PENETRATION AND RETENTION OF

BENTONITE SUSPENSIONS IN POROUS MEDIA

By

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FOREWORD

The work reported herein was conducted as part of a project to study and evaluate canal lining by sedimentation. The phase of the work conducted by Mr. Curry resulted in a thesis leading to the degree of Master of Science in Irrigation Engineering. This thesis fully reports the results of the research conducted by Mr. Curry and accordingly is presented as the project report for the penetration and sealing phase of the work.

ACKNOWLEDGMENTS

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American Colloid Company, Chicago, Illinois.

Baroid Sales Division of National Lead Company, Houston, Texas.

Benton Clay Company, Casper, Wyoming.

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Magnet Cove Barium Corporation, Houston, Texas.

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Chapter I

INTRODUCTION

In many arid regions of the world, the loss by seepage of much needed water from irrigation canals is a major problem. The problem in many instances is two-fold: the actual loss of the use of the water, and the detrimental effect of the seepage by water-logging adjacent irrigable land.

There is evidence that the problem of canal seepage has been magnified in recent years by the construction of reservoirs which control the flow of water, but which also remove the suspended sediment. Prior to the construction of the reservoirs, the canals carried muddy water during the early part of the irrigation season. The fine sediment carried by this water produced a temporary cake on the bed of the canals. This cake was rather impermeable and therefore reduced the seepage loss from these canals. With reservoirs in use, the water is clear and carries no material to produce such a cake, therefore, the seepage losses are greater -- particularly in newly constructed canal systems. Also, the clear water has a tendency to produce more scouring of the bed and sides of the canals.

Seepage losses have led to construction of canal linings of a great many types. Concrete linings have been used more extensively than any other kind. They are usually the most permanent and effective kind of lining. The cost is high and almost prohibitive on all but the most productive and intensively cultivated irrigated lands.

Besides concrete linings some of the other types of canal linings used to reduce seepage have been asphalt, compacted earth, synthetic plastic and bentonite membrane linings. All have been satisfactory in some respects but not in others. The cost of these various linings has been somewhat lower than that of concrete linings, but in many cases uneconomic nevertheless. In general, these various linings have shorter life and less effectiveness than concrete linings. There exists, therefore. a definite need for further investigation and development of low cost canal linings.

Recently a project has been undertaken cooperatively by the United States Bureau of Reclamation, Colorado Agricultural and Mechanical College and the United States Geological Survey, to develop the use of fine-grained materials carried by the canal water for canal lining. The initial investigations involved the use of colloidal suspensions of bentonite. In general, concentrations of approximately one per cent by weight have been used. Two different procedures have been tried: 1) ponding the suspension in succeeding reaches of the canal, 2) allowing the suspension to pass unretarded down the canal. In both cases, the hypothesis has been that the suspension would pass into the pores of the canal bed wherever the seepage was taking place. As a result of such seepage, bentonite might be deposited rendering the bed material impermeable to water ~~movement~~. Some cost advantages of this type of canal lining are: 1) transporting and placing of the lining are done by the irrigation water, 2) sealing is selective, that is, sealing occurs only where there are leaks and in that way the lining material is conserved and required seepage surveys are minimized, 3) readily available facilities are used, i.e., irrigation water, canal structures, operating personnel, with need for very little extra equipment.

Need for Study

In order to develop the method more rapidly, there exists a need for basic understanding of the mechanics of sediment lining. The following study was conducted as part of a general program to investigate and develop the sediment lining of canals.

Purpose of Study

To study the transfer of colloids by seepage from water suspensions into porous media with the objective of obtaining basic information necessary to install canal linings by sedimentation.

Problems to be Considered

1. What techniques are available or can be developed to determine quantitatively the depth of penetration and distribution of colloids from a stable suspension seeping through porous media?
2. What are the factors that influence the penetration and retention of bentonite suspensions in porous media?
3. How may these factors be controlled in order to achieve better penetration and distribution of colloids in the canal bed and sides using sedimenting methods?

Delimitations

1. Uniform sand, glass beads and a commercial zeolite will be used for the porous medium.
2. A single commercial high-swelling Wyoming bentonite will be used.
3. Only stable bentonite suspensions will be used.

Definition of Terms

1. Bentonite. For a complete definition refer to the review of literature. In this study "bentonite" refers to a commercial Wyoming-type, high-swelling clay of which montmorillonite is the principal constituent.
2. Stable suspension. As applied to this study a mixture of bentonite and distilled water will be considered stable if, after standing for 24 hours, it is still dispersed, with no clear water break at the surface.
3. Chemically inert sand. "Chemically inert sand" refers to sands which have very little or no ion exchange capacity, or soluble ions for chemical reaction.
4. Hydraulic conductivity. Hydraulic conductivity in this study will refer to the proportionality constant in Darcy's formula as defined by the American Society of Agronomy (12). The formula

is not corrected for temperature. The units will be feet per day.

5. Median diameter. The median diameter is the width of a square screen opening such that 50 per cent by weight of a sample will pass through such an opening and 50 per cent by weight will be retained above it.

6. Uniformity coefficient. The uniformity coefficient is the ratio of the D_{60} size to the D_{10} size, where these sizes are the screen sizes respectively, such that 60 per cent of a sample passes a screen corresponding to D_{60} size, and 10 per cent passes a screen of D_{10} size.

7. Sediment lining. A method of lining irrigation canals in which fine-grained lining material is dispersed in canal water and carried by the flowing water to wherever seepage is taking place; the suspension is allowed to pass into the pores of leaking canal beds and sides and is retained below the surface thereby reducing permeability.

8. Zeolite. A hydrous silicate, characterized by a high base exchange capacity. The zeolite used in this study was a commercially produced, granular material.

9. Chemical reactivity. The chemical characteristics of any system studied which involve ionic exchange and solution reactions.

Chapter II

REVIEW OF LITERATURE

A study of bentonite penetration and retention in porous media involves several related bibliographical subjects.. Among these are: 1) bentonite, 2) canal linings, and 3) flow through porous media. Extensive literature can be found on all of these subjects. A full literature review of them has not been made because they are fairly well known and already well summarized (1, 4, 6, 11)[1]. Because these three topics are related only in that they are each of interest to this study, they are discussed separately. Little literature has been found which directly relate to the subject of colloid penetration in porous media.

Bentonite

Bentonite is defined by the American Petroleum Institute in their book, "Reference Clay Minerals" (1) as follows:

> A name given to a type of clay first described from Rock Creek, Wyoming, which originally was called taylorite. Taylorite (Knight 1897) was found to be preoccupied, and so, the name bentonite was proposed for the same mineral (Knight 1898) . - - Ross and Shannon (1926) proposed the following definition of bentonite which has been accepted by mineralogists:
>
> "Bentonite is a rock composed essentially of a crystalline clay-like mineral formed by devitrification and accompanying chemical alteration of a glassy igneous material, usually a tuff or volcanic ash."
>
> In their description of the rock, they state:

[1] Numbers in parentheses are entries in the Bibliography.

"It contains variable proportions of accessory crystal grains that were originally phenocrysts in volcanic ash. There are feldspar (commonly orthoclase and oligoclase), biotite, quartz, pyroxenes, zircon, and various other minerals typical of volcanic rocks. The characteristic clay-like mineral has a micaceous habit and facile cleavage, high birefringence and a texture inherited from volcanic tuff or ash, and it is usually the mineral montmorillonite, but less often beidellite."

The word bentonite has at times been applied as a trade term to adsorptive clays or drilling mud. Such a choice does not appear based on sound scientific usage. It has also erroneously been applied to material that swells in contact with water. This usage is likewise not fundamental and should be discouraged. (Reference Clay Minerals, American Petroleum Institute). (1)

Bentonite has many uses, e.g., as a drilling mud in the oil industry, as a foundry clay, and as a material for sealing canals, ponds, and reservoirs.

Canal Linings

Many types of canal linings have been used (11). A few of these are mentioned in Chapter I. One of these, a lining method utilizing clay materials, will now be discussed in greater detail.

The sealing effect of clays was used by Sokolovskii (8) to reduce the seepage from canals and reservoirs in Russia. His method was to apply a salt solution (NaCl) to a canal in which a layer of clay-containing loess was placed and protected by a sand cover. The sodium salt had the effect of dispersing the clay producing a sealing effect.

Bentonite has been used for many years as a material for seepage control in canals, ponds, and reservoirs. Most of the experiments have been conducted with bentonite as a membrane lining, that is, mixing some bentonite with a layer of the bed material and covering this with a layer of sand or gravel. (6)

A continuing study of the use of bentonite for lining of irrigation canals is being conducted by the United States Bureau of Reclamation under their Low Cost Canal Lining Program.

Flow in Porous Media

Because the permeability of porous media has been investigated by many workers, there is an abundance of literature on the subject. Some of the earliest research was conducted by Darcy in 1865, who presented the relationship that velocity is proportional to the hydraulic gradient. The object of investigators since Darcy has been to establish the factors upon which the proportionality constant depends, and to delineate the interrelationships and effects of these factors. The subject of flow in porous media has been covered very thoroughly by Muskat (4) and many other writers.

Penetration of Colloidal Suspensions in Porous Media

Some study of the penetration of colloidal suspensions into porous media has been conducted by investigators interested in the problem as it pertains to rapid sand filters for water and sewage treatment.

Stanley (9), in a study of rapid sand filters, found that he could trace the penetration of hydrous ferric oxide flocs into sand beds by the use of radioactive tracers. He found that his penetration index, defined as the penetration in centimeters caused by the passage into a filter of one mg of Fe per sq cm of filter area, varied linearly with the sand size and directly with the flow rate. The penetration index increased with the addition of $NaCl$ and Na_2SO_4 to the suspension and decreased with an increase in floc size. His conclusions were that the effects of van der Waals forces, electro-kinetic force, 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.

Summary and Implications

A summary of the literature relating to bentonite penetration and retention in porous media and associated phenomena indicates a wealth of information on subjects of indirect interest, such as bentonite, canal lining, and flow through porous media. Little work has been done on penetration of colloidal suspensions into porous media. This work was conducted using floc suspensions containing comparatively coarse particles by investigators interested in rapid sand filters.

Chapter III

METHODS AND MATERIALS

To obtain basic information about the penetration and deposition of bentonite in sand columns, it was necessary to set up equipment in which a column of sand could be held. The hydraulic conductivity of this column was determined, and the depth and distribution of bentonite in the column were determined for different inert sands. This chapter deals with the design of the equipment and the methods and materials used in this study.

Equipment Used

The design of the basic equipment for this study followed common design of permeameters for soil permeability studies. The basic equipment consisted of plastic cylinders, $5\frac{1}{2}$ in. inside diameter and one ft high with manometer taps at 1-in. intervals along the side of the cylinders as shown in Fig. 1. The end caps were steel plates, with a section of 6-in. steel pipe welded to the plate. Rubber gaskets $\frac{1}{4}$-in. thick were glued to the inner face of the plate. A tap for a $\frac{3}{4}$-in. hose connection was placed in the center of the steel plate. The two end plates were attached to the plastic cylinder with $\frac{3}{8}$-in. rods threaded on both ends. Slits were cut in each corner of the top cap to facilitate removal of the rods which held the cap to the cylinder.

Two sections of $5\frac{1}{2}$-in. plastic pipe, each two ft long, which could be attached to the top of the cylinder when the top cap was removed, completed the system for the introduction of the bentonite suspension, see Fig. 2. The pipe was connected to the cylinder by the steel rods. A rubber gasket formed the seal between the pipe and the cylinder.

Constant head was maintained for initial and final hydraulic conductivity determinations through the use of a constant head tank. The constant head tank was a 55-gal. drum placed about 10 ft above the cylinder. The drum was so constructed that the water entering from the city supply through the bottom of the drum came up through a cylinder filled with sand and gravel, giving some degree of air removal from the water. The drum had an overflow on the top, which emptied into the sump. Control of the constant head was maintained by two valves located on the inflow and outflow ends of the cylinder. By adjusting these valves, a particular hydraulic head on the column could be maintained.

The manometer board consisted of 16 $\frac{3}{8}$-in. glass tubes five feet long fastened to a plywood board. Each of the manometer taps on the cylinder was connected to one of the glass tubes by rubber tubing. The head loss in the section of material between any two taps could be read directly from the scale on the manometer board. The discharge through the column was measured with a 1000-ml graduated cylinder and a stop watch.

Soil hydrometers of the Bouyoucos type, reading 0-10 gm of material in suspension per liter of suspension, were used to measure the initial and final concentrations of the bentonite suspension. One-liter hydrometer jars were used to hold samples of the suspension.

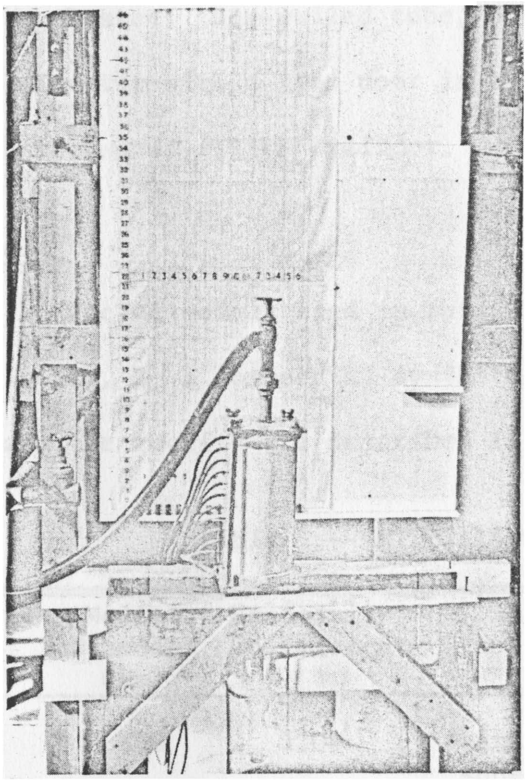


Fig. 1. Apparatus for permeability determinations showing permeameter and manometer board.

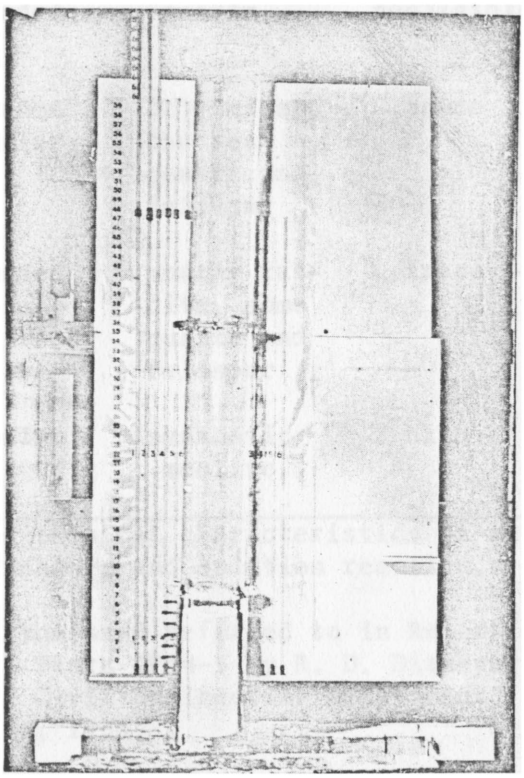


Fig. 2. Apparatus for introduction of the bentonite suspension showing the 4-ft stand pipe above the column of sand.

A steel thin-walled tube, or "tremie", three ft long and two in. in diameter with a trap door in the bottom was used to place the sand in the water-filled cylinder.

Materials

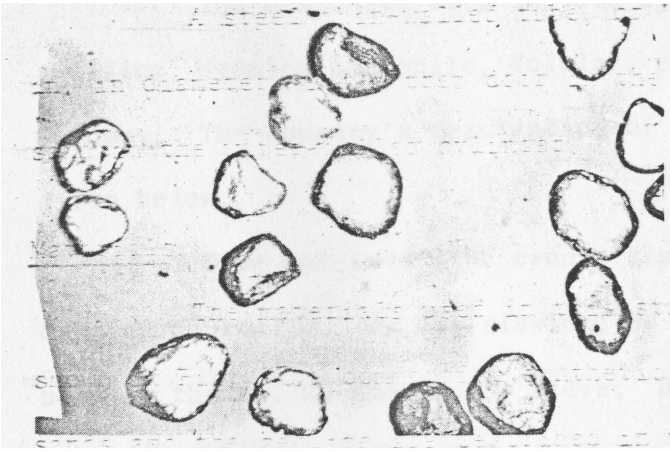
The materials used in this study consisted of four sands as shown in Fig. 3, a commercial synthetic zeolite, and bentonite. The sands and the zeolite are described in the following table.

Table 1.--MATERIALS USED IN STUDY.

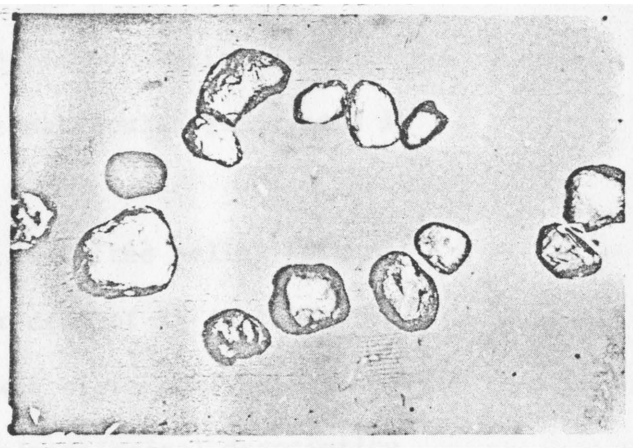
Material	Median Diameter (mm)	Uniformity Coefficient	Shape	Mineral Composition	Chemical Reactivity[1]
Ottawa sand	0.480	1.08	rounded and spherical	quartz	negligible
Loup River sand	0.280	1.50	rounded	quartz	negligible
Loveland Lake sand[2]	0.160	1.80	rounded angular	30% mica, the rest quartz and feldspar	trace
Salt Lake sand	0.310	1.74	rounded	mostly calcite, some quartz and feldspar	trace
zeolite	approx 0.5	--	angular	synthetic zeolite	high

[1] Chemical reactivity is defined as the chemical characteristics of any system studied which involve ionic exchange and solution reaction.

[2] Loveland Lake sand is the same as Barton sand referred to in Report of Sediment Lining Investigations Fiscal Years 1954-5 by R. D. Dirmeyer, published by Colorado A and M College Civil Engineering Department, CER No. 55RDD7, Fort Collins, Colorado, 1955.

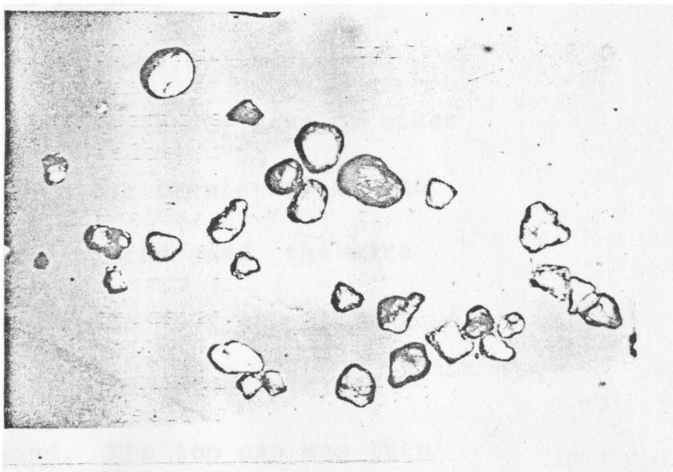


Ottawa sand



Loup River sand

Loveland Lake sand



Salt Lake sand

Fig. 3. Sands used photographed through a petrographic microscope(magnification 22X).

The bentonite used in this study was a commercial, high-swelling, Wyoming bentonite, Volclay, produced by American Colloid Company. The company's description of the particular grade used is given below.

Type KWK is a fine evenly sized dust-free pellet form of Wyoming bentonite. By dry sieving, 94 per cent of it is contained between the No. 20 and No. 50 sieve. By wet sieve analysis, 87 per cent of it is finer than 0.3 microns. A mineralogical description of bentonite is included in Chapter II.

Procedure

The cylinder section of the permeameter was placed in the lower end cap, and fine gravel was placed in the cylinder to a depth of one in. Over this was placed a 100-mesh screen. This arrangement permitted free flow of water below the sand column.

With the above arrangement completed, the cylinder was filled with water. The tremie was then filled with dry sand or other material and lowered into the cylinder. When the tremie was at the bottom or touching the top of the previously placed sand, the wire attached to the trap door was pulled, opening the door and letting the sand flow into the cylinder under water. This procedure was repeated until the cylinder was full of sand. The top cap was then placed on the cylinder and fastened with the long steel rods. An electrically driven vibrator was held on the pipe fitting on the top of the permeameter to vibrate the whole permeameter until the level of the sand was observed to be stable.

After the sand was placed, a valve, with a hose from the constant head tank attached, was connected to the tap on the top cap. This valve was opened slightly to allow water to enter from the tank. The lower valve was then opened slightly to allow flow from the column. The rubber tubes connected to the manometers on the manometer board were attached to each tap on the cylinder. The two valves were adjusted to give the desired head of approximately four ft across the column and also to keep the level in the manometer connected to the lowest tap on the cylinder above that of the top of the cylinder. This was done to keep positive pressure on the cylinder at all times.

The water was allowed to flow through the cylinder for 24 hrs. Several times during the 24-hr period, the rate of flow was calculated by measuring the discharge collected in a graduated cylinder, during a period timed by the stop watch. Also the manometers were read and recorded during this period. The several rates of flow were averaged, giving a mean rate of flow for the 24-hr period. The observations of total head loss across the entire length of the sand column were averaged, giving an average head loss for the 24-hr period. With these values, and the diameter and length of the column, the hydraulic conductivity of the sand was calculated.

After the determination of the initial hydraulic conductivity, the valves were closed and the top cap removed. The 4-ft plastic pipe was then connected to the cylinder by means of the long steel rods. The system was then ready for introduction of the bentonite suspension.

The bentonite suspension was prepared by first soaking a quantity of granulated Volclay in distilled water. This slurry was then diluted with distilled water to the approximate concentration desired. Originally it was planned to use a dispersing agent, but it was found that this was not needed for one to two per cent Volclay suspensions in distilled water. The diluted slurry was then well mixed and allowed to stand for 24 hours before using. The suspension to be used in the experiment was removed from the container at a point at least six in. from the bottom to avoid removing silt or coarse bentonite particles. The concentration was checked with a hydrometer at the time of removal, and this concentration was recorded as the initial concentration.

The bentonite suspension was introduced into the apparatus by pouring it into the top of the 4-ft stand pipe. One problem encountered in the introduction of the suspension was the scouring of the surface of the sand column. This was overcome by placing several thicknesses of fine and coarse screens on top of the sand column before the introduction of the suspension. After the stand pipe was filled with the suspension, the screens were carefully removed with an attached wire.

With the stand pipe above the sand filled with bentonite suspension, the lower valve was opened in order to determine whether or not the suspension would move through the column. If the suspension passed through the column, the stand pipe was refilled and kept at a level between three and four ft above the sand surface. A sample of the suspension which had passed through the column was checked with a hydrometer and the final concentration recorded. After enough time had passed to indicate that the suspension was continuing to pass through the column, the suspension was drained out of the column and the stand pipe removed. The top cap was replaced on the cylinder and the final hydraulic conductivity determined in the same manner as initially. The results were reported as final hydraulic conductivity.

With the final hydraulic conductivity determined, the top valve was closed and the column drained. The top cap was removed and the rubber manometer connections detached. The sand was then removed, samples being taken at the surface, and at one-in. intervals below the surface, to the bottom. Two 50-gm samples were taken at each location. These samples were set aside for determination of the presence of bentonite.

Several methods were considered for determination of the presence of bentonite: 1) staining the sample with benzidine. which reacts colorimetrically with bentonite; 2) mechanical analysis before and after sedimentation to see if there had been an increase in the clay content; 3) x-ray diffraction of the sample to determine presence of clay; 4) petrographic examination of thin sections of the samples to determine extent and kind of colloids present; and 5) cation exchange capacity before and after sedimentation. An increase would indicate an increase in clay content. After consideration of these methods the benzidine method was chosen because it was the simplest for materials containing no clay prior to sedimenting.

Since benzidine is rather insoluble in water, the solution to be used was prepared by first dissolving the benzidine in alcohol. This solution was then diluted with distilled water.

A few drops were applied on the samples to be analyzed. The presence of bentonite was indicated by a blue color. The intensity of the color was an indication of the quantity of bentonite present. From the color obtained from the different samples, the depth and distribution of the bentonite in the column was indicated.

After tests were conducted on all of the four sands, and in every case the suspension passed through the sands, it was decided to change the chemical environment of the system, and thereby attempt to induce flocculation of the bentonite suspension in the sand column.

A column of Loveland Lake sand of known hydraulic conductivity was saturated with a 2-N solution of calcium acetate by pouring the solution through the column. After draining, the stand pipe was placed on the cylinder and the bentonite suspension introduced into the column in the same manner as before. When the suspension had passed through the column, the stand pipe was removed and the final hydraulic conductivity determined. Samples were removed from the column and checked with benzidine for the presence of bentonite.

To produce a more active chemical environment a layer of commercial zeolite was placed on top of a layer of Loveland Lake sand. The zeolite had been calcium-saturated by being stirred in a solution of calcium-acetate for half an hour. After stirring, the zeolite was removed, washed with distilled water, and dried. The zeolite was placed in the cylinder on top of the sand layer with the tremie as for the sand.

The hydraulic conductivity of the column was then determined. The stand pipe was placed on the cylinder and the bentonite suspension introduced. Although the suspension passed through the column, the effluent was in a flocculated condition. The final hydraulic conductivity was determined. Samples were removed and analyzed for the presence of bentonite.

The same test was conducted using a column containing a mixture of equal parts by volume of zeolite and Loveland Lake sand. This mixture was not compacted, since such treatment caused the zeolite to segregate from the sand because of the large difference in the specific gravity between zeolite and sand. As in the preceding test, the suspension passed through the column with the effluent in a flocculated condition.

To give an indication of whether or not time had an effect on the system, a test was again conducted with a zeolite layer on a layer of Loveland Lake sand. The hydraulic conductivity was determined and the bentonite suspension was introduced. After the level in the stand pipe had dropped about two ft, the lower valve was closed and the system left to stand for 24 hours. When the lower valve was again opened, no flow occurred. The suspension was then removed from the stand pipe and the stand pipe removed from the cylinder. Samples of the column were removed and analyzed for the presence of bentonite.

A test using the same period of standing as the above was conducted on the mixture of zeolite and Loveland Lake sand. At the end of the period, no flow occurred when the valve was opened.

A check test was conducted using the technique of stopping the flow for 24 hours on a column containing only Loveland Lake sand. After reopening the lower valve, the flow continued and the final and initial hydraulic conductivities were the same.

It was originally intended to run replications of all tests. Because the suspension passed through the columns in all cases where inert sands alone were used, no replications of these were conducted. Duplicate determinations were made on the chemically reactive systems, i.e., Ca-saturated sand column and zeolite-sand mixtures. The data presented were the averages of the two runs which varied within five per cent of each other.

Chapter IV

PRESENTATION OF DATA

The penetration and retention of bentonite suspensions in porous media depend on many factors. The data on the determination of some of these factors and their effect on penetration and retention are presented in this chapter.

Data From Colorado A and M College

Data are presented in summary form in Table 2. Detailed data are not included, since in the original set of tests the suspension passed through the material, and therefore there were no significant variations in the readings of the manometers along the column of sand.

The porosity of each medium was determined by using the weight of the material in each cylinder, the specific gravity of the sand, and the volume of the cylinder.

The hydraulic conductivity was determined by the Darcy formula,

$$k = \frac{Q}{tA} \frac{L}{H},$$

where k = Hydraulic conductivity in ft/day

A = Cross-sectional area of sample in sq ft

Q = Volume of water in cu ft discharged in time, t

t = Time in days

L = Length of column in ft

H = Head loss across length of column in ft

Table 2.--DATA FOR PENETRATION STUDY CONDUCTED AT COLORADO A AND M COLLEGE.

Material	Bentonite Concentration (%) Initial	Bentonite Concentration (%) Final	Porosity (%)	Hydraulic Conductivity (ft/day) Initial	Hydraulic Conductivity (ft/day) Final	Depth of Bentonite Penetration	Presence of Bentonite in sand Column
Ottawa sand	0.5	0.5	32	165	162	Passed thru column	None
"	1.0	1.0	33	171	165	"	"
"	1.5	1.5	32	161	163	"	"
"	2.0	2.0	34	178	177	"	"
Loup River sand	0.5	0.5	36	43.1	42.0	"	"
"	1.0	1.0	35	40.2	41.0	"	"
"	1.5	1.5	37	45.1	44.5	"	"
"	2.0	2.0	35	41.5	39.0	"	"
Loveland Lake sand	0.5	0.5	41	38.0	33.2	"	"
"	1.0	1.0	43	41.5	38.6	"	"
"	1.5	1.5	42	39.0	36.1	"	"
"	2.0	2.0	43	42.0	38.4	"	"
Salt Lake sand	1.0	1.0	33	58.0	53.0	"	"
Loveland Lake sand saturated with Ca-acetate	1.0	1.0	42	40.1	37.6	"	"
Zeolite layer on Loveland Lake sand layer	1.0	Effluent flocculated	--	81.0	77.0	"	Trace[1]
After standing 24 hrs	1.0			81.0	0	Throughout zeolite and upper 2 in. of sand	Much[2]
1:1 mixture of zeolite and Loveland Lake sand	1.0	Effluent flocculated	Loosely packed	205	194	Passed thru column	Trace[1]
After standing 24 hrs				205	0	Throughout column	Much[2]

[1] Color of blue produced by the benzidine reaction barely detectable.
[2] Deep blue color produced by the benzidine reaction.

Note: Hydraulic gradient = 4.0

Data from the U. S. Geological Survey

The data presented here were obtained from tests conducted in the hydrologic laboratory of the Ground Water Branch, Water Resources Division, United States Geological Survey at Denver, Colorado. The work was conducted as part of the co-operative agreement on sediment lining research between Colorado A and M College and the U. S. Geological Survey. The details of the testing as done by the U. S. Geological Survey are also presented here.

Materials -- The materials used in this study were sands and glass beads. The sands used were Ottawa, Salt Lake and Loveland Lake. These sands were the same as those used in the tests at Colorado A and M College. The glass beads were obtained from Minnesota Mining and Manufacturing Company, Minneapolis, Minnesota. Their median diameters were: 28, 36, 57, 82, and 120 microns.

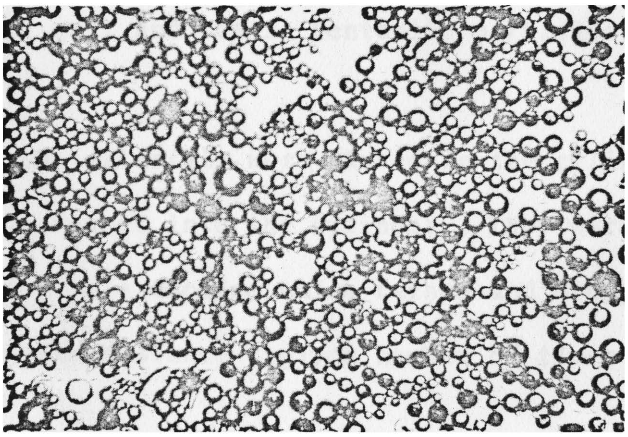


Fig. 4. Photomicrograph of the glass beads(magnification 22X).

The beads are spherical, rounded in shape, and of nearly uniform material. They were described mineralogically as being almost pure glass.

Equipment -- The permeameters used in these tests were plastic cylinders two in. in diameter and 13.5 cm long with manometer taps spaced at 2-cm intervals on the sides (Fig. 5). The end caps were also of plastic with a rubber gasket inset in the face to produce a seal. The caps were attached to the cylinder by brass tension rods running the full length of the cylinder.

The inlet and outlet heads were controlled by the use of two constant head tanks as shown in Fig. 8. These tanks were plastic cylinders constructed so that constant head could be maintained by an overflow arrangement.

The bentonite suspension was introduced into the sand column through an arrangement whereby the suspension was siphoned from a 3-gal. bottle at a height of six in. from the bottom of the bottle to prevent removal of the grit and coarse bentonite particles. The bottle is shown in Fig. 6.

Methods -- The materials were placed in the cylinder by pouring them through a funnel into the cylinder. They were compacted by placing the cylinder in a machine which raised and dropped the cylinder through a definite distance a given number of times as shown in Fig. 7.

The initial hydraulic conductivity was determined by measuring the head loss through the sample with manometers and measuring the rate of flow with a graduated cylinder and stop watch. The hydraulic conductivity was then calculated using the following formula:

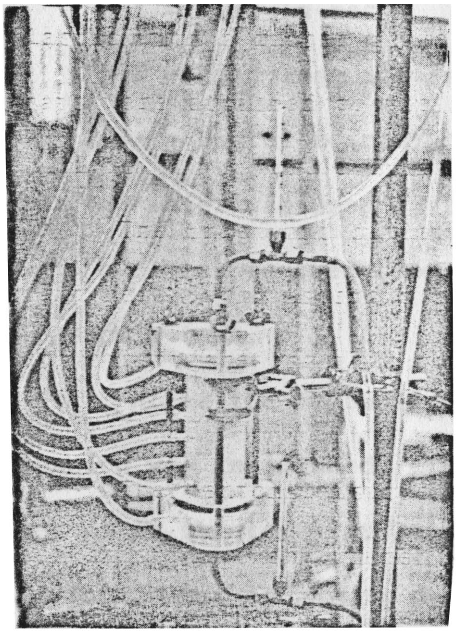


Fig. 5. Apparatus for permeability determination.

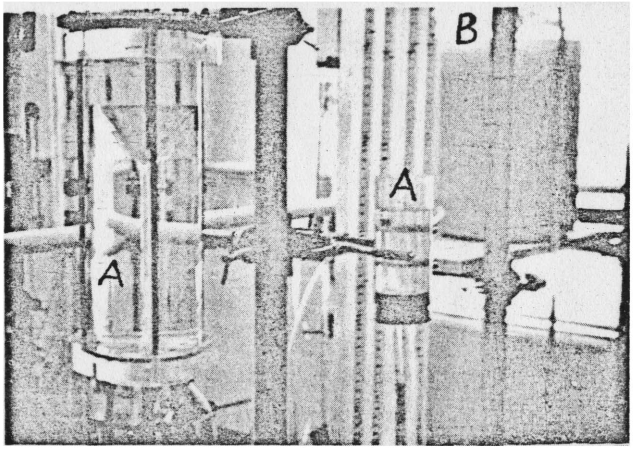


Fig. 6. Constant head control tanks (A) and bentonite suspension supply (B).

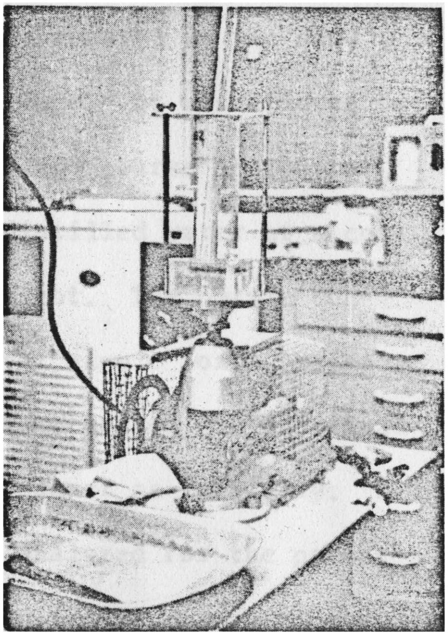


Fig. 7. Apparatus for uniform compaction of samples.

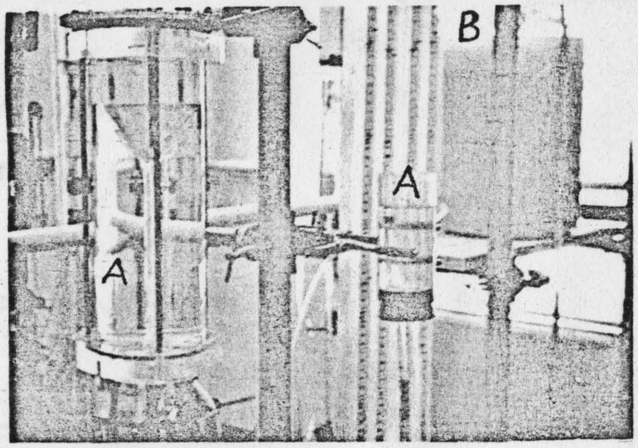


Fig. 6. Constant head control tanks (A) and bentonite suspension supply (B).

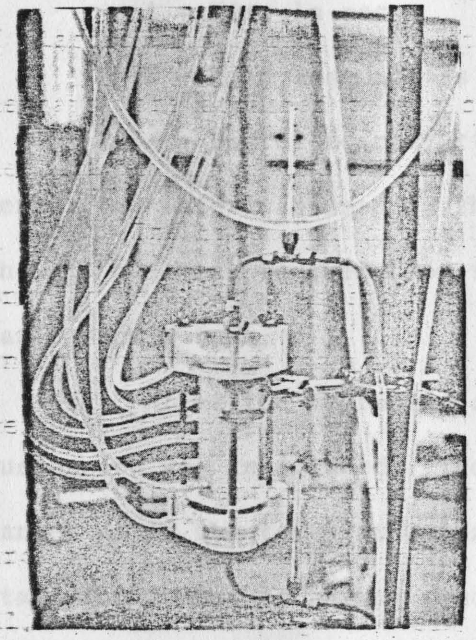


Fig. 5. Apparatus for permeability determination.

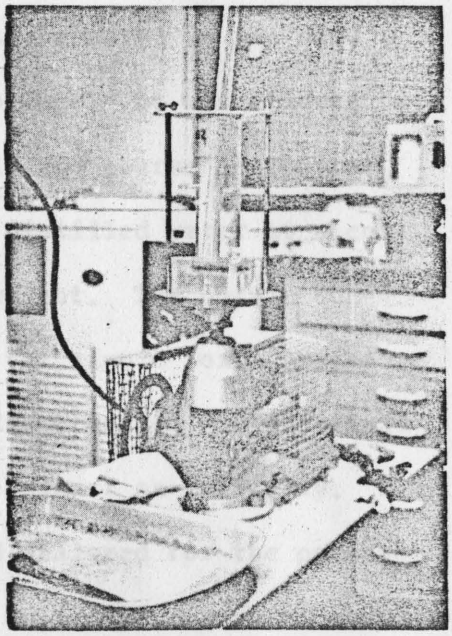


Fig. 7. Apparatus for uniform compaction of samples.

$$k = \frac{2834\,Q\,\ell}{A\,t\,H},$$

where k = Hydraulic conductivity in ft/day

Q = Volume of flow in cc collected in time, t

ℓ = Length of cylinder in cm

A = Cross-sectional area of column in sq cm

t = Time in sec

H = Head loss across ℓ in cm

2834 = Factor to convert k to ft/day

Denver tap water was used in the hydraulic conductivity determinations. The air had been removed from the water by a vacuum pump attached to a large supply tank.

After the hydraulic conductivity was determined, the bentonite suspension was introduced. The suspension was prepared in the same manner as in the tests at Colorado A and M College. It was allowed to stand for 24 hrs to insure removal of the silt and coarse bentonite particles. The suspension was prepared with distilled water at a concentration of approximately one per cent by weight. The bottle containing the suspension was kept connected to the sample for a period of 24 hrs. At the end of this time, it was disconnected and the final hydraulic conductivity determined in the same manner as initially. The sample was then removed from the cylinder and analyzed for the presence of bentonite by the benzidine method.

<u>Summary of data</u> -- The data are reported in Table 3.

The porosity was determined from the oven-dry weight of the sample, specific gravity of the material, and the volume of the cylinder.

The tests were conducted in duplicate on all the sands and individual sizes of glass beads. A test was also conducted on a column containing two layers of equal depth of 120-micron and 28-micron beads. Another test was conducted on a column of three layers of equal depth of 120-micron , 57-micron, and 28 micron beads.

Table 3.--DATA FOR PENETRATION STUDY CONDUCTED AT U. S. GEOLOGICAL SURVEY HYDROLOGIC LABORATORY. DENVER FEDERAL CENTER.

Material	Bentonite Concentration (%)		Porosity (%)	Hydraulic Conductivity (ft/day)		Depth of Bentonite Penetration	Presence of Bentonite in Sand Column
	Initial	Final		Initial	Final		
Ottawa sand	0.9	0.9	35.1	200	175	Passed through column	Trace[1]
Salt Lake sand	1.0	1.0	37.0	68.1	6.5	"	Small amount[2]
Loveland Lake sand	1.1	1.1	42.2	38.5	18.1	"	"
Beads							
28-micron	1.2	1.2	42.6	2.35		Surface cake; did not penetrate column	
36-micron	1.0	1.0	40.2	3.30		"	
57-micron	1.2	1.2	37.8	9.8		Some surface cake; penetration and retention appeared throughout column	
82-micron	1.1	1.1	38.2	17.0	11.6	Completely passed through column	Trace[1]
120-micron	1.2	1.2	37.8	29.5	24.2	Passed through column	Trace[1]
Stratified layer of 120-micron over 28-micron	1.2	1.2	39.0	5.5		Penetrated 120-micron; stopped at surface of 28-micron layer	
Triple stratified layer of 120-micron over 57-micron over 28-micron	1.2	1.2	37.8	5.4			

[1] Color of blue produced by the benzidene reaction barely detectable.
[2] Color of blue slightly deeper than above, therefore slightly greater amount of bentonite.

Note: Hydraulic gradient less than one.

Chapter V

DISCUSSION

In the limited conditions for the experiment, the data from both the Colorado A and M College and Geological Survey phases of the study support the following observations:

1. Bentonite in suspension did not penetrate uniform-sized particulate material with a median diameter below a certain size owing to the filtering action of such material.

2. Bentonite did not deposit from a stable suspension when passing through, or standing in the pores of a chemically inert sand, of sufficiently large particle size so that the suspension entered the media. 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 and 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.

Several factors appear to be involved in the penetration and retention of bentonite suspensions in porous media. These factors are: nature of the porous media, characteristics of the bentonite suspension, and the forces involved in penetration and retention.

Nature of Media

The characteristics of a porous medium which appear pertinent are chemical reactivity, size, shape, uniformity, and packing. The chemical reactivity of a porous medium is a function of its mineralogical composition. Quartz sand, for instance, is essentially chemically inert. Micaceous sands yield soluble cations through exchange reactions. A small amount of calcium ions is in solution in calcite sand systems.

The other characteristics of a porous medium: size, shape, uniformity, and packing, influence the effective size of the pores of the medium. Theoretically, if the medium consisted of uniform-sized spheres packed in the tightest possible arrangement, the diameter of the largest sphere that could pass into the medium would be 0.154 times the diameter of the spheres (2). This theoretical consideration reveals the importance of the size characteristics of a material designed to pass into the porous medium.

Characteristics of the Bentonite Suspension

The characteristics of a bentonite suspension which are important in this study are shape and hydration diameter. The shape of bentonite particles is platy instead of spherical. The sedimentation diameter, as calculated from settling time or fall velocity, is, in this study, less than 2 microns. This, however, may not be the hydration diameter. The hydration diameter is influenced by the sphere of hydration, i.e., the adsorbed water layer around the bentonite particle. Such a layer of tightly held water results in a hydration diameter many times that of the bentonite particle and is especially important with respect to filtration effects.

Forces Involved

The forces involved in penetration and retention of bentonite suspension in porous media are divided into two groups: impeding forces or forces tending to cause retention, and non-impeding forces or forces tending to cause penetration. The impeding forces may also be divided into two groups: the forces tending to cause adhesion (bonding between sand and bentonite), and the forces tending to cause flocculation(bonding between bentonite particles).

The forces tending to cause adhesion are primarily van der Waals forces of attraction. These forces depend upon the mass of the particles and the distance between them (5). A reduction in zeta potential, which allows the particles to come closer together, strengthens the bond produced by these forces. Such a reduction in zeta potential may be produced by a change in the chemical environment brought about by the replacement on the bentonite particles of monovalent exchangeable ions by multvalent ions (10). The chief cause of this type of retention is probably chance contact with a surface which allows these forces of attraction to produce a bond.

The other group of impeding forces consists of those tending to produce flocculation. A floc is a group of bentonite particles which is held together by a bond between particles and therefore acts as a single particle. Flocs can form when the zeta potential is reduced, which allows the particles to come close enough together for the attractive forces to become greater than the repulsive forces. This allows the attractive forces to pull the particles even closer together (3). The time and space required for the formation of flocs are also factors to be considered.

The second group of forces involved in the penetration and retention of bentonite in porous media are the non-impeding forces, or forces tending to aid flow through a porous medium. These forces depend upon the hydraulic gradient, viscosity of the suspension, gravity, and the electro-kinetic potential between particles of like charge, which results in stability of a colloid suspension.

Interpretation of Observations

Interpretation of the data in the light of the hypotheses previously advanced indicates that the first phenomenon to be considered is that of filtration. Filtration occurs when the suspended particles do not pass through the pores of the medium but are retained at its surface. The bentonite suspension did not pass through the 36-micron beads but passed into, and not through, the 57-micron beads under a hydraulic gradient less than one. Using the theoretical formula for spheres of tightest packing to calculate the theoretical diameter of a bentonite particle which would barely pass through the 57-micron beads, the diameter was found to be approximately 9 microns. However, the diameter calculated from the settling velocity was found to be less than 2-microns. The explanation for this discrepancy may be that the sphere of hydration and the shape affect the bentonite particles in such a way as to prevent them from passing through the media. The size, shape, uniformity, packing, and surface activity of the porous media are also factors which influence filtration. This explanation substantiates the statement made at the beginning of this chapter, viz., bentonite from a suspension did not penetrate material with a median diameter below a certain size.

If the bentonite suspension is not filtered but passes into the porous medium, the explanation may be based on the forces involved together with the characteristics of the medium and the bentonite suspension. There are three possible cases of the interaction of these forces: 1) the non-impeding forces are greater than the impeding forces, 2) the two groups of forces are nearly balanced or are approximately equal, and 3) the impeding forces are greater than the non-impeding forces.

Case 1, in which the forces producing penetration are greater than the forces producing retention, is exemplified in the data from tests conducted under large hydraulic gradient on inert sands. The bentonite suspension moved through the porous medium without deposition in the medium or reduction in hydraulic conductivity.

Case 2, in which the impeding and non-impeding forces are approximately equal, is exemplified by the data from tests conducted under small hydraulic gradient conditions. Under these conditions, there is the possibility of some retention, with a resultant slight reduction in hydraulic conductivity. The tests under low head on the Ottawa sand and the 82 and 120 micron beads are examples of this case. If the sand had a slight chemical reactivity, as in the case of the Loveland Lake and Salt Lake sands, more retention occurred and the reduction in hydraulic conductivity was greater.

Case 3, in which the impeding forces are greater than the non-impeding forces, is exemplified by the data from tests conducted using a period of standing and a chemical environment produced by the calcium-zeolite. The factors which are apparently involved in retention in this case are time, forces, and chemical environment, or a combination of them. In this study, no attempt was made to separate the factors of time and chemical environment.

Summary

As exemplified by the data and in the light of hypothetical considerations relating to penetration and retention of bentonite suspension in porous media, any of the possibilities of filtering, passing entirely through, retention, complete stoppage, or some combination thereof may occur depending on the existing relationship of the physical and chemical factors involved. If these factors can be controlled the particular results desired can be produced.

This study was limited to inert sands and glass beads, the slightly chemically reactive Loveland Lake and Salt Lake sands, and the chemically reactive zeolite. The study was also limited to two hydraulic heads, four ft and 10 cm respectively. These heads produced hydraulic gradients ranging from approximately one to four. In the study, no attempt was made to separate the effect of time from that of chemical environment, except that chemical reactivity of some kind seemed necessary for retention regardless of time. The effect of hydraulic gradient on the system was not fully investigated. Also unknown is whether a period of complete stoppage of flow is always necessary for retention.

For practical application of the method of sediment lining of canals, it appears that many of the factors involved need to be carefully controlled. Much more information will be necessary before methods can be developed to control these factors. The tests reported were conducted under controlled conditions on simple, artificial systems in an effort to eliminate some of the variables and to evaluate others. In the field, these conditions are usually complex. The factors associated with the bed material in the field would be very difficult or impractical to control or change. However, the indications are that the factors associated with the suspension can be controlled to produce effective penetration and sealing in many types of bed materials.

Future Work

Further study is needed for better understanding of the process of penetration and retention of bentonite suspension in porous media. There is a need for investigation of the factors of particle shape, particle size gradation, hydraulic gradient and pore velocity, chemistry of the transporting waters, and initial moisture condition of the medium. Other possible sedimenting materials, particularly Ca-bentonite should be investigated.

Chapter VI

SUMMARY

The problem of penetration and retention of bentonite suspensions in porous media is of fundamental importance in lining of canals by the sedimenting method.

Very few investigations have been made of the problem of penetration of colloidal suspensions into porous media. The investigations that have been made were made by people interested in rapid sand filters.

Two phases to the study are reported here: one phase conducted at Colorado A and M College and the other at the U. S. Geological Survey laboratory in Denver, Colorado.

Equipment was set up to test the depth of penetration and the retention of bentonite in several sands and glass beads. A commercial zeolite was used to produce a medium of high chemical reactivity. Stable bentonite suspension of 0.5 to 2.0 per cent concentration were used. Data taken included hydraulic conductivity and porosity. Presence of bentonite and depth of penetration were determined by analyzing the sample with benzidine.

The results were as follows:

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 action 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.

Interpretation of the data indicated that the first phenomenon to be considered is that of filtration. If the diameter of the opening in the media is considered, the bentonite particles appear to be sufficiently small to go through the finest material used in this study. Since the suspension did not go through this material, the explanation for this discrepancy may be that the sphere of hydration and the shape affect the bentonite particles in such a way as to prevent them from passing through the medium. The size, shape, uniformity packing, and surface activity of the porous medium are also factors which influence filtration.

If the bentonite suspension is not filtered but passes into the porous medium, the explanation may be based on the forces involved together with the characteristics of the medium and the bentonite suspension. Three possible cases of the interaction of these forces are postulated.

Case 1 occurs when the forces producing penetration (primarily the force produced by the hydraulic gradient) are greater than the forces producing retention (primarily van der Waals forces of attraction which tend to produce bonding between bentonite and sand particles). In this case, typified by a large hydraulic gradient on inert sands, the bentonite suspension moves through the porous media without deposition in the medium or reduction in hydraulic conductivity.

Case 2, in which the forces producing penetration and the forces producing retention are approximately equal (small hydraulic gradients), there is the possibility of some retention, with a reduction in hydraulic conductivity. If the sand has a slight chemical reactivity, more retention occurs and the reduction in hydraulic conductivity is greater. The slight chemical reactivity gives rise to some reduction in the zeta potential, which allows the particles to come together, producing a stronger bonding between the bentonite and sand particles.

Case 3 occurs when the forces producing retention are greater than the forces producing penetration. In the experiment, this case was exemplified by the tests conducted using a period of standing and a chemical environment produced by the calcium-zeolite. The factors which were apparently involved in retention in this case were time, forces, and chemical environment, or a combination of these.

In this study no attempt was made to separate the factors of time and chemical environment.

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