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The Flow of Colloidal Suspensions Through Porous Media

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CONTENTS

Summary	3
Introduction	4
Review of Literature	5
Materials, Equipment, and Procedure	8
Data and Discussion	20
Bentonite Retention in the Column	22
Electrical Data	23
Sealing	24
Discussion of Errors and Scatter in the Data	28
Conclusions	31
References	31
Appendix	33

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SUMMARY

Knowledge of the fundamental relationships involved in the flow of colloidal suspensions through porous media is important to provide a satisfactory solution for various problems in the field of water resources. The purpose of this study was to establish some of these fundamental relationships.

Carborundum was used as the porous media. De-aired, double-distilled water and stable colloidal suspensions of Wyoming bentonite in double-distilled water were used.

The carborundum was placed in permeameters made of Lucite. These permeameters had an inside diameter of 2 inches and would hold a column of carborundum approximately 6 inches long.

A vacuum-tube voltmeter was used to measure the streaming potential between two platinum electrodes placed at either end of the column of carborundum in the permeameter.

Tests were conducted on uniform-sized carborundum with mean diameters of 775, 385, 274, 163, 80, and 63 microns. Hydraulic gradients of 0.1 to 2.0 were used. The bentonite suspensions were prepared and used in two concentrations, 0.1 and 1.0 per cent. All tests were conducted under conditions of laminar flow.

The test procedure involved three phases: (1) an initial flow of distilled water, (2) the introduction of the suspension, and (3) the re-introduction of the distilled water. Specific discharge, permeability, and the zeta potential of the carborundum were calculated for each phase.

A comparison of the reduction in specific discharge between the first and second phase and between the first and third phase was used to determine the effect of various hydraulic gradients and suspension concentrations on flow through the column of carborundum.

Comparisons were made to determine whether any relationship existed between the calculated zeta potentials, and the reduction in specific discharge.

The study indicates the following conclusions: (1) mechanical filtering is the main process by which bentonite particles are removed from suspension by the carborundum column, (2) the degree of sealing, as measured by the reduction in specific discharge or permeability, increases with decreasing particle size, (3) the degree of sealing increases with increasing hydraulic gradient, (4) the degree of sealing increases with increasing concentration of the suspension, (5) the shape of the particles of the media has a considerable effect on the sealing process, (6) electrokinetic measurements can be made on large size columns of porous media under low pressures and in conjunction with hydraulic measurements, and (7) the calculated zeta potential of the carborundum can be correlated with the degree of sealing.

The Flow of Colloidal Suspensions Through Porous Media

R. BRUCE CURRY AND ROBERT P. BEASLEY

INTRODUCTION

Water is one of our most important resources. The future development of our nation will depend to a large extent on how well we utilize this resource. Considering the United States as a whole, sufficient water falls in the form of rain and snow to provide for all uses. The problem, then, is one of transportation, storage and utilization. In recent years investigators in the field of water resources have intensified their work in the following areas; seepage loss reduction from storage and conveyance structures, ground water recharge, purification of water supplies, and the deposition of wastes. In all these areas the phenomenon of flow of water, or water containing colloidal material, through porous media, must be taken into consideration.

Since the phenomenon of flow of water, or water containing colloidal material, through porous media is common to many of the above problem areas in water resource development, it would seem possible that the solution of some of these problems could be obtained by applying fundamental knowledge of the phenomena. The flow of water through porous media has been investigated by many workers and the basic relationships have been developed. However, the flow of colloidal suspensions in porous media has been investigated by only a few workers. Further investigations are needed to provide a fundamental understanding of this phenomenon.

The purpose of this study was to investigate the flow of colloidal suspensions in a porous media, in order to establish some basic relationships.

Specific problems considered were:

1. What effect does hydraulic head have on the flow of a colloidal suspension in porous media?
2. What effect does the concentration of a colloidal suspension have on the flow of the suspension in porous media?

3. What is the relation between the zeta potential of the porous media and the sealing effect of the colloidal suspension?

The study was limited to the use of granular carborundum as the porous media, a commercial high-swelling Wyoming bentonite as the colloidal material, double-distilled water, and stable colloidal suspensions.

REVIEW OF LITERATURE

The flow of fluids through porous media has been investigated by many workers and there is an abundance of literature on the subject.

A classical experiment performed by Henry Darcy (2) in 1856 established the relationship for the flow of water through a bed of filter sand. This relationship, which stated that when water flows through a bed of sand, the rate of flow is proportional to the cross sectional area of the bed and the hydraulic gradient across the bed, has come to be referred to as "Darcy's Law." The proportionality constant in the above relationship is commonly called hydraulic conductivity.

Investigators since Darcy have sought to establish further factors upon which the proportionality constant depends and to determine the inter-relationships of these factors. A recent example of the derivation of Darcy's Law has been given by Hall (5).

Two other approaches to the development of an equation for the flow of fluids through porous media have been presented in the literature. Kozney (7) (1927) developed an empirical equation which related the permeability of a porous medium to the geometrical properties of the media. Rose (10) and later Rose and Rizk (11) used dimensional analysis in an investigation of the flow of fluids through porous media. The equation they developed related the hydraulic resistance of the media to Reynolds number.

The flow of colloidal suspensions in porous media is a specific example of fluid flow in porous media. Filtration and the sealing of canals and reservoirs by sedimentation methods are examples of application of flow of colloidal suspensions in porous media to field problems.

The literature on the flow of colloidal suspensions in porous media is very limited. A series of investigations was started in 1954 at Colorado State University as part of a project to develop a sedimentation method of lining irrigation canals to prevent seepage. The first of this series was investigated by Curry (1), who used sands and glass beads as the porous media and Wyoming bentonite in the colloidal suspensions. The granular material was held in a permeameter during the tests. He reported the following results:

1. Bentonite in suspension did not penetrate uniform-sized particulate material with a median diameter below a certain size (approximately 57 microns for this study), owing to the filtering of such a medium.
2. Bentonite did not deposit from a stable suspension when passing through

or standing in the pores of a chemically inert sand. Under a large hydraulic gradient, no deposition was observed for sands of slight chemical reactivity.

3. At small hydraulic gradients, a very small amount of bentonite was deposited and there was a reduction in hydraulic conductivity in the sands having slight chemical reactivity and diameter sufficiently large for the suspension to enter the pores of the medium.
4. When a chemical environment of high chemical reactivity was present, a standing period was used, complete sealing and deposition of bentonite occurred in those media of sufficiently large particle size so that the suspension entered the media.

In conclusion, Curry emphasized the need to further investigate the role of particle shape, particle size gradation, and hydraulic gradient in penetration and sealing.

Newman (8), continuing the work on penetration and sealing, made permeability measurements on columns of a natural dune sand, using as fluids, a 1 percent bentonite suspension and a solution of a dispersant (sodium tripolyphosphate). He found that the hydraulic gradient was a factor in penetration and sealing and for his tests there was a critical value between 0.03 and 0.30. At values of hydraulic gradient lower than critical, filtering occurred at the surface. But at hydraulic gradients greater than the critical value, bentonite was not retained in the sand in significant quantities. Newman also found that the dispersant solution caused leaching and movement of the natural clay in the sand, which in turn caused a reduction in permeability due partly to settling. This phenomenon, he indicated, could lead to a sealing method for some field conditions using in-place sedimentation with a dispersant solution.

The research on penetration and sealing was continued by Shen (13), using two soils, a Greeley fine sandy loam and a sand from the shore of Loveland Lake. Permeability measurements on columns of these materials were made using either a 1 percent dispersed Wyoming bentonite suspension, or a 0.2 percent solution of sodium tripolyphosphate. Shen found that sealing occurred in different degrees at various depths in the columns, but all columns were sealed at the surface. Deeper penetration and more complete sealing occurred with higher hydraulic gradients (hydraulic gradients from 0.1 to 1.0 were used). No complete sealing was observed because of the insensitivity of the system of measurement in the region near complete sealing.

Stanley (15), investigated the mechanism of suspended particle removal from water by rapid sand filters using radioactive techniques. Hydrous ferric oxide flocs were used as the suspended particles. The radioactive tracer used was the isotope, I^{131} . The filter medium was uniform Ottawa sand. He defined the penetration index, as the penetration in centimeters caused by the passage into a filter of one milligram of Fe per square centimeter of filter area. This index varied linearly with the sand size and directly with the flow rate. Also the pene-

tration index increased with the addition of NaCl and Na₂SO₄ to the suspension and decreased with an increase in floc size. His conclusions were that the effects of van der Waals forces, electrokinetic forces, chance contact with a surface, and possibly sedimentation, were the most important processes in the removal of flocs from the suspension. Straining, inertia, and Brownian movement were unimportant removal processes.

Colloidal clays have been used to reduce seepage losses from water conveyance and storage structures. In 1953, Dirmeyer (3) initiated a project to develop and evaluate methods of sealing canals by sedimentation. In general, the procedure was to disperse a fine-grained lining material in canal water and allow this suspension to be carried by the flowing water to wherever the seepage was taking place. The suspension then would pass into the pores of the leaking canal beds and sides and be retained below the surface, thereby reducing the seepage. The results varied, but in general, satisfactory results were obtained in the loessial and sandy soils.

Since any study of the flow of fluids in porous media is concerned with the movement of a fluid past the surfaces of the particles making up the media, an understanding of both the physical and chemical behavior is necessary. In considering the hydrodynamics of the system, its physical shape and surface configuration have been taken into account. If there is no chemical reaction between the solid surface and the fluid, one other physiochemical phenomenon, electrokinetics, must be considered. This phenomenon involves electricity and the tangential movement of the solid and liquid phases along each other.

The example of this electrokinetic phenomenon which is most applicable to this study is streaming potential (the development of a potential difference by the application of an external pressure to the liquid in a porous plug).

In 1879, Helmholtz (6), developed an equation from theoretical considerations of the double layer and the streaming potential concept. He showed that the ratio of the streaming potential, (ΔE), to the pressure difference, (P), was a constant. Smoluchowski (14), generalized this equation for any shape conduit, including a porous plug. This equation is:

$$\frac{\Delta E}{P} = \frac{D\zeta}{4\pi\eta\lambda_s}$$

in which (ΔE) is streaming potential; (P), the pressure difference across the plug; (D), the dielectric constant of the liquid; (ζ), the zeta potential; (η), the viscosity of the liquid; (λ_s), the electrical conductivity of the liquid. The equation is generally known as the Helmholtz-Smoluchowski equation.

Investigators in recent times have attempted to broaden the understanding of the theory, and to use streaming potential methods as a tool in other areas of science.

Streaming potential techniques have been used to study the surface chemistry of minerals. Fuerstenau (4) used this technique to investigate quartz. He de-

veloped equipment and a procedure for measuring the zeta potential of quartz by the streaming potential method.

O'Conner, *et. al.* (9), investigated electrokinetic properties of quartz and corundum.

The streaming potentials of very uniform spherical-grained sands were measured by Schriever and Bleil (12). They found that the ratio of the streaming potential, (ΔE), to the pressure difference, (P), was independent of the changes in configuration of the sand matrix as well as its porosity and length, which is in accord with the generally accepted theory. A variation in ($\Delta E/P$) with grain diameter was found which could only be partially accounted for by surface conductance alone. They developed an empirical equation to relate ($\Delta E/P$) to grain diameter.

A summary of the literature indicates:

(1) the need for further investigation of the flow of colloidal suspensions in porous media, particularly with respect to the effect of hydraulic gradient and suspension concentration.

(2) Darcy's law can be applied to the analysis of the flow of colloidal suspensions in porous media if laminar flow conditions prevail.

(3) the concept of streaming potential should be used in conjunction with a study of the flow of colloidal suspensions in porous media in an attempt to relate the physio-chemical properties of the media to flow through the media.

MATERIALS, EQUIPMENT AND PROCEDURE

The purpose of this study was to investigate the flow of colloidal suspensions in porous media. Carborundum was used as the porous media; the colloidal suspensions were prepared from Wyoming bentonite and double-distilled water. These suspensions were allowed to flow through the carborundum. Measurements of rate of flow and hydraulic head loss were made. Also, since the electrokinetic properties of the carborundum were important in this study, electrical measurements were taken to determine these properties. All measurements were taken during the same period of time in such a manner that they did not interfere with the flow of the suspension through the carborundum.

Materials

Water

Double distilled water was used in these tests. This water was pumped into a cylindrical Lucite tank, 6 inches in diameter and 48 inches long, for de-airing. The water was de-aired by applying a vacuum to the tank for one hour. The water was then allowed to flow by gravity into a storage tank at a very slow rate in order to prevent the water from becoming aerated again. This tank—8 inches high, 18 inches wide, and 36 inches long—was constructed of Lucite. The water was stored in this tank until needed.

Carborundum

The carborundum used in these experiments was obtained from the Carborundum Company, Niagara Falls, New York. This material was designated as silicon carbide grains and powders, type RA (medium sharp). The material was obtained in the following grit size numbers; 30, 54, 90, 150, 180, 220, 280, 320 and 500. The material was sized by using a complete set of U. S. standard sieves. It was assumed that the material retained between two adjacent sized sieves was uniform.

These uniform-sized lots of carborundum were then placed in an oven for 24 hours at a temperature of 600° F to remove any organic contaminants which might have been present. The material was then cooled, thoroughly washed in distilled water by agitation, and then dried and stored in sealed containers for further use.

The Suspensions

The suspensions were prepared from Wyoming bentonite and distilled water. The Wyoming bentonite, a Na-montmorillonite type clay, was obtained from the American Colloid Company, Chicago, Illinois. The trade name for this material is "KWK Volclay." Chemical analyses and X-ray diffraction patterns of the clay and clay suspensions are given in the Appendix.

A slurry of the clay and distilled water was prepared by vigorous stirring. The slurry was then diluted to a 2 percent suspension and placed in a bag made of semipermeable membrane in order to remove the exchangeable calcium and sulfates by dialysis. The bag was placed in a 3-gallon polyethylene container filled with distilled water. The water was changed daily until the electrical conductivity of the water removed after 24 hours was less than 20 micromhos. At this point it was assumed that most of the calcium and sulfates had been removed. The suspension was removed from the bags and placed in a 15-liter, Pyrex glass container for storage until needed. Fifteen liters of the suspension to be used in a test were prepared by diluting the previously prepared suspension to the desired concentration and placing it in a carboy. A Bouyoucos hydrometer was used to measure the concentrations.

The suspension was mixed thoroughly and a sample was taken on which a pH determination was made. Sufficient NaOH was added to the sample to bring the pH up to 9.0. This value was chosen because it is in the pH range in which a bentonite suspension is the most stable. From the information on the sample, the correct amount of NaOH was added to the large volume of the suspension to bring its pH up to 9.0. The suspension was again thoroughly stirred and allowed to stand 24 hours before being used in a test. This procedure was followed in order to yield the most stable clay-water suspension with as little modification of the bentonite particle as possible. The standing period was used to insure that the particle size of the suspended material was less than 2 microns.

Equipment

The equipment was placed in an insulated chamber 8 feet long, 8 feet wide and 8 feet high. The temperature of this chamber could be controlled to within 1° C. The tests were conducted in this chamber so the temperature variable could be controlled and considered constant in the analysis of the data.

For Measuring the Hydraulic Properties

The equipment was designed to provide downward flow through the carborundum. Also, because of the possibility of chemical reactions, metal in contact with the carborundum, water, or suspensions was avoided. Therefore, glass, plastic, and rubber were used in constructing the equipment. The plastics used were Lucite and Plexiglas, transparent acrylic materials.

Permeameters—The permeameters were constructed to hold the carborundum during the tests. They were made almost entirely of Lucite and Plexiglas in order that the carborundum could be observed. A 2-inch cylinder was chosen since the cross-sectional area of the cylinder should be large in comparison to the diameter of the media particles. This condition insured that the effect of the flow at the media-wall interface and the influence of any irregularities of the surface of the media would be negligible. The ratio of the diameter of the cylinder to the diameter of the largest particles of the carborundum was 65. This value is within the limits set by Rose (10), who stated that for ratios greater than 50, the wall effect could be neglected.

The top and base of the permeameter were made of Plexiglas blocks. The dimensions are shown on a cross-sectional view of the permeameter in Figure 1. A recess was machined in the base to hold a gasket. The top was made in two pieces: one was machined to fit over the cylinder and was then glued to it, and the other piece was clamped to the cylinder and held the gasket. The permeameter was held together with brass rods. The cylinder was fastened to the base and the top plate clamped in place with these rods. The top plate could be removed for filling the permeameter without disassembling the rest of the permeameter.

Screens of various materials were used to hold the carborundum in the cylinder. These screens were glued to a piece of Lucite which fit inside the cylinder and which had been perforated and cupped on the bottom to allow the fluid to flow from the carborundum out through the base. The screen block was placed at the lower end of the cylinder against the base plate.

Eight manometer taps were attached to the cylinder. The top manometer tap was located just below the top of the cylinder; the bottom manometer tap was located just above the screen in the base of the cylinder. The other six manometer taps were evenly spaced along the cylinder. A detailed drawing of one of the six manometer taps is shown in Figure 2. All manometer taps were connected to a manometer board with rubber tubing, which had an inside diameter of 0.25 inches.

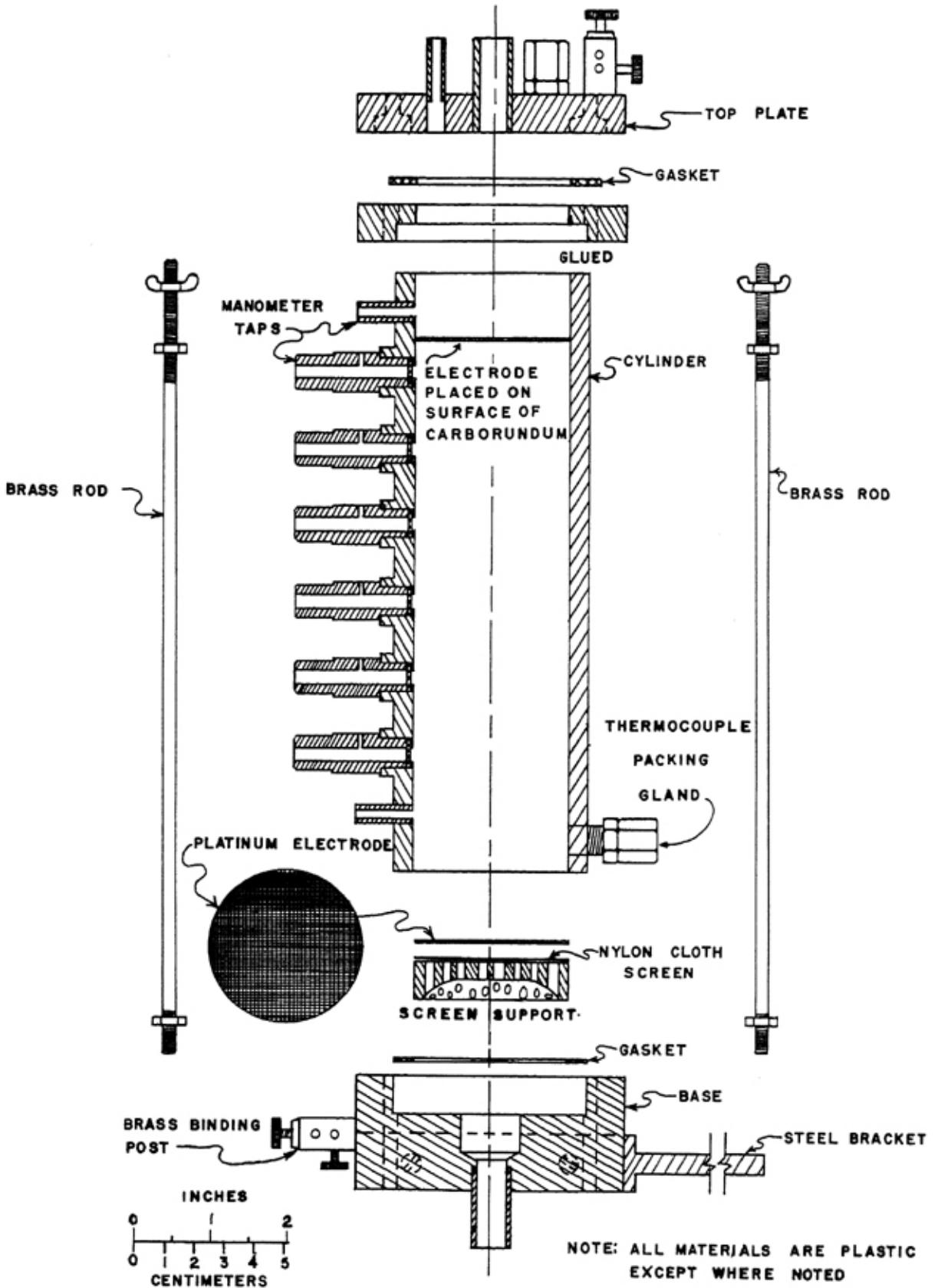
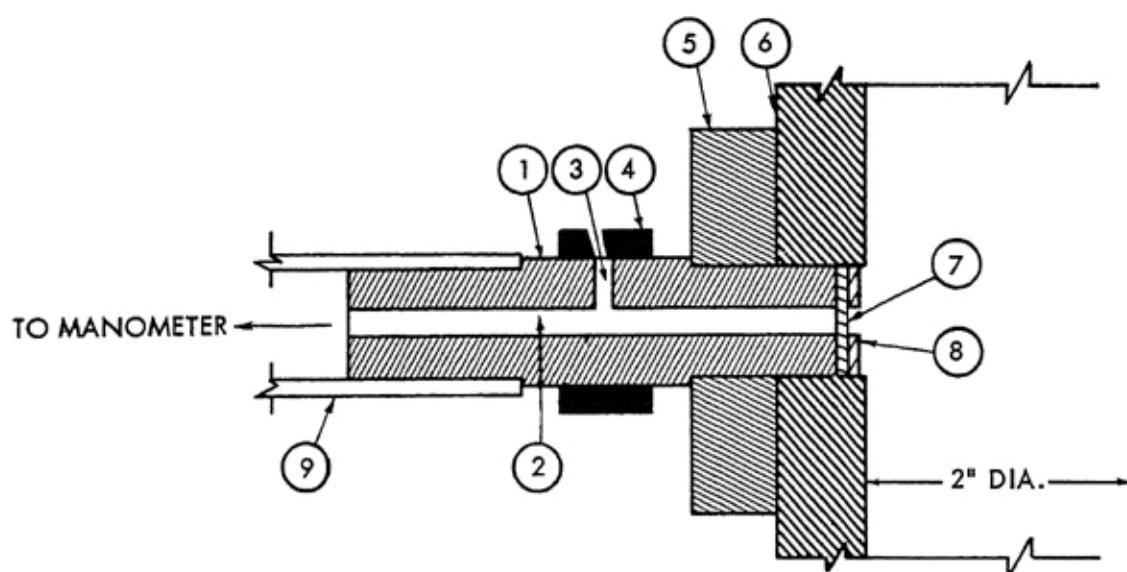


Fig. 1—Expanded cross-sectional view of the permeameter.



1. 1/2 INCH DIAMETER LUCITE ROD, TURNED TO FIT 3/8 INCH DIAMETER HOLE IN CYLINDER WALL
2. 3/16 INCH DIAMETER BORE
3. 1/16 INCH DIAMETER AIR HOLE
4. RUBBER TUBING
5. REINFORCING PATCH (LUCITE)
6. CYLINDER WALL
7. HEAVY NYLON MATERIAL OR BRASS SCREEN
8. LUCITE WASHER, 0.010 INCH THICK
9. 3/8 INCH INTERIOR DIAMETER, 1/16 INCH WALL, MAYON TUBING

NOTE: THE NYLON MATERIAL OR BRASS SCREEN IS FIRST GLUED TO THE WASHER AND TRIMMED. THE COMPLETE FILTER IS THEN GLUED INTO THE RECESS.

Fig. 2—A detailed cross-sectional drawing of a manometer tap.

Manometer Board—The manometer board consisted of eight Pyrex glass tubes, 8 millimeters inside diameter and 28 inches long, mounted on a plywood board which had been covered with cross-section paper.

Constant Head Controls—The flow of either water or suspension through the carborundum in the permeameter was controlled in order to provide an absolute pressure gradient across the permeameter. This positive gradient prevented air from entering the system. Also the constant head controls were designed to

(1) maintain a constant hydraulic gradient during the tests, (2) provide a range of hydraulic gradients (0.1 to 2.0), and (3) provide for changing the liquid flowing in the system from water to suspension with a minimum of disturbance.

Three constant head controls were built: one to control the inflow of water to the permeameter, one to control the inflow of the suspension, and one to control the outflow of either the water or the suspension. The inflow constant head controls were identical and were mounted on a common bracket shown in Figure 3, to provide the same water level in each.

Compaction Machine—In order to eliminate the porosity variable, the carborundum had to be placed in the permeameter and compacted to the same porosity for each test. The carborundum was placed in the permeameter under water and compacted to remove entrapped air in the column of carborundum in the permeameter. A machine was designed and built which would compact the carborundum in the permeameters by raising the permeameter 2 inches and then allowing it to drop to its original position. A compaction time of one minute produced uniform compaction of the carborundum for all sizes except the 63-micron material which would not settle during the operation of the machine. It was compacted in the permeameter by gently tapping the sides of the cylinder with a plastic mallet until no further settling was observed.

Viscosity Measurements—The viscosity of both the distilled water and the suspensions was determined with an Ostwald viscometer.

Equipment for Electrical Measurements

As stated previously, electrical measurements were made to determine electrokinetic properties of the water-carborundum or suspension-carborundum systems. The electrokinetic properties of interest were the streaming potential and the zeta potential. The streaming potential, as defined previously, is the voltage developed across the column of carborundum in the permeameter by the liquid flowing through the column. The zeta potential can be calculated from the streaming potential by the Helmholtz-Smoluchowski equation, provided the electrical conductivity of the liquid in the pores of the porous media is known. In order to determine this conductivity, the electrical resistance of the column of liquid and carborundum in the permeameter must be measured. Therefore, the electrical measurements made on the system were the voltage across the column and the resistance of the liquid-filled column.

The Electrodes—The voltage and resistance measurements were made across two electrodes which were located at either end of the carborundum column in the permeameter. Each of the electrodes was made by spot welding a 52-mesh platinum screen, 2 inches in diameter, to a 26-gauge platinum wire formed in the shape of a circle. This platinum wire gave rigidity to the electrode and provided a lead to the outside of the permeameter.

The electrodes were washed, first in concentrated nitric acid, then in dis-

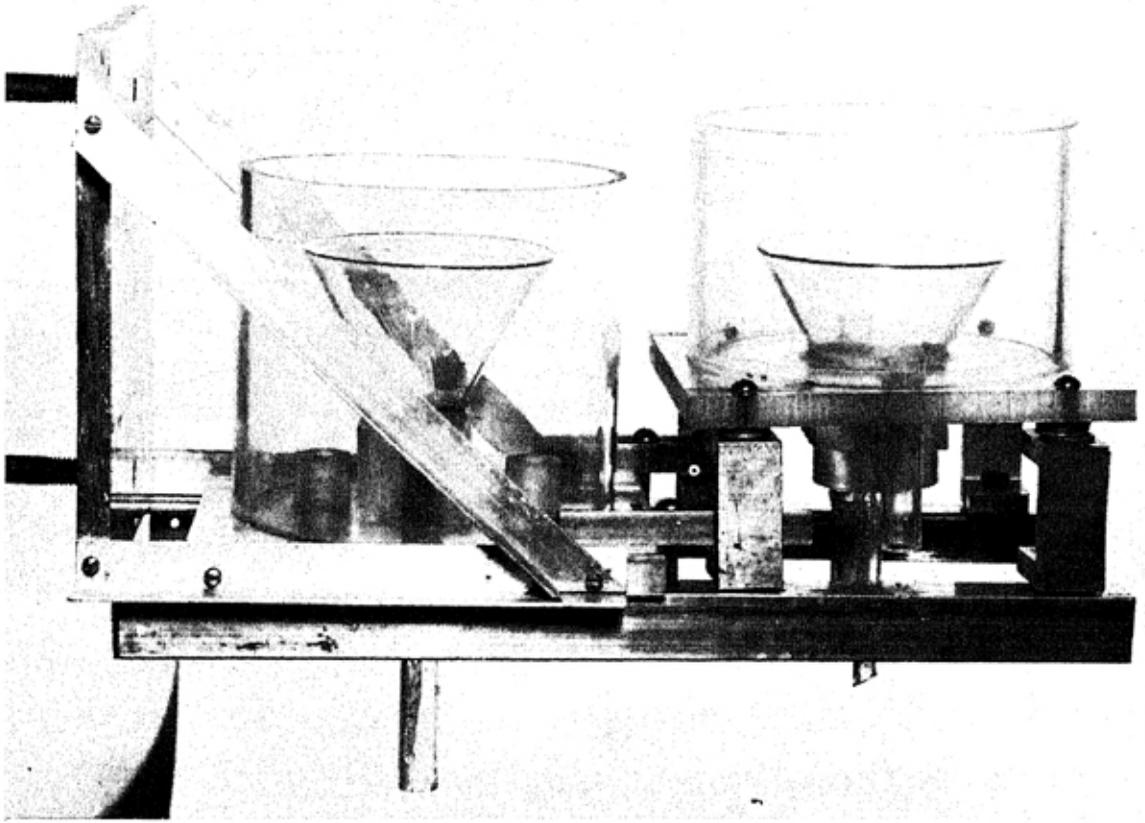


Fig. 3—The inflow constant head controls.

tilled water, and heated over an open flame to a red heat to clean them before being used. This process was repeated several times during the course of the study.

The Vacuum Tube Voltmeter—A vacuum tube voltmeter was used to measure the voltage between the two electrodes. A direct current vacuum tube voltmeter, Model 200B, built by Keithley Instruments, Inc., Cleveland, Ohio was used. This instrument had an input grid current of less than 5×10^{-14} amperes on all ranges. Eight voltage ranges of 0.008, 0.02, 0.08, 0.20, 0.80, 2, 8, and 20 volts full scale were provided. The calibration accuracy was within 2 percent of full scale on all ranges. Also, a polarity switch allowed positive or negative voltages to be read. Shielded leads were used to connect the meter to the binding posts on the permeameter.

Switching Box—A switching box was built and placed in the line between the voltmeter and the permeameter. This switching box provided a means of short circuiting the electrodes and also short circuiting the terminals of the volt-

meter at all times except when voltage readings were being taken. This arrangement eliminated the necessity of turning the voltmeter off and on several times during a test.

Shielding—During preliminary tests with the equipment, considerable drifting and instability in the voltage readings were observed. In order to reduce this drifting to a minimum and provide more stable voltage measurement, both the voltmeter and the permeameter were shielded with boxes made of 30-mesh brass screen soldered to a frame made of brass rods. These shields are shown in Figure 4. These shields, the voltmeter, and the switching box were connected to a good electrical ground.

Resistance Measurements—The resistance of the carborundum column in the permeameter was measured across the electrodes by using a Bouyoucos bridge, Model C, manufactured by the Wood and Metal Products Company, Bloomfield Hills, Michigan. This bridge is a portable, battery-operated AC Wheatstone Bridge, utilizing earphones as the balance indicator and operating at a bridge frequency of 1000 cycles. The resistance range is from 0 to 5×10^6 ohms. The overall accuracy is within plus or minus 1 percent of the reading. An adjustable-capacitance balance is provided.

Procedure

Filling The Permeameter

The permeameter was filled with distilled water which was forced into it at the bottom. This operation forced all of the air out of the permeameter. The tubing connected to the base of the permeameter was clamped and the permeameter was placed on the compaction machine.

The carborundum was placed in the permeameter under water with the aid of a glass funnel. The glass funnel was kept in motion inside the permeameter to maintain a uniform distribution of the carborundum over the area of the permeameter. The filling proceeded until the carborundum was level with the top of the permeameter. The top plate was placed on the permeameter, and the carborundum compacted.

After the carborundum was compacted the top electrode was placed on the surface of the carborundum and secured by a plastic snap ring. The permeameter was detached from the compaction machine, placed in the shield, and clamped to a vertical rod for support. Tubing connections were made from the permeameter to the inflow constant head control for water and to the outflow control.

The leads from the switching box were connected to the binding posts on the top and bottom of the permeameter. These leads were connected so the lead from the positive terminal of the voltmeter was connected to the bottom binding post through the switching box. The switches on the switching box were set so that the circuit would be closed between the two electrodes, and the terminals of the voltmeter would be short circuited and grounded.

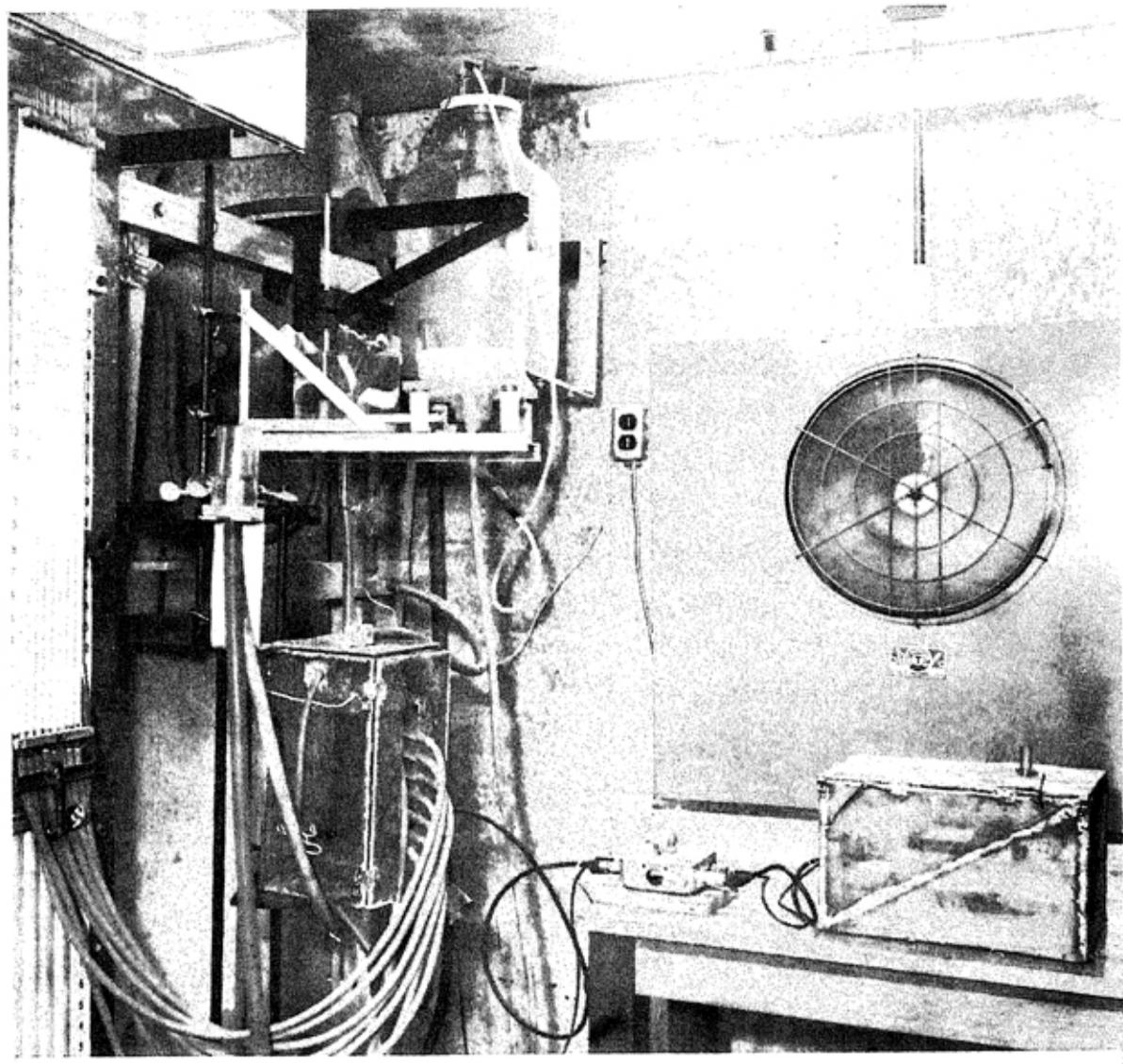


Fig. 4—A general view of the equipment showing the shields around the voltmeter and the permeameter.

Initial Tests With Water

The flow of distilled water was started through the carborundum. The constant head controls were adjusted to maintain a hydraulic gradient approximately equal to one. The level of overflow in the outflow constant head control was always maintained at a point above the top of the permeameter to insure that a positive pressure was maintained in the permeameter. The flow of water through the permeameter was continued until the electrical conductivity of a sample of the effluent was approximately equal to the electrical conductivity of the influent. The constant head controls were then adjusted to maintain the desired hydraulic gradient for the particular test under way. The manometers were filled and connected to the manometer taps on the permeameter.

The flow, which had continued while the constant head controls were adjusted and the manometers were connected, was continued for an hour or until the flow reached a steady state determined by observing whether any changes occurred in the heights of any of the manometer water columns. After this steady state was reached, the temperature was read and the electrical conductivity of a sample of the effluent was determined. The flow was then stopped and the resistance of the column of carborundum in the permeameter was determined.

The voltmeter was connected to the switching box, turned on, and allowed to warm up for a short period of time. The switch was opened briefly, completing the circuit between the electrodes and the voltmeter, and the no-flow voltage across the electrodes was measured. The flow was turned on and allowed to stabilize. A graduate cylinder was placed under the discharge from the outflow constant head control and the stop watch started. As the flow continued, a starting voltage reading was taken, the manometers read, and a final voltage reading was taken. The graduate cylinder was removed from under the discharge and the watch stopped. These readings of volume of flow and length of time were recorded. The flow was stopped and another no-flow voltage reading was taken. These readings, taken during the period of time from the initial reading on no-flow voltage to the final reading of no-flow voltage, were considered as a single "group of readings." Therefore, in the following discussion the use of the term, "group of readings," will refer to this sequence of readings.

After three groups of readings had been taken, if analysis of volume and time data indicated that the flow was steady, the flow was stopped. If the flow was not steady, additional groups of readings were taken until the flow did become steady. Then after the flow was stopped the resistance bridge was connected to the switching box and the resistance of the carborundum column was determined.

Tests with Bentonite Suspension

The next phase of the test was made using the suspension instead of the distilled water.

The tubing connecting the permeameter to the inflow constant head control for water was disconnected and connected to the inflow constant head control for the suspension, and the flow was started through the permeameter. Voltage readings were taken every few minutes as the suspension entered the permeameter. During this initial period of flow, the manometers were observed for any fluctuation in the readings. If all the manometers were steady, and the suspension was observed to be passing out of the outflow constant head control, a group of readings was taken in the same manner as outlined in the procedure with water. Then two more groups of readings were taken, and if the flow was steady during these three groups of readings, no more were taken. If the flow was not steady, groups of readings were taken until the flow did become steady.

If, during the initial period of suspension flow, the level in the manometers which indicated the head loss across the sections of the column of carborundum dropped, this drop indicated an increase in the resistance of these layers to flow. This increase in the resistance could be caused by the sealing effect of bentonite particles retained either on the surface of the carborundum column or in the pores beneath the surface. Therefore, if the manometer levels were dropping, they were read every five minutes. After a period of 20 to 30 minutes, the volume of flow during a given period of time was collected. This volume, the period of time, and voltages during flow were recorded along with the manometer readings. The manometer tubing was clamped and the flow shut off briefly in order to obtain a no-flow voltage reading. The flow was started again and, as before, groups of readings were taken at 30-minute intervals until either the flow reached a steady state or complete sealing of the column occurred. During this period the time at which the suspension passed through the column was recorded.

After the flow of the suspension reached a steady or complete sealing occurred, the manometers were clamped, the flow stopped and the resistance of the suspension in the carborundum column measured. The electrical conductivity of the suspension in bulk was determined.

Final Tests with Water

The tubing connecting the permeameter to the inflow constant head control was disconnected and connected to the water control, and the flow of water was started. Voltage readings were taken and recorded every few minutes as the water re-entered the permeameter. After 15 to 20 minutes, readings were taken in the same manner as before. These groups of readings were taken at successive intervals of time until three consecutive groups of readings indicated that the flow had reached a steady state. The manometers were then clamped and the flow stopped. The electrical resistance of the carborundum column was measured and the electrical conductivity of the final effluent was determined.

The permeameter was disconnected and dismantled. The column of carborundum was placed in a Pyrex dish and dried in an oven at 110° C for 24

hours. The carborundum was removed from the oven, weighed and the net weight used to calculate the porosity of the column.

Determination of the Quantity of Bentonite Retained in the Column

Samples of approximately 50 grams each were taken from the top inch, the next inch, the middle 2 inches, and the lower 2 inches of the column. These samples were analyzed at the Agricultural Experiment Station chemical laboratory for bentonite in the following manner. The samples were dried for 24 hours at 110° C., then weighed in 150-milliliter beakers which had been cleaned thoroughly, dried, and weighed empty. To each beaker containing the carborundum was added 100 milliliters of a dispersing solution. The solution contained 35.7 grams/liter of Calgon (sodium hexametaphosphate) and 7.94 grams/liter of sodium carbonate. This mixture of carborundum and the dispersing solution was stirred in the beaker for 15 minutes with a magnetic stirrer. This process dispersed any bentonite in the sample. The sample was then transferred to a glass crucible with a fritted glass bottom, which had been previously cleaned, dried and weighed. The material in the crucible was then washed several times, first with the dispersing solution, then with successive dilutions of the dispersing solution and finally with double-distilled water. The intent of this process was to wash any bentonite, which had been dispersed, out of the carborundum. The crucible containing the carborundum was then dried for 24 hours at 110° C and weighed. Both the crucible and the beaker were again weighed.

The difference in weight of the original sample and the final weight of the sample after dispersing and washing was taken as the quantity of bentonite retained in the sample. Re-weighing the beakers and crucibles gave a check for any error in the procedure due to loss in weight of these containers or due to weighing errors. Since the amount of bentonite in the sample and the weight of the sample were known, the quantity of bentonite in the layer from which the sample was taken could be calculated. Samples of carborundum which were known to contain no bentonite were analyzed by this procedure as a check of the precision of the method.

Cell Constant Determinations

The cell constant must be determined experimentally. The permeameter is filled with carborundum in the same manner as outlined in the test procedure except 0.10 normal KCl is used as the fluid. This electrolyte is used because the electrical conductivity is high enough to suppress the effect of the surface conductivity of the particles on the total conductivity of the column. Therefore, the bulk conductivity of the KCl is the same as the conductivity of the KCl in the pores. The resistance of this KCl-carborundum system is then determined and the cell constant calculated by multiplying the conductivity of the KCl by the resistance of the KCl-carborundum system. This cell constant which has been determined with the surface conductivity suppressed can be used to cal-

culate the electrical conductivity of the liquid used in the tests as it exists in the pores of the carborundum column. Several cell-constant determinations were made for each size material. A summary of these values is given in the Appendix.

DATA AND DISCUSSION

Tests were made on carborundum of particle sizes of 775, 385, 273, 163, 80, and 63 microns. The fluids used were double-distilled water, and 0.1 and 1.0 percent suspensions of Wyoming bentonite in double-distilled water. The hydraulic gradients ranged from 0.1 to 2.0.

Hydraulic Data

Initial Tests with Double-Distilled Water

For each test, the initial measurements were made with double-distilled water flowing through the system. All tests were made under conditions of laminar flow.

Relation of rate of flow to hydraulic gradient—The rate of flow (Q) is plotted versus hydraulic gradient (i) for each size of particles in Figure 5. The hydraulic gradient was computed by using the head loss between the second and seventh manometer taps from the top of the permeameter and the distance between them. The data plot straight lines on log-log paper at 45° to the horizontal, which indicates that the relationship between rate of flow and hydraulic gradient is linear, and that the flow is laminar. Since this relationship exists Darcy's law can be applied. The Reynolds numbers for the flow conditions of each test are given in the Appendix. The values are all less than 10, which fact further establishes that the flow in all tests was laminar.

Permeability—Since Darcy's law applies, the permeability of the media was calculated using the following form of the Darcy equation:

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

The Darcy equation was modified by insertion of the viscosity (η) and density (ρ) of the fluid and the acceleration of gravity (g). The permeability calculated by this equation is a property of the medium alone and independent of the fluid. In order to eliminate the effects of the interface losses at the top and the bottom of the column, the permeability calculations were based on the hydraulic gradient across the center-five inches of the carborundum column.

Tests with Bentonite Suspensions

The data indicate that for the larger particle sizes (775 and 385 microns) the flow rate is proportional to the hydraulic gradient, as was true with distilled water. For the particle sizes 163, 80, and 63 microns, the data were quite variable

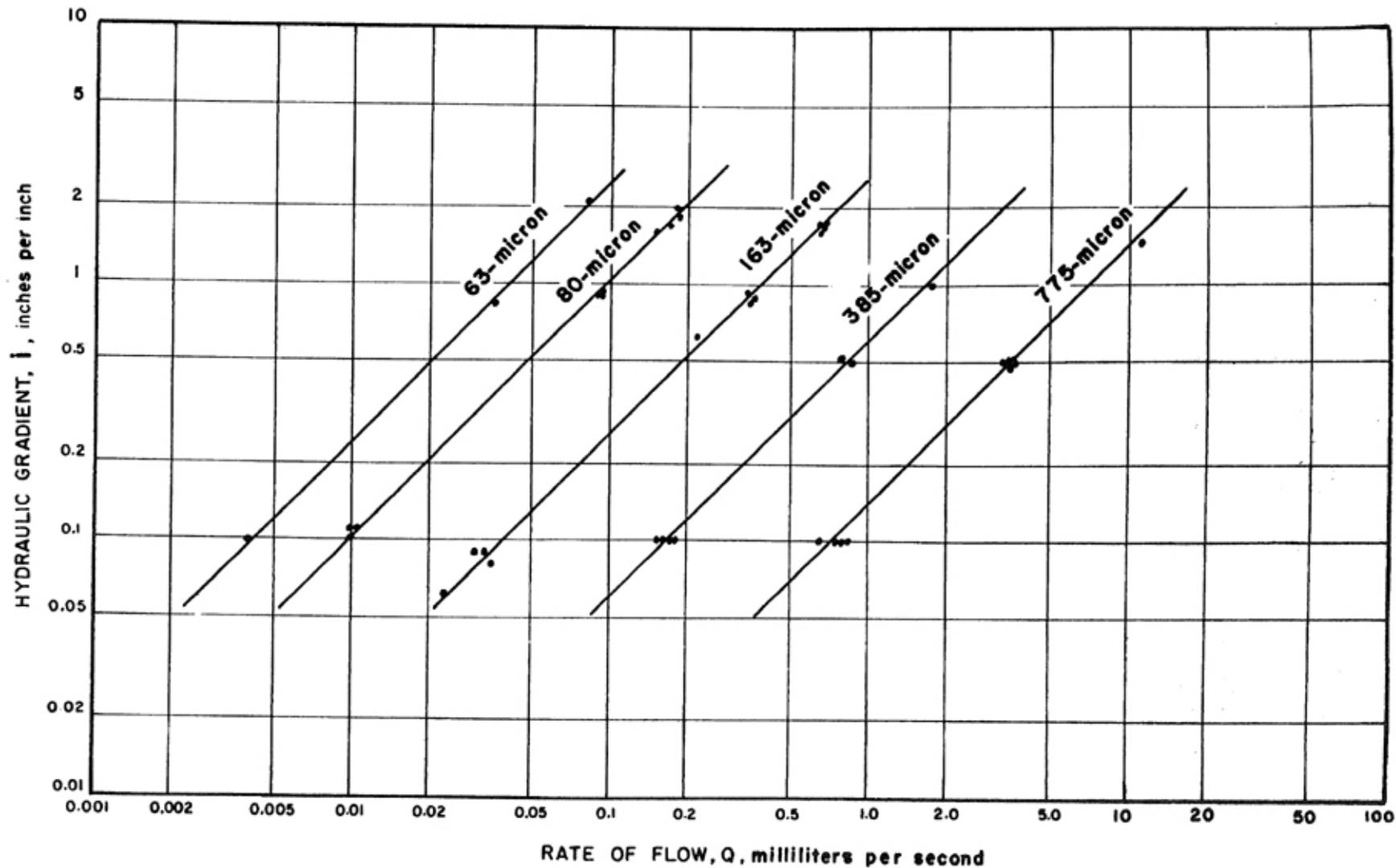


Fig. 5—Relationship of hydraulic gradient to rate of flow for each particle size.

and the linear relationship did not hold. The variability may be explained by (1) occurrence of considerable sealing in tests on these sizes which introduced a degree of unsteadiness into the flow, (2) possible error in head-loss measurements because of sealing that may have taken place at the screens which were used to keep carborundum from moving into the manometers.

Permeability—Even though variability did exist in the hydraulic measurements on the suspension-carborundum systems, the permeability of the column was calculated. The calculations were based on measurements taken when the flow rate reached a constant value. The permeabilities were corrected for the viscosity of the suspensions.

Specific discharge—Since the problem encountered in the measurement of head loss for the suspension-carborundum system also affected the permeability calculation, a term—specific discharge (Q')—was calculated. This term was suggested by Newman (8), and is equal to the permeability (k') multiplied by the hydraulic gradient. The specific discharge therefore takes into account viscosity, density and gravity but does not include the hydraulic gradient. Since specific discharge was not affected by the variability in the measurement of head loss due to sealing of the manometer taps, it was calculated for each test and compared to the corresponding value for distilled water.

Final Tests with Water

After the flow of the suspension had reached a steady value or the column had become sealed, double-distilled water was re-introduced into the permeameter. The permeability and specific discharge were calculated as before. A summary of these calculations is given in the Appendix.

BENTONITE RETENTION IN THE COLUMN

After the hydraulic measurements were completed, the carborundum was removed from the permeameter and samples were taken and analyzed to determine the quantity of bentonite retained in various sections of the column. These data are reported in the Appendix. The amount in each section of the column is reported in milligrams of bentonite retained per 100 grams of carborundum.

The data indicate that very little bentonite was retained in the column for the particle sizes of 775 and 385 microns. For the sizes of 163, 80, and 63 microns most of the bentonite retained was in the top inch of the column. The amount retained in the top inch for these sizes increased with the concentration of the suspension. The data on the relationship between the amount retained in the top inch and the hydraulic gradient are quite variable. This variability reflects the errors in the method of determining the quantity of bentonite in the column as well as those caused by disturbance of the surface of the carborundum column on re-introduction of the water.

ELECTRICAL DATA

During each test, measurements of the electrical resistance of the column, the streaming potential across the column, and the electrical conductivity of the water and of the suspension were taken concurrently with the hydraulic measurements. A summary of these data is given in the Appendix.

Electrical Conductivity of the Liquid in the Pores

As mentioned previously, the calculation of the zeta potential from the streaming potential measurements involves the knowledge of the electrical conductivity of the fluid in the pores of the carborundum column. Since this conductivity is affected by the surface conductivity of the particles, it must be determined indirectly from measurements taken on the column as a whole. As indicated in the test procedure, the resistance of the carborundum column was measured. The electrical conductivity of the liquid in the pores can be calculated from the following relationship:

$$\lambda_s = \frac{\text{Cell constant}}{\text{Resistance of the column.}}$$

Zeta Potential

The zeta potential (ζ) was calculated from the Helmholtz-Smoluchowski equation,

$$\zeta = \frac{4 \pi \eta \lambda_s \Delta E}{DP}$$

in which (η) is the viscosity of the liquid; (λ_s), the electrical conductivity of the liquid in the pores of the column; (ΔE), the streaming potential; (D), the dielectric constant of the liquid; and (P), the pressure difference across the column determined from the hydraulic gradient and the length of the column. The zeta potentials calculated for each test are given in the Appendix.

The values of zeta potentials were largest for the larger particle sizes and decreased with particle size. This may be explained by the fact that as the particle size decreased, the total surface conductivity increased. This increase in surface conductivity had an effect even though the electrical conductivity of the liquid in the pores of the column was used in calculation of zeta potential.

The zeta potential decrease with the introduction of the suspension into the column may be explained by a combination effect: suppression of the zeta potential of the carborundum by a coating of bentonite particles on the carborundum particles, and a suppression of the surface conductivity of the carborundum system by the increased electrical conductivity of the suspension over that of distilled water. It would be very difficult to separate these effects.

In most tests the zeta potential increased with the re-introduction of water. For the tests on the larger particle sizes, (775 and 385 microns), this final value

of zeta potential for water returned to nearly the initial value for water. The return to near the original value indicated that the bentonite was almost entirely removed from the column, which agrees with the data on bentonite retention in the column.

The zeta potential calculated for tests on the smaller particle sizes, (163, 80 and 63 microns), increased only slightly with the re-introduction of water. The fact that the final value for water was near the value for the bentonite suspension indicates that there was still an influence of the bentonite suspension in the column. The data on retention of bentonite in the column indicate a greater retention for these sizes which agrees with the fact that the zeta potential remained low for these tests with the re-introduction of water. The data on reduction in permeability by the bentonite suspension indicate that for these sizes there was a considerable reduction in permeability, which again agrees with the data on zeta potential.

It should be stated that the data on zeta potential obtained when the bentonite suspension did not pass through the column are of questionable validity because of the non-uniform composition of the liquid throughout the column.

SEALING

Two of the more important aspects of this study were to determine the relationships between hydraulic gradient and the flow of colloidal suspensions in the porous media, and between the concentration of the suspension and the flow in porous media. In this study the two extreme cases of flow of colloidal suspensions in porous media were encountered: (1) the suspension passed through the media with no significant change in the media or the suspension, and (2) the suspension did not enter the media because the suspended particles were filtered out at the surface, causing a stoppage of flow.

For the flow conditions between these two extremes, the problem arises as to how to measure the change in the system caused by the flow of the suspension in the media. In this study the reduction in permeability from the initial flow of water to that determined from the final flow of water is reported as a percent reduction in permeability. This reduction also could be thought of as a change in the degree of sealing.

Two problems arose: the problem associated with the sealing of the manometer taps by the suspension, and the problem associated with increase in final permeability with water because of the disturbance of the surface of the carborundum column. The first of these problems was overcome by using the reduction in specific discharge instead of reduction in permeability, since the specific discharge does not include the head loss in its computation. The second problem was eliminated by using the reduction in specific discharge or permeability between the initial flow of water and the final values for the flow of the suspension.

A summary of the reductions in permeability and specific discharge is given in Table 1.

Effect of Hydraulic Gradient on Sealing

The relationship between hydraulic gradient and reduction in specific discharge for each particle size is shown in Figure 6. The hydraulic gradient used in plotting is the overall gradient across the entire length of column, which differed slightly from the hydraulic gradient across the center-five inches of the column, which was used in computing the permeabilities for the initial flow of water.

The data indicate that for the tests with particle sizes 775 and 385 microns, there was only a small reduction in specific discharge in each test and no general relationship between hydraulic gradient and reduction in specific discharge existed.

For the 163 and 80-micron material the data show an increase in sealing (greater reduction in specific discharge) with increasing hydraulic gradient. The differences between the values of the reduction in specific discharge from initial water flow to suspension flow and from initial water flow to final water flow are probably due to the effect of surface disturbance by the re-introduction of water into the permeameter.

The carborundum of 63-micron particle size was sealed completely at both hydraulic gradients of 0.10 and 2.0.

An explanation of the effect of hydraulic gradient on sealing may be based on the rate of movement of the suspension through the pores in relation to the pore size and the orientation of the particles in this moving liquid. The carborundum used in this study is angular in shape. When angular material is packed in a column at random, the pores in the column will have a wide distribution of sizes as well as a wide range in shape.

If the average size of the pores is large as is the case for the 775 and 385-micron material, bentonite particles may be trapped in the small irregularly-shaped pores. But the successive build-up of bentonite particles on the original particles trapped does not develop to the point of bridging across these large pores to produce a significant retardation of flow.

If the average size of the pores is somewhat smaller, as in the case of the 163 and 80-micron carborundum, the successive build-up of bentonite particles on the original particles trapped does continue until a considerable portion of the pores have been closed off. An increase in hydraulic gradient causes this process of build-up to take place at a more rapid rate. In addition, this greater pressure causes the trapped material to be packed more tightly, producing a stronger bridge across the entrance to the pores. Also there is the possibility that the bentonite particles are oriented in a more nearly horizontal plane in the flow under higher hydraulic gradients. If this is true, there would be a greater tendency for these plate-like bentonite particles to be trapped and form bridges.

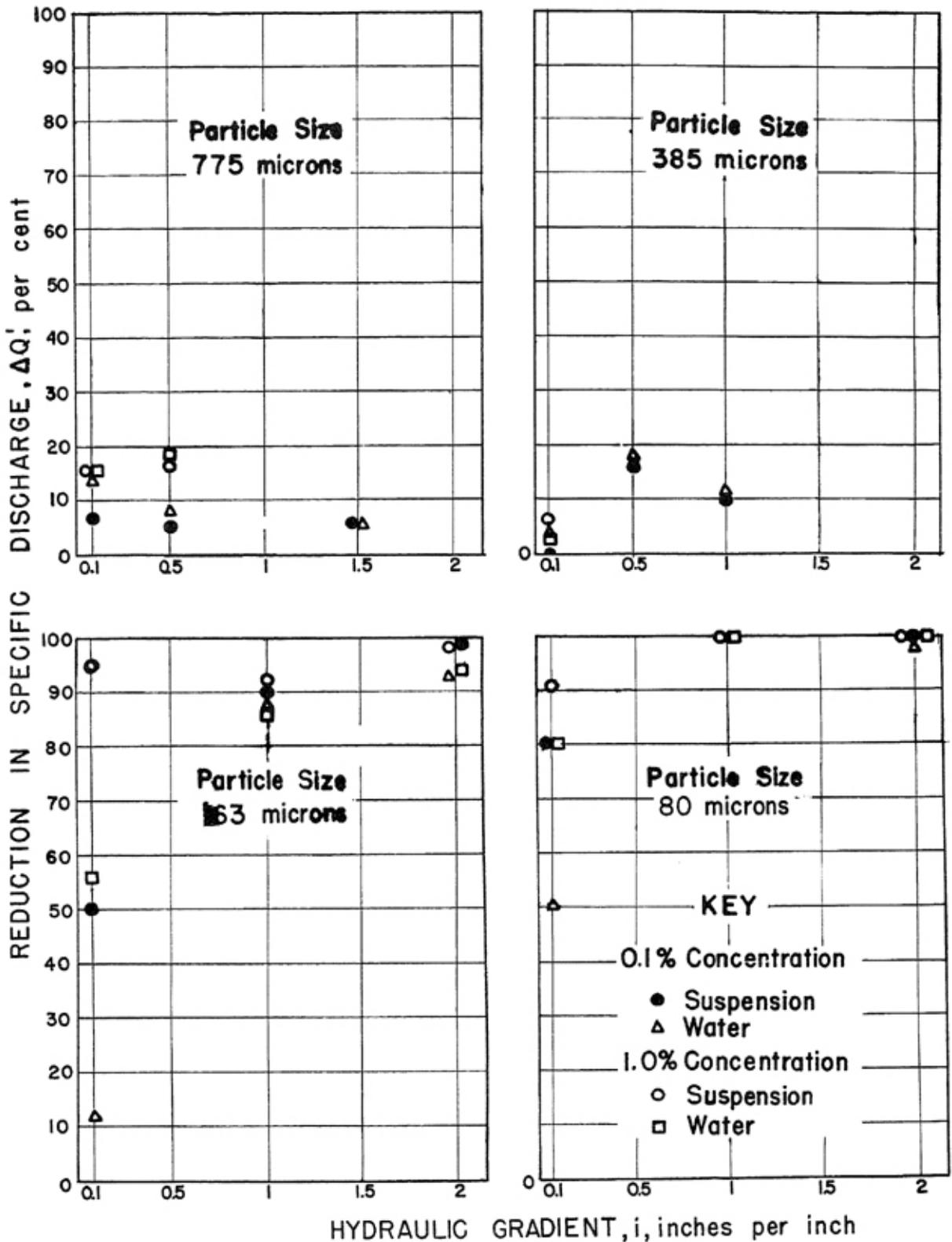


Fig. 6—Relationship of reduction in specific discharge to hydraulic gradient for each particle size and concentration of suspension.

In the case of the 63-micron carborundum the average pore size is still many times greater than the diameter of the bentonite particles. But yet the pores are small enough that the wide distribution of the pore sizes and pore shapes of this angular material provides a mechanism for trapping the bentonite particles and the subsequent bridging-over of the pores to the point of complete sealing regardless of the hydraulic gradient.

In a previous investigation it was found that bentonite suspensions would not enter columns of spherical glass beads with a diameter equal to or less than 36 microns under a hydraulic gradient of 1.0 (1). This fact, when compared with the data for 63-micron carborundum, gives comparison of the effect of particle shape on sealing. Since the angular carborundum has a greater range of pore sizes and shapes than the spherical material, the fact that sealing occurred for larger mean particle size of the carborundum would substantiate the statement that the pore-size distribution and pore shape have a pronounced effect on sealing.

Effect of Concentration on Sealing

The relationship between the concentration of the bentonite suspension and the reduction in specific discharge is shown in Figure 6. Since only two concentrations (0.1 and 1.0 percent) were used, the extent of this relationship is limited. But for these two concentrations the reduction in specific discharge (degree of sealing) increased with increase in concentration. The increases were small in most cases.

This increase in sealing with increase in concentration can best be explained by the increased amount of bentonite moving through the column per unit volume of liquid thus increasing the probability of some bentonite particles becoming trapped.

Relation between Degree of Sealing and Bentonite Retained

The data reported did not show a good correlation between degree of sealing and bentonite retained. But the data did indicate a tendency for the quantity of bentonite retained to increase with an increase in the degree of sealing. Since most of the bentonite retained was retained on the surface or in the top inch of the column, this indicated that mechanical filtering was the main process by which bentonite was removed from the suspension.

Correlation with Zeta Potential

The zeta potential of the carborundum decreased with the introduction of the bentonite suspension into the column of carborundum. Also the zeta potential of the carborundum calculated from the data on the final flow of water through the column returned to nearly the original value for water in some cases and in other cases increased only slightly over the value for the suspension. The calculation of zeta potential during the re-introduction of water showed a

correlation between degree of sealing and this change in zeta potential of the carborundum. In those tests where very little sealing occurred, the zeta potential of the carborundum returned to nearly the original value; but in those tests where considerable sealing occurred, the zeta potential of the carborundum did not increase appreciably above the values for the bentonite suspension. An explanation of these changes in the zeta potential of the carborundum was presented previously under the discussion of zeta potential calculations.

DISCUSSION OF ERRORS AND SCATTER IN THE DATA

Hydraulic Measurements

Two types of errors were present in the hydraulic measurements; errors in readings, and errors caused by equipment operation.

Head—The hydraulic head at points in the column of carborundum was measured by reading the height of a column of water in a manometer. These readings could be made to the nearest 0.05 inch. Although an attempt was made to read the manometer in the same manner each time, the variation of 0.05 inch would produce a significant error in tests at low hydraulic gradients.

In measuring the head while the bentonite suspension was flowing through the system, sealing occurred at the screens which held the carborundum out of the manometer tap. This sealing caused sluggish operation of the manometers.

Discharge—The principal error in measuring the discharge from the permeameter was in reading the volume of liquid caught in a graduate cylinder during a given length of time. These graduate cylinders could be read to the nearest milliliter for the 100-milliliter cylinder and to the nearest 5 milliliters for the 1000-milliliter cylinder. The error of reading was greatest for low flows. This error also contributed to the problem of determining when the flow of the suspension reached a steady state, which influenced the degree of sealing and the scatter in the data.

Disturbance of the surface—During the final phase of the test, it was difficult to re-introduce the water without disturbing the surface of the carborundum column. The disturbance of the surface caused an increase in rate of flow through the column and therefore the calculated degree of sealing was less than it would have been if no disturbance had occurred.

Electrical Measurements

Errors in readings and errors caused by equipment operation were present.

The voltmeter—The accuracy of the voltmeter, as stated by the manufacturers, was 2 percent of the full scale reading on all scales. The principal variation in the voltage readings occurred when the no-flow voltage was high (100-200 millivolts), which meant that the instrument was set on a scale which would cover this no-flow reading. Therefore, on this scale, 2 percent of full

scale might be equal to or greater than the actual potential difference between flow and no-flow conditions.

Errors caused by drifting were eliminated by the use of the switching box. Also errors caused by impressed stray EMF's were almost entirely eliminated by the shields around the voltmeter and permeameter and the shielded cable connecting them.

Electrical resistance—The electrical resistance was measured by the Bouyoucos bridge with an accuracy of 1 percent of the full scale reading. Since most of the readings were on the lower scales, this error was unimportant in this study.

Electrical conductivity—Errors in measuring the electrical conductivity of the liquid used in the study were due primarily to personal judgment in determining the null point of the conductivity solution. The determination of this null point is more difficult for liquids of low electrical conductivity.

Determination of Quantity of Bentonite Retained in the Column

One of the more difficult problems associated with this study was finding a method to determine the quantity of bentonite retained in the column. Errors were present in several steps of the method used and contributed to the scatter in the data. First of all, it was difficult to remove the column from the cylinder and obtain representative samples from the various layers to be analyzed. Also, no way was found to determine separately the amount of bentonite retained on the surface and the amount retained in the top inch of the column.

In the procedure the samples were weighed to the nearest 0.1 of a milligram. The loss of weight of the carborundum sample was reported as bentonite retained, but this loss could have included small particles of foreign matter in the carborundum, small particles of carborundum, or other materials which could be washed through the fritted glass crucible after being dispersed by stirring. One other error which developed in the procedure was that due to loss in weight of the beakers in which the carborundum sample was dispersed and stirred. This loss of weight was caused by an etching away of the glass by the abrasive carborundum.

X-RAY DIFFRACTION PATTERNS

- Trace No. 1 Wyoming Bentonite (Vol-Clay), original material, powdered sample.
 - Trace No. 2 Wyoming Bentonite (Vol-Clay), 1 per cent suspension in double-distilled water, dialyzed, NaOH added to raise pH to 9.0, oriented sample.
 - Trace No. 3 Same as No. 2 except glycolated.
-
- Peak A 7.1 degrees 2 Θ , 001 spacing, 12.5 Angstroms.
 - Peak B 61.8 degrees 2 Θ , 060 spacing, 1.50 Angstroms.
 - Peak C 7.1 degrees 2 Θ , 001 spacing, 12.5 Angstroms.
 - Peak D 5.2 degrees 2 Θ , 001 spacing, 17.0 Angstroms.

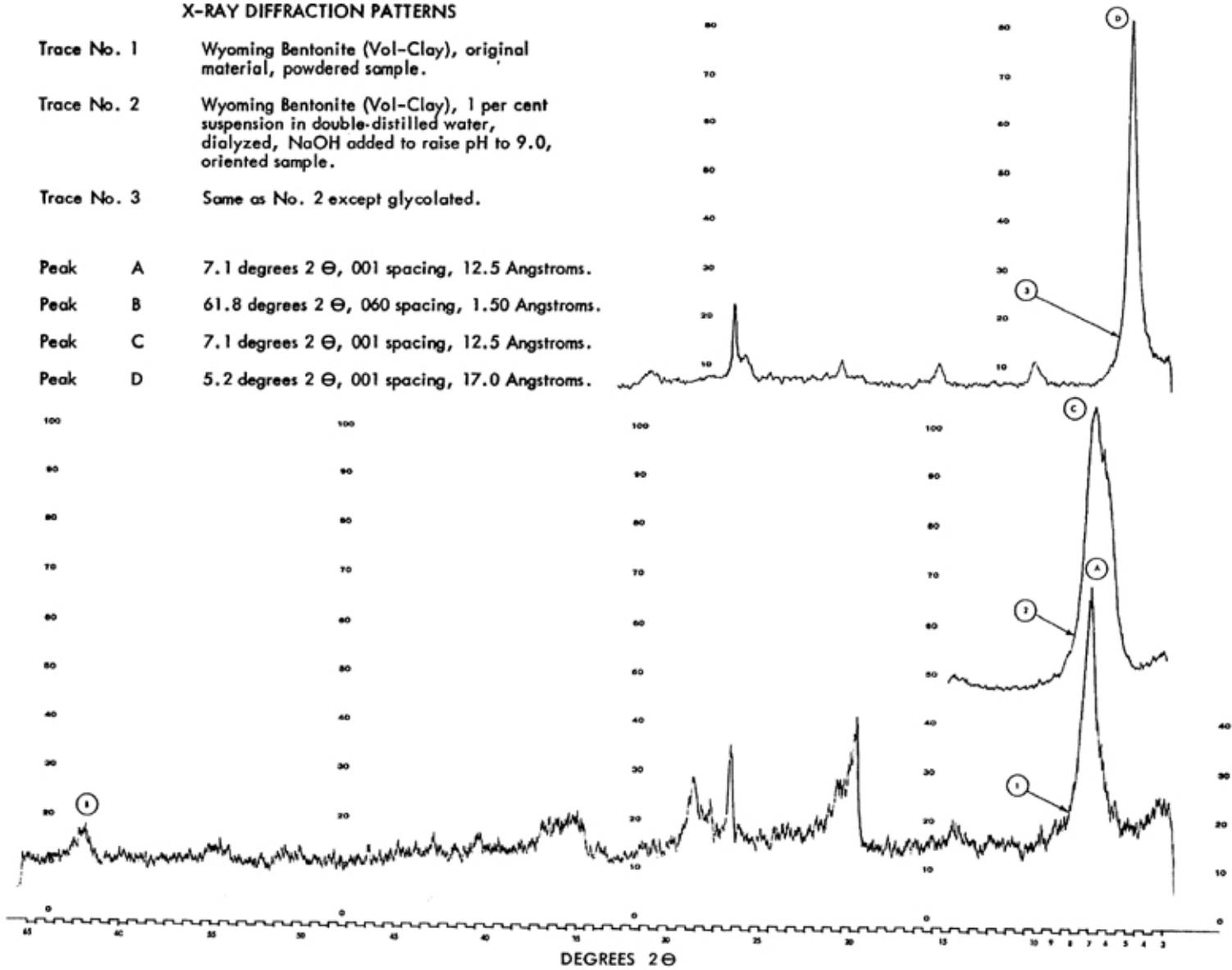


Fig. 7—X-Ray diffraction patterns.

CONCLUSIONS

From the results of this study, the following conclusions are suggested:

1. Mechanical filtering was the main process by which the bentonite particles were removed from suspension by the carborundum column.
2. The degree of sealing, as measured by the reduction in specific discharge or permeability, increased with decreasing particle size.
3. The degree of sealing increased with increasing hydraulic gradient.
4. The degree of sealing increased with increasing concentration of the suspension.
5. The shape of the particles of the media had a considerable effect on the sealing process. Complete sealing (regardless of hydraulic gradient or suspension concentration) occurred for the angular-shaped carborundum at a particle size of 63 microns in this study, compared to 36 microns for spherical-shaped glass beads reported in a previous study.
6. Electrokinetic measurements can be made on large-size columns of porous media under low pressures as was done in this study.
7. Electrokinetic measurements can be made in conjunction with hydraulic measurements of the flow of colloidal suspensions in porous media.
8. The calculated zeta potential of the carborundum can be correlated with the degree of sealing.

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APPENDIX

SUMMARY OF ORIGINAL DATA

The original data recorded during the experiment are summarized in the following tables. The data recorded during the actual test operation are presented in Tables 2 and 3. The cell-constant determinations are presented in Table 4. A summary of the analysis of the column of carborundum for bentonite is presented in Table 5. The data are reported to the number of significant digits warranted by the accuracy of the measuring equipment.

The first column of Tables 2 and 3 contain the test numbers. The letters "w", "b" and "w" located to the right of the test numbers in this column designate that line of data as representing the initial flow of water, the flow of bentonite suspension, and the final flow of water, respectively. The data represent the averages for three successive groups of readings taken after the flow had reached a steady state. The hydraulic gradient sub-scripts refer to the manometer tap numbers which were numbered from the top of the column down. Therefore, i_{2-7} is the hydraulic gradient across the center-five inches of the column, while i_{1-8} is the hydraulic gradient across the entire column since manometer taps 1 and 8 were located above and below the column respectively. All tests were conducted at a temperature of $21 \pm 0.5^\circ \text{C}$.

The average values of the cell constant for each particle size in Table 4 were used in calculating the electrical conductivity of the liquid in the pores of the carborundum column.

TABLE 1
SUMMARY OF DATA ON REDUCTION IN SPECIFIC DISCHARGE
AND PERMEABILITY

Test Numbers	Hydraulic Gradient	Concentra-	Particle	Reduction		Reduction in	
		tion of	Size of	in Specific	For	Permeability	For
		Suspension	Carbo-	Discharge	Suspension	Water	Suspension
			rundum			Per	Per
	Inches per	Per	Microns	Per	Per	Cent	Cent
	inch	Cent		Cent	Cent		
1 & 2	0.10	0.10	775	14	7	13	13
12 & 13	0.10	0.10	385	4	0	3	0
20 & 21	0.10	0.10	163	12	50	10	53
30	0.10	0.10	80	50	80	51	83
39	0.10	0.10	63	100	100	100	100
6 & 7	0.10	1.00	775	16	16	16	15
16 & 17	0.10	1.00	385	3	3	1	7
24 & 25	0.10	1.00	163	56	95	50	96
31 & 32	0.10	1.00	80	80	91	75	89
3,4& 5	0.50	0.10	775	8	5	8	4
11 & 14	0.50	0.10	385	18	16	21	18
8 & 9	0.50	1.00	775	18	17	19	22
15	1.00	0.10	385	12	10	11	90
18 & 19	1.00	0.10	163	88	90	88	89
41 & 42	1.00	0.10	274	68	90	68	90
26 & 27	1.00	1.00	163	86	92	86	92
37	1.00	1.00	80	100	100	100	100
10	1.50	0.10	775	6	6	9	8
22 & 23	2.00	0.10	163	93	99	94	99
33 & 34	2.00	0.10	80	98	100	99	100
38 & 40	2.00	0.10	63	91	100	92	100

TABLE 2
ORIGINAL DATA, HYDRAULIC MEASUREMENTS

Test No.	d_m micron	L cm	i %	C %	i_{2-7} in/in	i_{1-8} in/in	Q ml/sec	Re --	Q' micron ²	k' micron ²
1w	775	16.50	44.3	---	0.10	0.11	0.76	0.28	37	370
b	---	---	---	0.10	0.10	0.11	0.64	---	33	330
w	---	---	---	---	0.10	0.11	0.62	---	30	300
2w	775	16.50	44.2	---	0.10	0.11	0.77	0.29	37	370
b	---	---	---	0.10	0.10	0.12	0.71	---	36	360
w	---	---	---	---	0.10	0.11	0.70	---	34	340
3w	775	16.50	44.8	---	0.50	0.52	3.5	1.3	170	340
b	---	---	---	0.10	0.50	0.52	3.2	---	160	320
w	---	---	---	---	0.51	0.52	3.2	---	155	300
4w	775	16.50	44.0	---	0.50	0.52	3.6	1.4	175	350
b	---	---	---	0.10	0.50	0.52	3.2	---	160	320
w	---	---	---	---	0.50	0.52	3.2	---	155	310
5w	775	16.50	44.7	---	0.50	0.53	3.6	1.4	175	350
b	---	---	---	0.10	0.50	0.53	3.4	---	175	350
w	---	---	---	---	0.50	0.53	3.5	---	170	340
6w	775	16.50	43.8	---	0.10	0.10	0.67	0.25	33	330
b	---	---	---	1.00	0.10	0.11	0.33	---	28	280
w	---	---	---	---	0.10	0.10	0.55	---	27	270
7w	775	16.25	42.0	---	0.10	0.11	0.77	0.29	37	370
b	---	---	---	1.00	0.10	0.12	0.36	---	31	310
w	---	---	---	---	0.10	0.12	0.55	---	32	320
8w	775	16.25	42.3	---	0.50	0.54	3.4	1.3	165	330
b	---	---	---	1.00	0.51	0.55	1.6	---	140	275
w	---	---	---	---	0.51	0.53	2.8	---	135	265
9w	775	16.50	45.6	---	0.50	0.54	3.5	1.3	170	340
b	---	---	---	1.00	0.50	0.55	1.5	---	130	260
w	---	---	---	---	0.51	0.55	2.9	---	140	275
10w	775	16.50	45.2	---	1.43	1.52	11.0	4.2	535	370
b	---	---	---	0.10	1.45	1.53	9.87	---	504	350
w	---	---	---	---	1.46	1.57	10.4	---	505	350
11w	385	15.85	41.1	---	0.51	---	0.79	0.15	38	75
b	---	---	---	0.10	0.54	---	0.65	---	33	61
w	---	---	---	---	0.54	---	0.65	---	32	59
12w	385	16.35	42.5	---	0.10	0.10	0.16	0.030	7.9	79
b	---	---	---	0.10	0.10	0.11	0.16	---	8.2	82
w	---	---	---	---	0.10	0.11	0.16	---	7.9	79
13w	385	15.85	42.4	---	0.10	0.11	0.16	0.030	7.9	79
b	---	---	---	0.10	0.10	0.11	0.15	---	7.7	77
w	---	---	---	---	0.10	0.11	0.15	---	7.3	73
14w	385	16.31	43.7	---	0.50	0.54	0.86	0.16	42	84
b	---	---	---	0.10	0.50	0.62	0.66	---	34	68
w	---	---	---	---	0.50	0.57	0.68	---	33	66
15w	385	16.25	41.2	---	1.00	1.10	1.67	0.32	81	81
b	---	---	---	0.10	1.00	1.16	1.42	---	73	73
w	---	---	---	---	0.99	1.18	1.44	---	70	71
16w	385	16.20	43.9	---	0.10	0.11	0.17	0.032	8.3	83
b	---	---	---	1.00	0.10	0.12	0.094	---	8.0	80

TABLE 2 CONTINUED

Test No.	d_m micron	L cm	f %	C %	i_{2-7} in/in	i_{1-8} in/in	Q ml/sec	Re --	Q' micron ²	k' micron ²
w	---	---	---	---	0.10	0.12	0.16	---	7.8	78
17w	385	16.20	43.8	---	0.10	0.10	0.17	0.33	8.3	83
b	---	---	---	1.00	0.10	0.10	0.090	---	7.7	77
w	---	---	---	---	0.10	0.12	0.17	---	8.3	83
18w	163	16.05	44.8	---	0.93	1.00	0.35	0.028	17	18
b	---	---	---	0.10	0	1.00	0	---	0	0
w	---	---	---	---	0	1.00	0	---	0	0
19w	163	16.50	44.7	---	0.88	1.00	0.36	0.029	17	20
b	---	---	---	0.10	0.22	1.00	0.067	---	3.4	3.4
w	---	---	---	---	0.22	1.00	0.089	---	4.3	4.3
20w	163	16.50	45.8	---	0.08	0.10	0.035	0.0028	1.7	21
b	---	---	---	0.10	0.02	0.10	0.006	---	0.30	0.30
w	---	---	---	---	0.08	0.10	0.031	---	1.5	1.5
21w	163	16.00	44.8	---	0.09	0.10	0.033	0.0027	1.6	18
b	---	---	---	0.10	0.08	0.10	0.025	---	1.3	13
w	---	---	---	---	0.08	0.10	0.029	---	1.4	14
22w	163	16.50	44.9	---	1.69	2.00	0.66	0.054	32	19
b	---	---	---	0.10	0.34	1.99	0.016	---	0.82	0.41
w	---	---	---	---	0.16	2.00	0.033	---	1.6	3.2
23w	163	16.50	44.5	---	1.72	2.00	0.66	0.054	32	19
b	---	---	---	0.10	0	1.98	0	---	0	0
w	---	---	---	---	0.17	1.98	0.057	---	2.8	1.4
24w	163	16.51	46.7	---	0.09	0.11	0.030	0.024	1.5	17
b	---	---	---	1.00	0.03	0.11	0.0020	---	0.17	1.5
w	---	---	---	---	0.08	0.10	0.015	---	0.73	7.3
25w	163	16.20	44.5	---	0.06	0.11	0.022	0.0018	1.1	18
b	---	---	---	1.00	0	0.10	0	---	0	0
w	---	---	---	---	0.02	0.09	0.0080	---	0.40	4.4
26w	163	15.70	44.7	---	0.84	1.02	0.35	0.019	17	20
b	---	---	---	1.00	1.25	1.03	0.020	---	1.7	1.6
w	---	---	---	---	0.44	1.02	0.060	---	2.9	2.8
27w	163	16.20	44.4	---	0.62	1.00	0.22	0.018	11	18
b	---	---	---	1.00	0.03	1.00	0.0070	---	0.60	0.60
w	---	---	---	---	0.08	1.02	0.023	---	1.1	1.1
28w	163	15.90	44.5	---	1.60	2.00	0.65	0.052	32	20
b	---	---	---	1.00	0	2.00	0	---	0	0
w	---	---	---	---	0.20	2.00	0.037	---	1.8	0.90
29w	163	16.20	44.5	---	1.70	2.01	0.66	0.053	32	19
b	---	---	---	1.00	0.64	2.01	0.013	---	1.1	0.50
w	---	---	---	---	0.12	1.82	0.037	---	1.8	0.99
30w	80	16.65	46.0	---	0.11	0.11	0.010	0.0039	0.49	4.4
b	---	---	---	0.10	0.02	0.11	0.0020	---	0.10	0.90
w	---	---	---	---	0.05	0.11	0.0050	---	0.24	2.2
31w	80	16.70	46.4	---	0.10	0.11	0.010	0.0039	0.49	4.4
b	---	---	---	1.00	0.02	0.11	0.0020	---	0.10	0.90
w	---	---	---	---	0.06	0.11	0.0050	---	0.20	1.8
32w	80	16.50	48.3	---	0.11	0.11	0.010	0.0039	0.49	4.4
b	---	---	---	1.00	0	0.11	0	---	0	0
w	---	---	---	---	0	0.11	0	---	0	0

TABLE 2 CONTINUED

Test No.	d_m micron	L cm	f %	C %	i_{2-7} in/in	i_{1-8} in/in	Q ml/sec	Re --	Q' micron ²	k' micron ²
33w	80	15.55	47.3	---	1.59	2.17	0.15	0.0059	7.3	4.6
b	---	---	---	0.10	0	2.17	0	---	0	0
w	---	---	---	---	0	2.17	0	---	0	0
34w	80	16.03	49.1	---	1.70	2.00	0.17	0.0068	8.3	4.8
b	---	---	---	0.10	0	2.00	0	---	0	0
w	---	---	---	---	0.03	2.00	0.007	---	0.30	0.15
35w	80	16.20	46.7	---	1.94	2.00	0.18	0.0071	8.8	4.9
b	---	---	---	0.10	0	2.00	0	---	0	0
w	---	---	---	---	0	2.00	0	---	0	0
36w	80	16.05	45.4	---	1.83	2.00	0.18	0.0071	8.8	4.8
b	---	---	---	0.10	0	2.00	0	---	0	0
w	---	---	---	---	0	2.00	0	---	0	0
37w	80	16.50	47.6	---	0.88	1.0	0.099	0.0039	4.8	5.3
b	---	---	---	1.00	0	1.0	0	---	0	0
w	---	---	---	---	0	1.0	0	---	0	0
38w	63	15.80	---	---	1.98	2.03	0.080	0.0031	3.9	2.0
b	---	---	---	0.10	---	2.03	0	---	0	0
w	---	---	---	---	---	2.03	0	---	0	0
39w	63	16.50	46.5	---	0.10	0.10	0.0040	0.00015	0.19	1.9
b	---	---	---	0.10	0	0.10	0	---	0	---
w	---	---	---	---	0	0.10	0	---	0	---
40w	63	16.50	45.4	---	2.03	2.00	0.083	0.0033	4.0	2.0
b	---	---	---	0.10	0	2.00	0	---	0	0
w	---	---	---	---	0.22	2.00	0.015	---	0.73	0.36
41w	274	16.20	45.0	---	0.97	1.05	1.21	0.16	59	60
b	---	---	---	0.10	0.86	1.05	0.090	---	4.7	4.5
w	---	---	---	---	0.72	1.05	0.46	---	22	21
42w	274	16.50	45.0	---	0.96	1.0	1.23	0.17	60	62
b	---	---	---	0.10	0.74	1.0	0.087	---	4.4	4.4
w	---	---	---	---	0.86	1.0	0.33	---	16	16

TABLE 3
ORIGINAL DATA, ELECTRICAL MEASUREMENTS

Test No.	λ micro mhos cm^{-1}	Ω ohms	Cell Constant cm^{-1}	λ_s 10^{-4} mhos cm^{-1}	ΔE millivolt	$\Delta E/P$ millivolt cm^{-1}	ζ volt
775-Micron Carborundum							
1w	6.0	16,000	2.87	1.79	8	4.8	1.20
b	38	8,000	---	3.60	1	0.6	0.302
w	---	---	---	---	7.5	4.6	1.15
2w	6.8	27,000	2.87	1.91	7	4.2	1.12
b	37	8,000	---	3.60	1	0.6	0.302
w	---	---	---	---	6.5	4.0	1.07
3w	5.8	27,000	2.87	1.06	53	6.4	0.950
b	37	8,000	---	3.60	5	0.6	0.302
w	---	---	---	---	46	5.5	0.815
4w	6.0	8,000	2.87	3.60	8	0.90	0.455
b	35	5,300	---	5.42	4.5	0.50	0.380
w	---	---	---	---	10	1.2	0.590
5w	5.9	25,000	2.87	1.15	57	6.9	1.11
b	36	8,000	---	3.60	10	1.2	0.605
w	---	---	---	---	55	6.7	1.08
6w	6.7	23,000	2.87	1.25	6	3.9	0.680
b	140	6,500	---	4.42	+1.5 to -0.2	+0.9 to -0.1	---
w	---	---	---	---	3	1.8	0.315
7w	6.4	21,000	2.87	1.37	5	3.1	0.595
b	140	6,500	---	4.42	+0.4 to -0.5	+0.3 to -0.3	---
w	---	15,500	---	1.85	+10 to -1	+6 to -0.6	---
8w	6.4	25,000	2.87	1.15	17	2.1	0.338
b	140	7,250	---	3.96	+1.0, -1	+1.0, 0, -0.1	---
w	---	22,000	---	1.30	15	1.8	0.328
9w	6.6	23,000	2.87	1.25	20	2.4	0.420
b	150	6,000	---	4.78	0.5	0.1	0.067
w	---	20,000	---	1.44	18	2.2	0.440
10w	6.8	25,000	2.87	1.15	99	3.9	0.628
b	40	7,500	---	3.82	11	0.43	0.235
w	---	---	---	---	102	3.9	0.628
385-Micron Carborundum							
11w	6.1	12,500	2.96	2.36	21	2.6	0.860
b	40	11,000	---	2.69	11	1.3	0.490
w	---	21,000	---	1.41	19	2.2	0.435
12w	6.2	24,000	2.96	1.23	5	3.1	0.508
b	40	14,000	---	2.12	+15 to -0.5	---	---
w	---	---	---	---	8	4.9	0.845
13w	8.2	26,000	2.96	1.14	5	3.3	0.526
b	43	12,000	---	2.47	1	0.70	0.242
w	---	27,000	---	1.11	5	3.3	0.514
14w	8.5	27,500	2.96	1.12	32	3.9	0.612
b	34	12,000	---	2.46	5	0.6	0.206
w	---	---	---	---	22	2.7	0.424
15w	7.5	22,000	2.96	1.35	94.5	5.8	1.10
b	33	11,000	---	2.69	+7	+0.43	0.161

TABLE 3 CONTINUED

Test No.	λ micro mhos cm^{-1}	Ω ohms	Cell Constant cm^{-1}	λ_s 10^{-4} mhos cm^{-1}	ΔE millivolt	$\Delta E/P$ millivolt cm^{-1}	ζ volt
w	---	---	---	---	11	0.69	0.131
16w	6.8	22,000	2.96	1.35	6	3.7	0.700
b	145	8,500	---	3.48	+1 to -3	+0.6 to -1.9	---
w	---	22,000	---	1.35	+25 to -11	+15 to -6	---
17w	6.8	23,000	2.96	1.29	2.7	1.7	0.306
b	145	10,000	---	2.96	0 to -3	0 to -1.9	---
w	---	22,000	---	1.35	3.5	2.2	0.415
163-Micron Carborundum							
18w	6.5	30,000	2.50	0.83	44	2.8	0.320
b	56	14,000	---	1.78	6	0.37	0.092
w	---	15,000	---	---	---	---	---
19w	6.7	25,000	2.50	1.00	29	1.8	0.245
b	43	18,000	---	1.39	5	0.30	0.058
w	---	25,000	---	1.00	10	0.61	0.085
20w	6.8	-----	2.50	---	5	2.9	---
b	38	16,000	---	1.56	2	1.2	0.262
w	---	24,000	---	1.04	3	1.9	0.277
21w	14	20,000	2.50	1.25	4	2.4	0.420
b	45	16,000	---	1.56	1	0.62	0.135
w	---	18,000	---	1.39	5	3.2	0.623
22w	8.2	39,500	2.50	0.63	103	3.1	0.273
b	49	20,000	---	1.25	3	0.09	0.016
w	---	37,000	---	0.68	20	0.61	0.058
23w	7.3	41,000	2.50	0.61	143	4.3	0.367
b	51	17,500	---	1.43	3	0.121	0.024
w	---	39,000	---	0.64	24	0.735	0.066
24w	7.5	43,000	2.50	0.58	9.0	4.85	0.394
b	145	16,000	---	1.56	1	0.516	0.113
w	---	26,000	---	0.96	7.0	4.25	0.570
25w	9.5	38,000	2.50	0.66	7	4.40	0.406
b	140	30,000	---	0.83	2.5	1.40	0.163
w	---	26,000	---	0.96	5	3.28	0.440
26w	8.7	37,500	2.50	0.67	47.5	2.97	0.279
b	150	---	---	---	---	---	---
w	---	---	---	---	---	---	---
27w	9.5	37,000	2.50	0.68	47	3.0	0.285
b	150	14,500	---	1.72	1.4	0.15	0.036
w	---	22,750	---	1.10	5	0.30	0.046
28w	8.1	38,500	2.50	0.65	120	3.78	0.344
b	165	9,500	---	2.63	5	0.16	0.059
w	---	35,000	---	0.72	21	0.66	0.067
29w	8.2	38,750	2.50	0.65	12	0.38	0.035
b	150	18,000	---	1.39	1	0.03	0.006
w	---	35,500	---	0.71	20	0.68	0.068
80-Micron Carborundum							
30w	10	52,500	2.35	0.45	70	3.97	0.250
b	62	42,000	---	0.56	1.0	0.57	0.045

TABLE 3 CONTINUED:

Test No.	λ micro mhos cm^{-1}	Ω ohms	Cell Constant cm^{-1}	λ_s 10^{-4} mhos cm^{-1}	ΔE millivolt	$\Delta E/P$ millivolt cm^{-1}	ζ volt
w	---	40,000	---	0.59	1.5	0.65	0.054
31w	9.0	58,000	2.35	0.41	5.5	3.1	0.178
b	150	45,000	---	0.52	1	0.6	0.044
w	---	41,000	---	0.57	1	0.6	0.048
32w	7.0	57,000	2.35	0.41	4	2.2	0.126
b	150	27,000	---	0.87	1	0.5	0.061
w	Sealed						
33w	8.0	54,000	2.35	0.44	88	2.6	0.160
b	45	34,000	---	0.69	2	0.06	0.007
w	Sealed						
34w	9.0	51,500	2.35	0.46	66	2.1	0.135
b	38	28,000	---	0.84	---	0.1	0.012
w	---	38,000	---	0.62	2	0.06	0.005
35w	---	---	---	---	---	---	---
b	No Electrode						
w	---	---	---	---	---	---	---
36w	11	52,000	2.35	0.45	82	2.5	0.157
b	40	27,000	---	0.87	2	0.06	0.007
w	Sealed						
37w	7.0	36,000	2.35	0.42	15	0.92	0.054
b	150	17,000	---	1.38	0.6	0.04	0.008
w	Sealed						
63-Micron Carborundum							
38w	9.0	44,000	2.20	0.50	17	0.5	0.035
b	40	37,000	---	0.60	0.6	0.02	0.002
w	Sealed						
39w	9.0	56,000	2.20	0.39	2.3	1.42	0.078
b	40	45,000	---	0.49	0	0	---
w	Sealed						
40w	10	55,000	2.20	0.40	35	1.06	0.060
b	45	45,500	---	0.48	0	---	---
w	---	43,000	---	0.51	1.6	0.05	0.004
274-Micron Carborundum							
41w	7.0	27,500	2.73	0.99	72	4.26	0.590
b	59	10,600	---	2.58	2.5	0.15	0.054
w	---	27,000	---	1.01	36	2.11	0.300
42w	8.0	27,000	2.73	1.01	78	4.71	0.665
b	60	11,000	---	2.48	1.5	0.09	0.031
w	---	21,000	---	1.30	22	1.33	0.244

TABLE 4
CELL-CONSTANT DETERMINATIONS

d_m microns	Depth cm	Porosity %	Electrical Resistance of 0.1N KC1 ohms	Electrical Conductivity of 0.1N KC1 mhos cm^{-1}	Cell Constant cm^{-1}
775	16.50	43.7	245	0.0121	2.95
775	15.85	43.1	255	0.0112	2.86
775	15.85	42.9	248	0.0113	2.80
775	15.85	44.1	255	0.0117	2.95
775	15.85	44.4	245	0.0180	2.90
775	15.85	44.5	235	0.0123	2.89
775	15.85	44.2	245	0.0117	2.86
775	16.50	43.9	250	0.0115	2.88
775	15.25	44.8	230	0.0120	2.76
775	16.50	44.3	250	0.0117	2.92
				Average	2.87
385	16.50	---	245	0.0120	2.93
385	16.31	43.7	245	0.0121	2.95
385	16.50	43.8	280	0.0105	2.94
385	16.50	41.2	285	0.0105	2.99
				Average	2.95
163	15.70	44.5	210	0.0120	2.52
163	15.85	44.7	210	0.0120	2.52
163	16.00	43.6	250	0.0100	2.50
163	16.10	43.4	250	0.0100	2.50
163	16.20	---	250	0.0100	2.50
				Average	2.51
80	16.00	48.4	210	0.0120	2.52
80	17.00	48.5	230	0.0120	2.76
80	16.65	47.5	200	0.0120	2.40
80	16.75	---	215	0.0100	2.15
				Average	2.45
63	15.50	49.8	200	0.0115	2.30
63	15.50	49.8	190	0.0115	2.19
63	16.62	46.8	220	0.0100	2.20
63	16.50	49.4	210	0.0100	2.10
				Average	2.20

TABLE 5
BENTONITE RETAINED IN COLUMN OF CARBORUNDUM

Test Number	Quantity of Bentonite Retained*	
	Top Inch mg./100 gr.	Whole Column mg./600 gr.
1	20.9	125
2	21.4	128
3	30.4	236
4	30.9	240
5	20.9	126
6	38.0	228
7	63.0	378
8	25.5	153
9	34.9	209
10	---	---
11	18.7	112
12	17.1	103
13	18.5	111
14	18.8	92.4
15	23.1	123
16	24.2	163
17	13.8	82.8
18	36.8	152
19	76.6	138
20	7.3	76.1
21	15.8	77.0
22	189.0	227
23	37.6	46.5
24	39.7	63.6
25	8.3	44.1
26	215	376
27	120	257
28	72.8	177
29	87.6	228
30	---	---
31	23.1	64
32	202	619
33	77.9	108
34	34.2	93
35	196	313
36	73.4	163
37	418	1249
38	---	---
39	103	750
40	52.8	134
41	104	191
42	270	439

*Note: The accuracy of the method of analysis was within 12±5 milligrams of bentonite per 100 grams of carborundum, which was determined by the analysis of 12 samples in which it was known that no bentonite was present.

TABLE 6
CHEMICAL ANALYSIS OF THE BENTONITE

Determinations		Quantity present in per cent	
		Sample B-1-1960	Sample B-2-1960
Moisture at 105°C	H ₂ O	9.68	2.64
Additional Ignition loss, Not SO ₃ or Silica	CO ₂ SiO ₂	5.16 56.21	5.39 59.80
Alumina	Al ₂ O ₃	19.12	21.20
Total Iron as Ferric Oxide	Fe ₂ O ₃	3.46	4.38
Ferrous Oxide	FeO	0.37	0.10
Calcium Oxide	CaO	1.26	1.24
Magnesium Oxide	MgO	1.29	2.17
Sodium Oxide	Na ₂ O	2.04	2.07
Potassium Oxide	K ₂ O	0.27	0.09
Total Sulphur calculated to	SO ₃	0.43	0.11
Titanium Oxide	TiO ₂	0.12	0.11
Phosphorus Pentoxide	P ₂ O ₅	0.06	0.06
Carbon Dioxide	CO ₂	0.46	0.58
Chlorides	Cl	0.01	0.01
Undetermined		0.06	0.05

Note: Sample B-1-1960 was taken from original bulk quantity of Wyoming bentonite, (Vol-Clay, KWK, granulated). Sample B-2-1960 was taken from a 1 per cent suspension of the above Wyoming bentonite which has been prepared in double-distilled water, dialyzed, and NaOH added to bring the pH to 9.0. The analyses were made by The Bruce Williams Laboratories, Joplin, Missouri