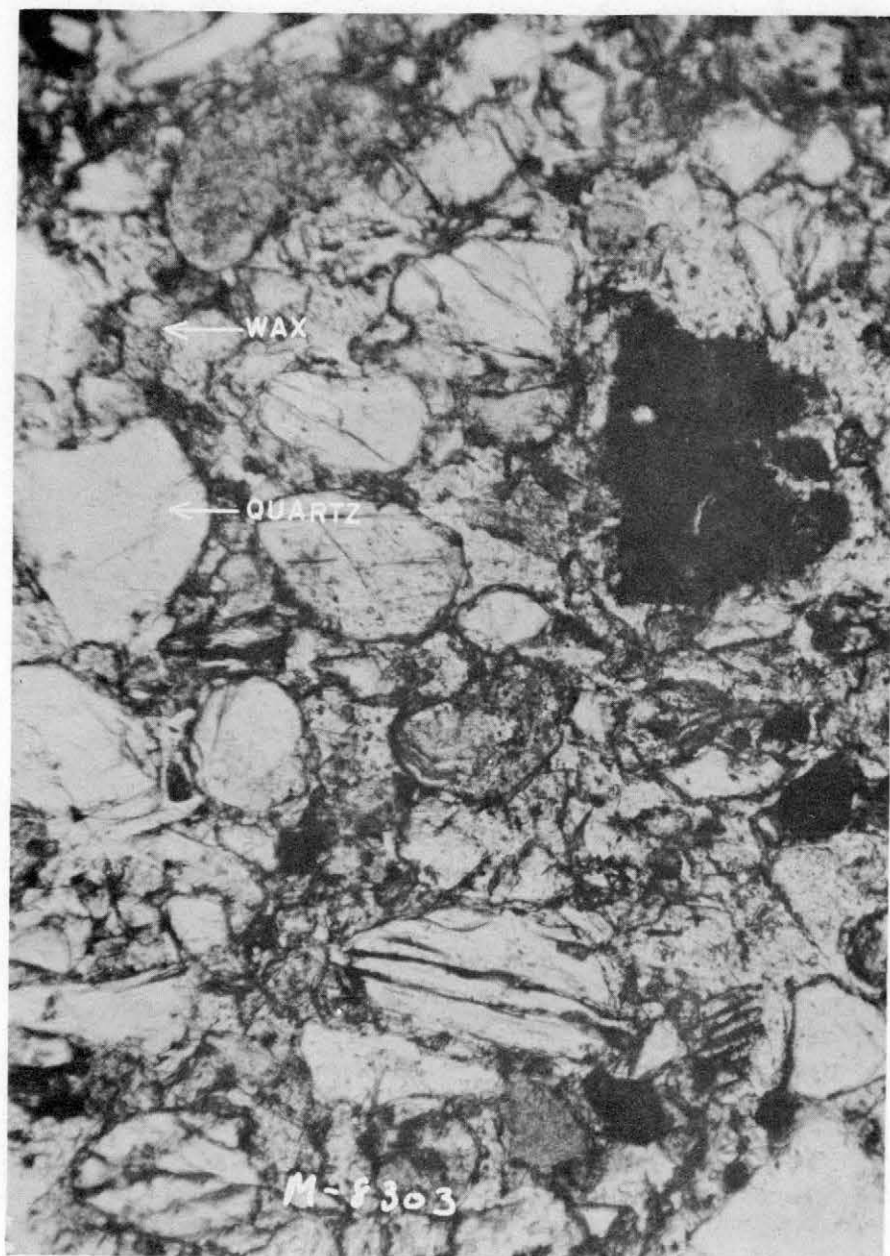


Fig. 3 - Photomicrograph of thin section (P-6481) 58I-1c composed of fine sand and silt showing texture (void spaces and fine grain size), light areas are quartz grains, intergranular areas are wax.

Magnification 150x

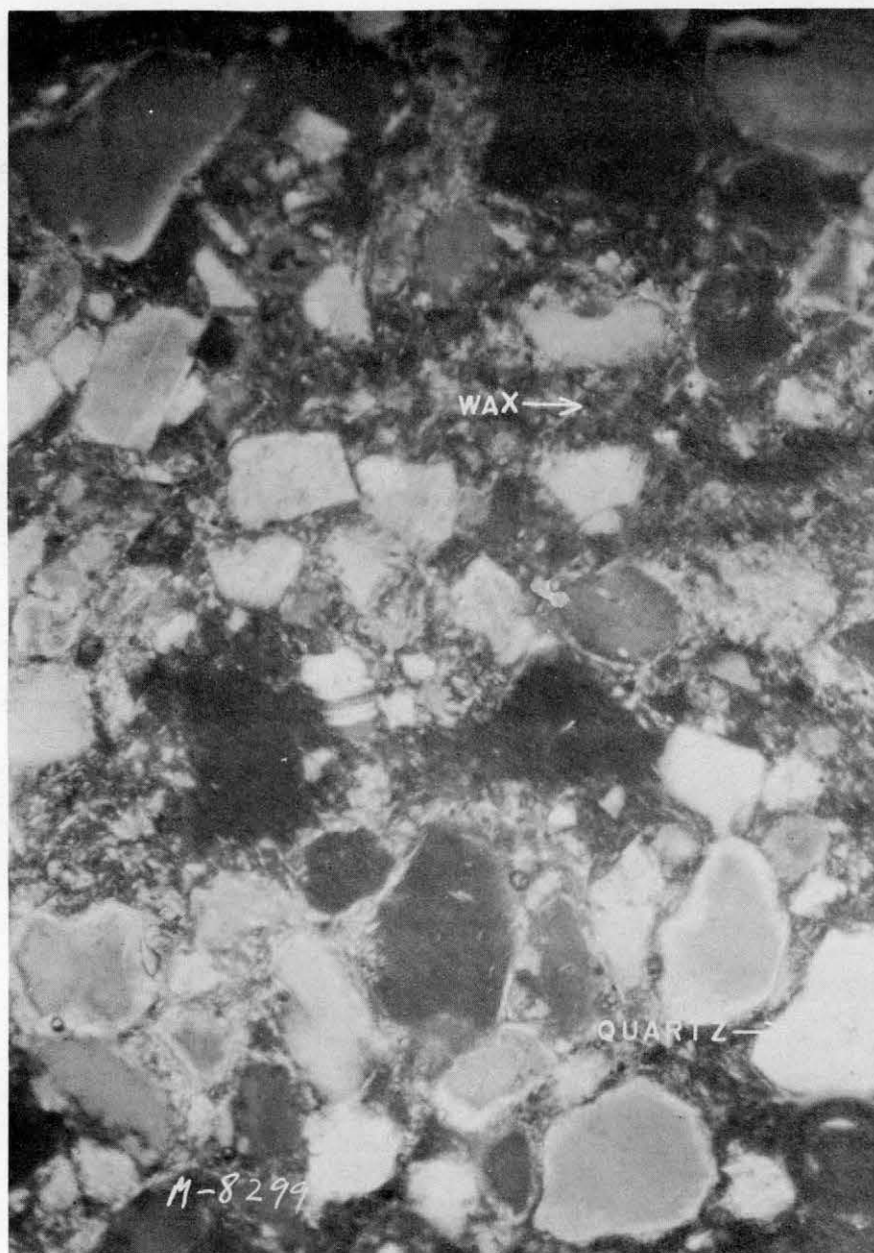


Fig. 4 - Photomicrograph of thin section (P-6496-A Sample 58I-1c) composed of fine sand and silt showing texture (void spaces and fine grain size), white and gray areas (quartz grains), shredded areas (wax).

X-Nichols

Magnification 150x

(Refer to Fig. 45 in the main report)

Figure 5- Photograph of surface of the bentonite sedimented soil Sample No. 58I-4C showing layer of clay on soil surface. White milky area (clay), rounded light areas (quartz grains), dark areas (voids). Lack of penetration of the clay is seen by the unfilled void spaces.