1964

Effect of ions in solution on the permeability of filter aids

Mustafa Salih Abdulrahman
Iowa State University

Recommended Citation

Abdulrahman, Mustafa Salih, "Effect of ions in solution on the permeability of filter aids " (1964). *Retrospective Theses and Dissertations*. 2977.
https://lib.dr.iastate.edu/rtd/2977

ABDULRAHMAN, Mustafa Salih, 1930–
EFFECT OF IONS IN SOLUTION ON THE
PERMEABILITY OF FILTER AIDS.

Iowa State University of Science and Technology
Ph.D., 1964
Engineering, sanitary and municipal

University Microfilms, Inc., Ann Arbor, Michigan

EFFECT OF IONS IN SOLUTION ON THE PERMEABILITY OF FILTER AIDS

by

Mustafa Salih Abdulrahman

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Sanitary Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1964

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

I. INTRODUCTION

A. Permeability

The ability of porous material such as diatomite or soil to transmit a liquid under the influence of a pressure differential or hydraulic gradient is termed the permeability of the material (7). The term "permeability" is often used as a synonym for "coefficient of permeability". The coefficient of permeability has dimensional units of velocity (length/time) and is usually stated as a flow rate per unit area produced by a hydraulic gradient of unity.

It is well established that the flow of water through a filter at rates common in diatomite filtration practice is in the laminar or streamline flow range and obeys Darcy's law (3). For laminar flow, Darcy's law states that the velocity of flow through a porous medium is proportional to some constant times the hydraulic gradient, or:

$$V = K_p S \tag{1}$$

Where:

V = velocity of approach of water to medium, ft/day

K_p = coefficient of permeability, ft^3/day/sq ft at unit hydraulic gradient, and

S = slope ratio of the hydraulic gradient.

Many workers have observed that the head loss through clean sand or diatomite is proportional to rate of flow and to the depth or thickness of filter medium (2). Since Q_T = AV and S = h/L, we may rewrite Equation (1) as follows:

$$Q_T = K_p AS = \frac{K_p Ah}{L} \qquad (2)$$

Where:

Q_T = filtration rate, ft^3/day
A = filter area, sq ft
h = head loss through filter, ft of water
L = thickness of filter cake or media, ft.

Permeability denotes the capacity of a porous media such as filter aid to conduct or discharge water under a hydraulic gradient. Coarse-grained filter aids are highly pervious and have correspondingly high permeability coefficients. With fine-grained filter aids, cake porosity may remain high, but their permeability will be reduced. This indication that permeability varied with particle size is in accord with our knowledge of laminar flow in small tubes or capillaries.

In this thesis, the permeability of a filter aid was measured by determining the rate of flow under constant head conditions through a given area of filter cake containing a fixed weight of filter aid in a constant head permeameter and also by means of a special filter recommended for use in determining a K_3 impermeability coefficient of filter aids.

The permeability of a diatomite filter aid may not be constant. It is affected, among other things, by the density of the filter aid in the filter cake. This is due to the fact that with compaction the diameter of the pore passages changes. When different methods of precoating a septum are employed (i.e. different filter aid slurry concentration, different flow rates during precoat application, etc.), different filter cake densities may be expected. Changes in filter cake permeability under such conditions have been studied by others (1).

When filter cake permeability studies are conducted under exactly similar conditions, reproducible permeability results are obtained (7). As a result of such studies, research personnel recommended use of a specific test and apparatus to be used to determine the permeability of filter aids (3).

Use of this test and apparatus on the same sample of filter aid at other locations with different waters did not produce results which were similar, but the results using any specific water were reproducible. Since the only variable involved appeared to be in the dissolved mineral matter in the test water, the question was raised as to whether variations in the chemicals in true solution in the test water could significantly affect filter cake permeability. If different cations and anions could and would cause a difference in thickness of the filter cake or in the structure of the fixed layer around a filter aid particle, the pore space available for flow might be changed together with a comparable change in the filter cake permeability.

If such effects exist and are significant, the waterworks industry will have to redirect their approach now being made to develop a standard test to determine the filtrability of water (12), and will need to modify the Iowa State University test procedure for determining filter aid permeability to provide for use of a standard water (3).

B. Purpose of This Thesis

The purpose of this study is to investigate the effect of different cations and anions composing the dissolved solids present in water on the permeability of a diatomite filter cake. The study was conducted in several phases:

1. A constant head permeameter was developed and used to give a qualitative effect of cations and anions on diatomite filter cake permeability.

2. Qualitative runs were made with specific cations and anions in several concentrations to determine the approximate magnitude of permeability change to be expected.

3. The apparatus and test procedures were modified to increase the degree of accuracy in the range in which the

experiments were conducted.

4. Tests were conducted with the constant head permeameter and a newly-developed K_3 filter to evaluate the quantitative effects of dissolved cations and anions in both natural and laboratory prepared water on the permeability of a diatomite filter aid.

Some important factors influencing the capacity of diatomite filters are the following: filtration pressure, filter area, weight of precoat, precoating rate, grade of filter aid, body feed (if any), characteristic of raw water, type of septum, salt concentration in the filtrate, time of filtration and temperature. The tests conducted in this study were designed so that only the effect of salt concentration would be involved in affecting filter cake permeability.

Some of the chemicals used in this study in true solutions were: sodium chloride, sodium hydroxide, magnesium sulfate, aluminum chloride and potassium sulfate.

C. Diatomite

Diatomite is a soft, earthy rock, varying in color from pure white through yellow buff, green, gray, to brown. The outstanding features of diatomite include its high porosity and high permeability, low apparent density, relative chemical inertness, and a high melting point, about 1500°C. It has been calculated that 1 in^3 of diatomite consists of the skeletons of 40-70 million diatoms (15). Approximately 10,000 distinct species of diatoms have been reported with sizes varying from 0.1 to 0.005 mm. Diatomite weighs approximately 7 lbs/ft^3 dry and loose, approximately 16 lbs/ft^3 when packed by wetting and up to 20 lbs/ft^3 in a filter cake (15). It has a specific gravity of approximately 2.35 and a filter cake porosity of 88 to 90 per cent (15).

Diatomaceous earth, commonly known as diatomite or diatomaceous silica, has been used in the filtration of sugars, paints, oils, and other substances. It is only during recent years that it has been used in the filtration of water. The Water Supply Branch of the Engineering Research and Development Laboratories of the U. S. Army utilized a pressure-type filter employing diatomaceous earth filter aid to successfully remove Entamoeba histolytica cysts and Shistosoma cercarie from water for field troops in 1944. Furthermore, the removals of these organisms was accomplished at rates of flow much higher than those used on gravity flow rapid sand filters, or on pressure type sand filters. As a result, the use of diatomite for water filtration expanded rapidly following the war, first for use in filtering swimming pool water and then for filtering potable water for municipal and industrial use.

D. Chemical Properties of Diatomite

Diatomite is practically pure silica (SiO_2) and is usually described as being chemically inert (18). However, the chemical analysis of a typical sample shown in Table 1 indicates that diatomite contains traces of chemically active compounds expressed as calcium, magnesium, and sodium oxides.

Table 1. Typical chemical analysis of diatomite filter aid*

Composition	Typical chemical analysis (Moisture free basis) Per Cent by weight
Loss on ignition	3.0
SiO_2	89.4
Al_2O_3	4.1
Fe_2O_3	1.5
TiO_2	0.1
CaO	0.2
MgO	0.7
Na_2O (K_2O)	0.8
Total	99.8

*Table reproduced from (13).

E. Surface Charge

Particles of diatomite suspended in water behave as if they are electrically charged negative. However, the particle charge can be deliberately changed to positive during manufacture or just before use by coating the filter aid with electropositive coatings (17).

When water is filtered through a porous medium, an electrical potential difference called a streaming potential is developed between the upstream and downstream sides of the filter. The streaming potential is positive if the upstream potential is positive with respect to the downstream potential. The streaming potential can be measured by placing an electrode in the inlet stream and another in the outlet stream and measuring the potential difference across the electrodes. The streaming potential becomes vanishingly small as the concentration of ions in the water increases. This is due to the decreasing resistivity of the water as the ion concentration increases. The ions provide a path for electrons to flow and this flow of electrons dissipates the streaming potential.

The zeta potential of diatomite can be determined from streaming potential measurements. However, Oulman has shown that the zeta potential of a solid in contact with a liquid may not be the same when determined by streaming potential measurements as it is when determined by electroosmosis or electrophoresis (17).

It appears that the electrical field that the filter aid is placed in for electrophoretic measurements is strong enough to separate most of the electropositive surface coating from coated filter aids. The resulting zeta potential determined by electrophoresis would then be negative rather than positive. On the other hand, the zeta potential determined by streaming potential measurements are positive for a positively coated filter aid. It appears that the hydrodynamic forces present under the conditions for a streaming potential test are not strong enough to separate the coating from the particle.

The zeta potential of a filter aid used in a filter cake can be determined from streaming potential measurements using distilled or deionized water. Use of distilled water will not provide the same magnitude of zeta potential that would be obtained with natural waters. In the latter case, the zeta potential of filter aids will be higher in magnitude than it is in distilled or deionized water (17).

Electrophoresis cannot be used as a test to determine effective surface charge of a filter aid because of the apparent ability of an electrical field to separate the positive surface coating from the filter aid (17).

II. LITERATURE REVIEW

The process of filtration has been known and used many years. Until the 19th century, however, no appreciable effort was made to understand the process of filtration. Since the middle of the 19th century tremendous advances have been made in the art of filtration, however, there are still many factors affecting the process which have not been studied or are incompletely understood.

Many studies have been made concerning the permeability of porous media. It is only recently that Baumann, Cleasby, and LaFrenz published their theory of diatomite filtration (3). Although they did not report the effect of electrolytes in solution on the permeability of the filter aid, they reported that the permeability of the filter aids using distilled water and tap water were different under identical conditions. They hinted that all K_3 determination should be made using distilled water (3).

Little attention has been devoted to studies of the effect of electrolytes in solution on the permeability of porous media. No report has appeared in the literature describing the effect of ions in solution on the permeability of diatomite as a filter aid. Those studies concerning effects of ions in solution which have been reported in the literature, are concerned with materials other than diatomite

(8, 14), or with their effects on diatomite characteristics other than its permeability (17).

Of interest here is a study of the effect of certain ion combinations commonly found in potable water on the rate of filtration through coffee and its effect on the taste of the brewed coffee (8). The minerals in water for example: iron, calcium, magnesium, sodium, potassium, bicarbonate, sulfate and chloride, were found to influence the filtration time of water through coffee.

After establishing a standard coffee brewing time (brewing time is the time required to collect a certain volume of filtrate) with deionized water, it was demonstrated that different inorganic compounds will affect the total brewing time differently. With some inorganic compounds, the brewing time was nearly doubled. With others, the brewing time decreased slightly below the standard.

This study indicated that carbonates and bicarbonates as a group appear to have the greatest retarding effect, while all other types normally present in municipal water supplies appear to have little effect. Typical brewing time obtained are shown in Table 2. Brewing time was determined by measuring the time required to collect a certain quantity of filtrate through a fixed weight and thickness of a standard coffee.

Additional experiments showed that the brewing time was

Table 2. Brewing times of 400 ppm of various inorganic compounds in deionized water (8)

Inorganic compounds	Total brewing time, seconds
Li_2CO_3	669
Na_2CO_3	620
$NaHCO_3$	595
$KHCO_3$	539
K_2CO_3	517
NaOH	485
Na_2SiO_3	470
Na_2S	445
Na_3PO_4	388
Na_2SO_4	351
Deionized water	350 (Standard Brewing Time)
NaCl	333
$MgSO_4$	330
$CaCl_2$	316
$CaSO_4$	308
KCl	306
HCl	305

greatly changed by an increase in the concentration of different chemicals as shown in Table 3.

As a summary to this report, we could conclude that most of the ions present in the water supplies changed the permeability of the coffee grounds slightly. However, the presence of carbonate or bicarbonate ions increased the

Table 3. Effect on total brewing time of varying concentration of compounds in solution (8)

Inorganic compound	Concentrations, ppm	Total brewing time, seconds
$NaHCO_3$	0	350 (Standard Brewing Time)
	100	336
	200	374
	300	491
	400	595
$CaCl_2$	0	350 (Standard Brewing Time)
	400	316
	1000	300
Na_3PO_4	0	350 (Standard Brewing Time)
	400	388
	1000	304

brewing time significantly and in direct relation to their concentration. This effect was accentuated by sodium ions, if water containing temporary hardness and softened in a zeolite conditioner was used.

A number of workers have studied different factors affecting the rate of filtration of liquids through porous media. Of interest here was the study of the surface properties of the solid phase of porous media, and the degree of their effect on the rate of filtration (9). In particular, the effect of electrical surface forces, characterized by the value of the electrokinetic potential (ζ-potential), has been studied.

It was found that there are differences between the rates of filtration of dilute solutions of electrolytes and of water through membranes and powder systems (9). In general, the rate of filtration of electrolyte solutions was found to increase with increasing concentration of the solutions.

This variation in the rate of filtration of aqueous solutions through powder systems was thought to be due to a change in the effective cross-section of the capillaries corresponding to the different electrolyte concentrations. Any change in the effective cross-section of the capillaries means a change in thickness of the double layer (related to the thickness of the hydrated layer) around the particle due to the change in the concentration of the electrolyte solution passing through.

Other workers did carry out qualitative verification of the relationships between the rate of filtration of aqueous solutions of various electrolytes through sand, chalk, asbestos and diatomite (9). Their results indicated an increase in the rate of filtration with increase of concentration of HCl solutions from 1×10^{-5} to 1×10^{-2} N.

III. THEORY OF DIATOMITE FILTRATION

A. General Theory

There is an increasing use of diatomite filtration to produce potable water. An equation has been developed relating the filtering characteristics of the suspended solids, body feed, and filtration rate with the filter cake head loss which could be expected in a diatomite filter after filtering any given amount of water (3). Such a relationship can be used to aid in determining the optimum filter operating characteristics which would produce potable water at the lowest cost per 1000 gallons (4).

The quantitative determination of the permeability of diatomite filter aids in this study will be confined to the evaluation of its K_3 coefficient in the recently developed diatomite filtration equation (3).

$$H = K_3 Q W_1 + K_4 C_D Q^2 t \times \frac{8.33}{10^6} \qquad (3)$$

Where:

H = total head loss through the filter cake (ft)

C_D = concentration of body feed (ppm)

K_3 = permeability coefficient for the clean precoat ($ft^5 \cdot min/lb \cdot gal$)

K_4 = permeability coefficient for the body feed layer ($ft^5 \cdot min/lb \cdot gal$)

Q = rate of flow (gpm/ft^2)

t = time of filtration (min)

W_1 = weight of precoat (lb/ft^2)

The theoretical development of Equation 7 is available in the literature (3, 15).

B. Determination of K_3

In Equation 3, the total head loss, H, represents the head loss through a precoat layer of pure diatomite, K_3QW_1, plus the head loss through the body feed plus suspended solids layer, $K_4C_DQ^2t(8.33 \times 10^{-6})$.

In this study, we are concerned only with flow through the precoat and Equation 3 reduces to:

$$H = K_3QW_1 \tag{4}$$

If a laboratory test is designed to provide a measure of head loss through a cake of known weight with a given flow rate, the value of K_3 is easily determined. A plot of H versus QW_1 will provide a straight line whose slope will be equal to the value of the impermeability coefficient K_3.

The value of K_3 can be determined by making a run filtering clean water containing no suspended solids and no body feed through a thick layer of precoat. There are several possible approaches:

1. Vary the rate of filtration and observe the head loss using a constant weight of precoat.

2. Vary the weight of precoat in several runs and observe the head loss using a constant rate of filtration.

3. Hold the head loss constant and observe Q using various weights of precoat.

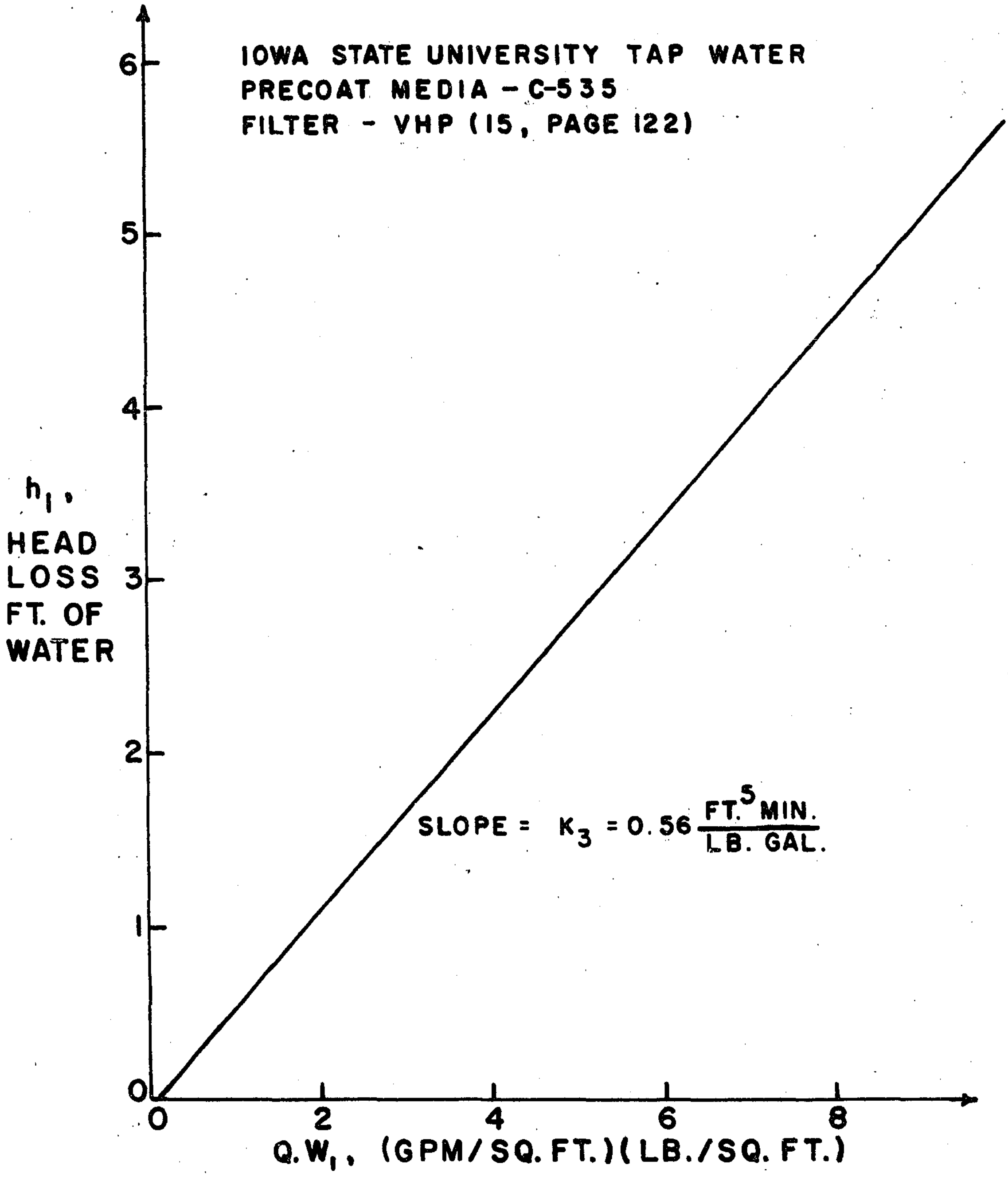
4. Vary the head loss and observe Q using various weights of precoat.

The first two approaches can be completed using a standard diatomite filter. The latter two approaches can be used in the laboratory in conjunction with a small constant head permeameter. In all approaches, the data would be plotted to show head loss through the precoat diatomite in feet of water, h_1, against QW_1 on arithmetic paper (Fig. 1).

At a constant temperature and under standard conditions for cake formation, K_3 is constant for a given filter aid and is representative of the permeability of the filter aid. Actually, K_3 is inversely proportional to the coefficient of permeability. K_3 is dependent on the viscosity and density of the water and, therefore, is dependent on the water temperature. Accordingly, all values of K_3 should be expressed at a standard temperature, $20^{\circ}C$ for example, for purpose of comparison.

A K_3 value expressed at temperature "T"$^{\circ}C$ $(K_3)_T$ can be

Fig. 1. Plot of head loss versus QW_1, as used to determine K_3 (15, page 122)[1]


IOWA STATE UNIVERSITY TAP WATER
PRECOAT MEDIA - C-535
FILTER - VHP (15, PAGE 122)
SLOPE = $K_3 = 0.56 \frac{FT.^5 MIN.}{LB. GAL.}$
h_1, HEAD LOSS FT. OF WATER
0
1
2
3
4
5
6
0
2
4
6
8
$Q.W_1$, (GPM/SQ. FT.)(LB./SQ. FT.)

changed to a corresponding value expressed at 20°C (K_3). This is done by simply dividing the $(K_3)_T$ value by the ratio of the viscosity of water at temperature 20°C to the viscosity of water at temperature "T"°C as follows:

$$K_3 = \frac{(K_3)_T}{\dfrac{\eta_{20^\circ C}}{\eta_{T^\circ C}}} \qquad (5)$$

Where:

K_3 = value of the impermeability coefficient at a temperature 20°C

$(K_3)_T$ = value of the impermeability coefficient at a temperature "T"°C

$\eta_{20^\circ C}$ = viscosity of water at 20°C

$\eta_{T^\circ C}$ = viscosity of water at temperature "T"°C

In this study, the change in water density with temperature was neglected since such changes proved to be insignificant in the range of temperature variations encountered.

C. Application of K_3

Equation 3 showed the total head loss H through a diatomite filter. In practice, the engineer will seek to establish the filtration rate to provide the lowest overall cost of filtration. The type of diatomite, the source and mineral composition of the water and, accordingly, the value of K_3 will be determined by the filter-aid grade required to produce the requisite quality of filtered water. The precoat weight W_1 will be fixed by the amount required to prevent fouling of the filter system, and W_1 will be in the range of 0.1 to 0.2 lb/sq ft.

Considerable variation in the K_3 value for the same grade of filter aid can be expected (7). Such variation is to the changes in the processing and source of the filter aid and to variations in the water used to evaluate K_3. Therefore, standard values of K_3 for all grades of filter aid published by manufacturers are not yet available.

IV. LABORATORY APPARATUS AND PROCEDURES

A. Introduction

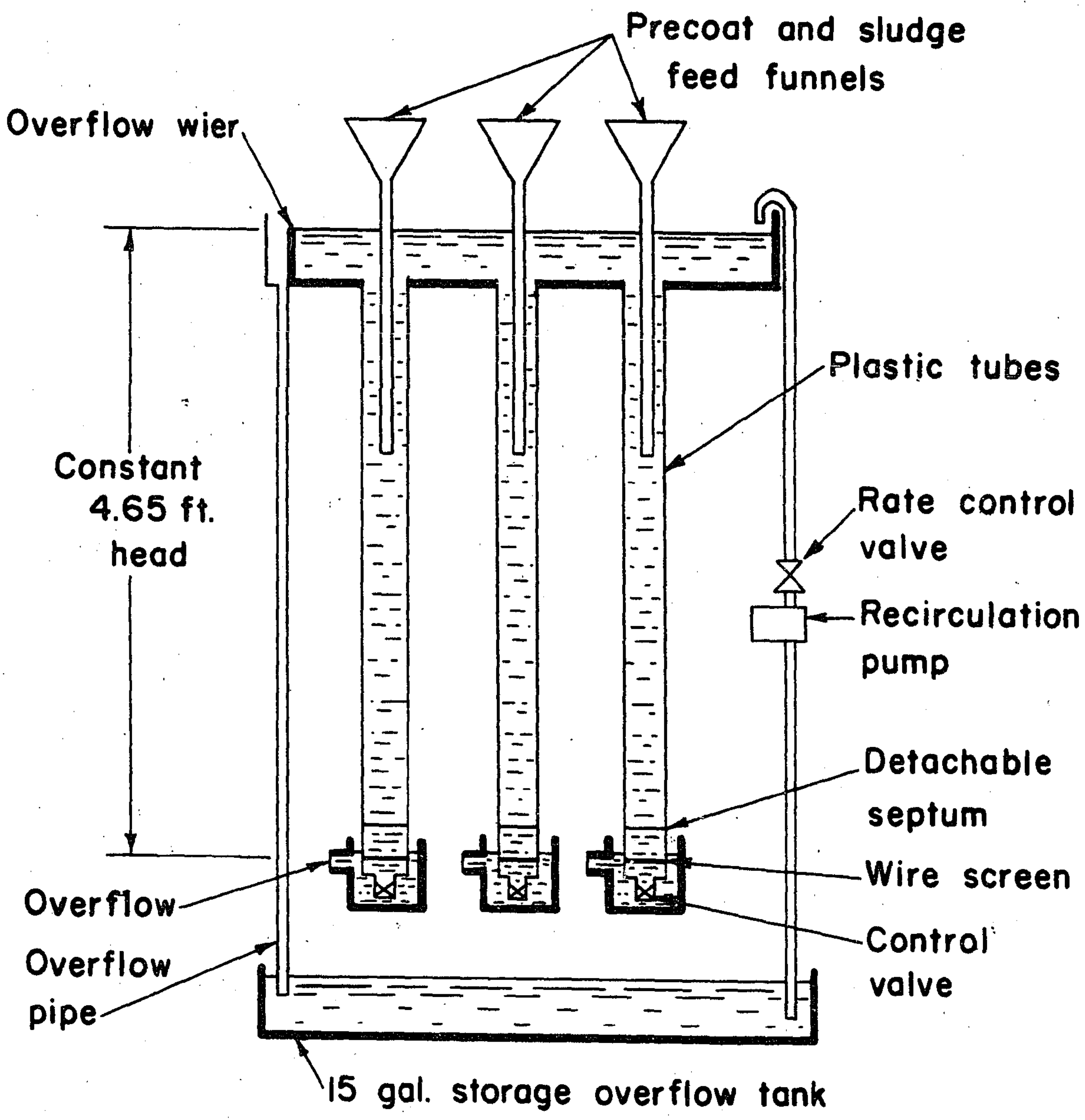
To evaluate the effect of dissolved ions on the permeability of diatomite filter aid, two separate laboratory apparatuses were designed and constructed. Early in the investigation, all efforts were directed to making a standard permeability determination using a typical constant head permeameter (CHP). During the investigation Baumann, Cleasby and LaFrenz published their theory of diatomite filtration (3) and proposed the use of the K_3 impermeability coefficient to represent the hydraulic characteristics of filter aid. In view of the fact that this method of expressing filter aid permeability appeared to offer significant advantages in saving laboratory time and providing increased accuracy of test results, a K_3 filter apparatus was designed, built and used to determine the effect of dissolved ions on K_3. Thus, the first half of the runs reported in this thesis were made with the CHP apparatus and the later runs were made with a K_3 filter.

B. Constant Head Permeameter

1. Construction

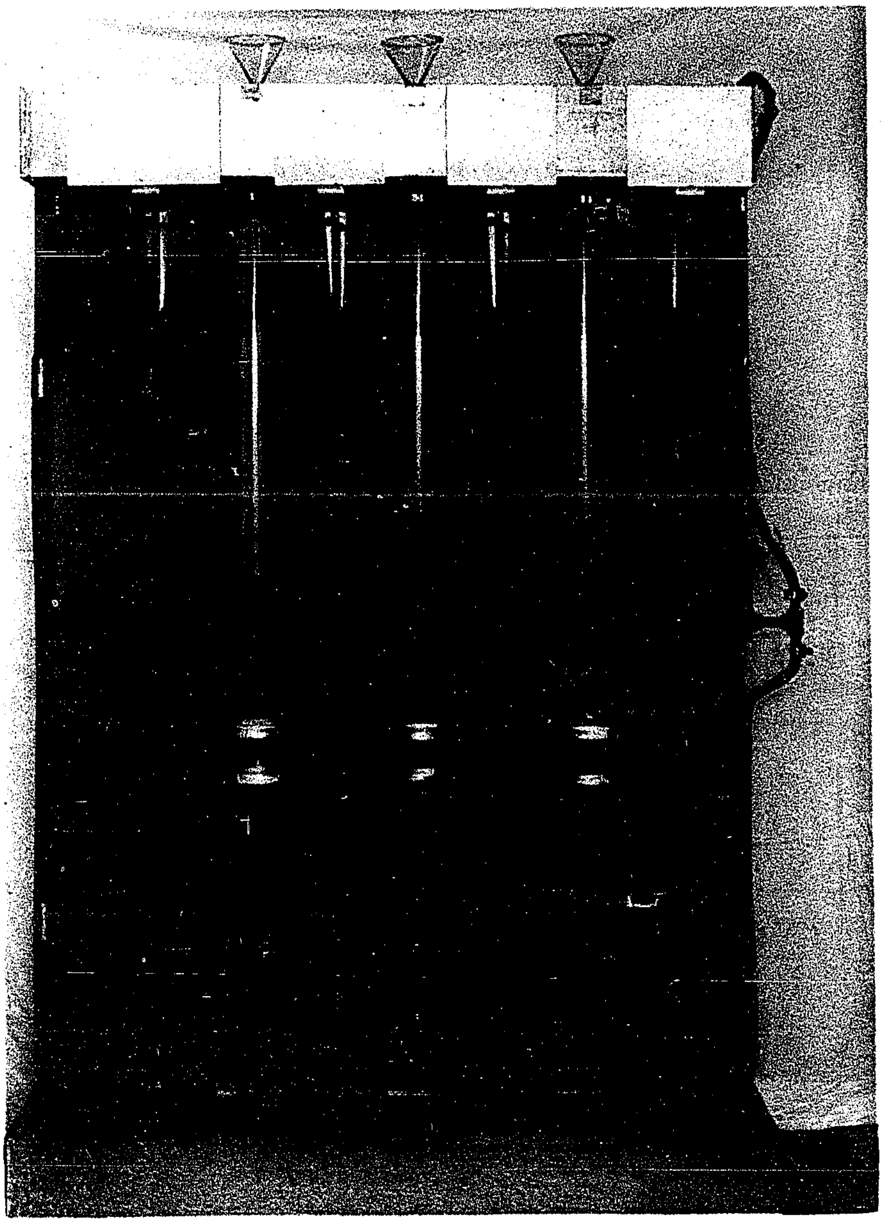
The constant head permeameter, (CHP), shown schematically in Fig. 2 and in the photograph in Fig. 3 was constructed and

Fig. 2. Schematic drawing of the constant head permeameter, CHP



Schematic of constant head permeameter

Fig. 3. Overall view of the constant head permeameter, CHP



used in this study. The permeameter consisted of a water storage tank, a constant head tank, a pump and water distribution system for supplying water from the storage tank to the constant head tank, and three separate filter tubes, each of which was equipped with its own filter septum, flow control and head control device. The constant head permeameter was employed in determining the effects of ions in solution on the permeability of typical commercial diatomite filter aid.

With the permeameter it was possible to precoat each of the three filters with a given weight and surface area of filter aid and to filter water under a constant head of 4.65 feet of water. It was possible to determine the rate of flow through these filter cakes of solutions of different salts at different concentrations after different periods of filtration. The data collected could be plotted to show the change in filter cake permeability with time of filtration and with change in type and concentration of the salts.

The water storage tank consisted of a rectangular tank, 12 in. wide x 6 in. deep x 4 ft long made of galvanized metal. When full the storage tank held approximately 15 gallons of water which was more than sufficient to fill the constant head tank, the recirculation system, and the filter tubes.

The water storage tank was connected to the constant head tank by means of a flow distribution system, including an electrically-driven pump. The distribution system consisted of 1/2 in. rubber tubing which was used to connect the suction of the pump to the water storage tank and the discharge of the pump to the constant head tank (Fig. 2). The pump [An Eastern Industries model B-1 Centrifugal pump] was driven by 1/20 Hp, 110 volt, single phase electric motor. The pump has a capacity of delivering 7 gpm against no head. A 1/2 in. needle valve was used on the discharge side of the pump initially to control the rate of flow to the constant head tank, but was subsequently removed.

The constant head tank consisted of a second galvanized metal tank 6 in. wide x 6 in. deep x 4 ft long. One end of constant head tank was fitted with a rectangular sharp crested weir, so as to maintain a constant head of 5 in. in the constant head tank. The discharge over the weir was collected and returned to the water storage tank through a 1/2 in. rubber hose.

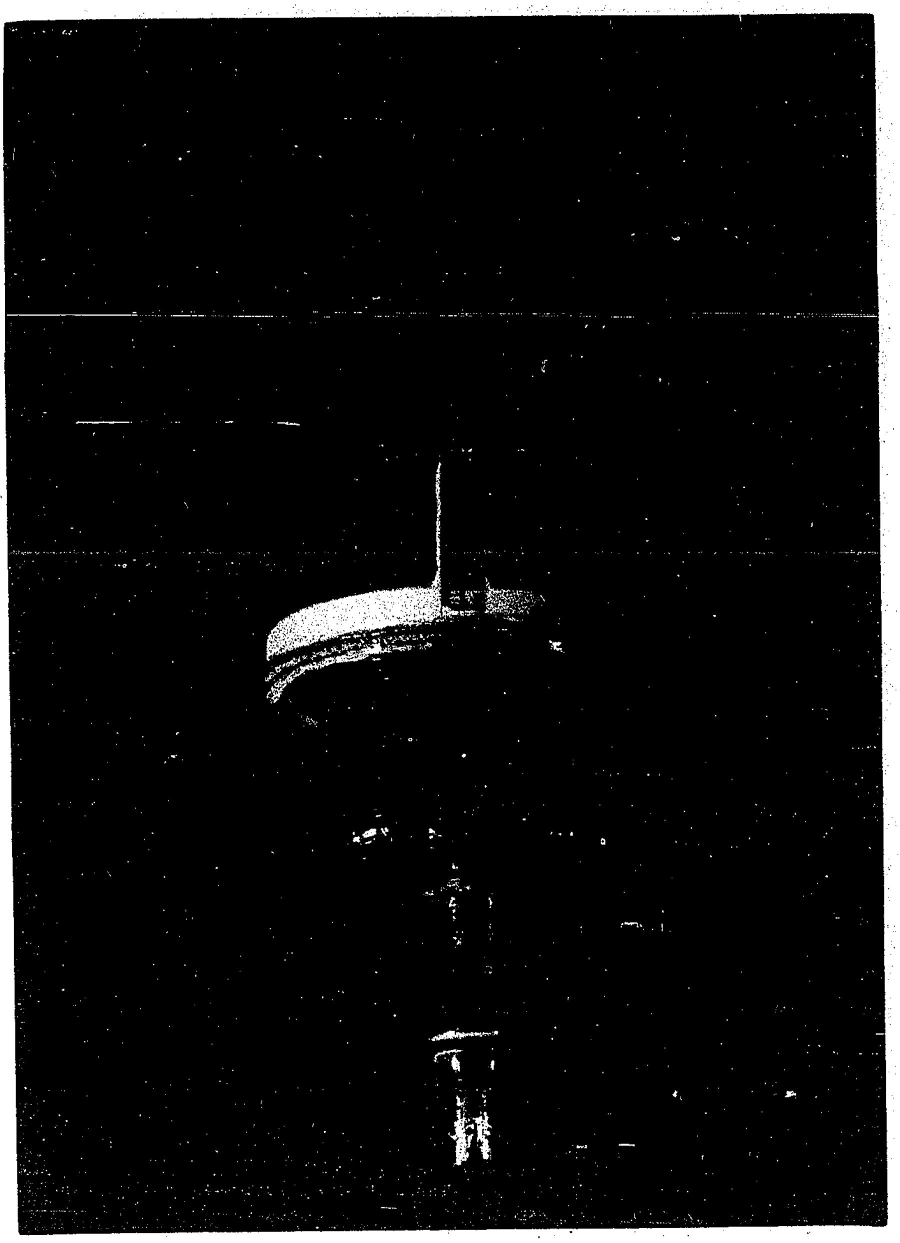
The bottom of the constant head tank was fitted with three 3 in. openings to which the three filter tubes were attached. The openings had a 2 in. length of cylindrical galvanized metal welded to the bottom of the constant head tank enclosing each filter tube opening. The filter tube fitted snugly into the cylindrical metal pipe. A rubber gasket was wrapped around the connection and clamped, to provide a water seal between the constant head tank and the filter tube.

The three filter tubes were each 3 in. in inside diameter by approximately 4 feet long. The filter tubes were made of clear plastic with a wall thickness of 3/16 in. The bottom 6 in. of each filter tube (Fig. 4) was cut off and used as a detachable filter housing. This detachable length of filter tube was sealed in place during a filter run by a wide rubber band, a piece of copper plate, and the use of two clamps on each tube to hold the septum tightly in place.

A filter septum was used to support the precoat filter aid whose permeability was to be determined. The septum itself (Fig. 4) consisted of stainless steel wire mesh cloth (24 x 110) cut with an effective plate diameter of 2.7 in. The wire mesh is a product of the Belleville Wire Cloth Co., Inc., 135 Little St., Belleville 9, New Jersey. The wire mesh filter septums were sealed in a horizontal position about 2 in. above the bottom of the filter tube. The bottom of the filter tube was sealed with a plastic plate which had a 1/2 in. outlet at the center (Fig. 4).

The bottom of the filter tube was located immediately above and discharged into a 1000 ml. liter beaker, which was fitted with a 3/8 in. diameter side overflow located about 4 in. above the bottom of the beaker. A constant head of 4.65 feet of water was maintained at all times between the constant head in the constant head tank and the level of water in the

Fig. 4. Filter housing used in the CHP filter showing precoat and wire screen septum



beaker. The constant head was adjusted merely by raising or lowering the beaker such that the side overflow in the beaker was kept at about the same level as the septum wire mesh. The rate of water flow through each filter tube was determined by collecting water as it discharged from the side outlet of the beaker.

2. <u>Operating test procedure</u>

The same test procedure was used in all tests with the CHP apparatus. In order to assure reproducibility of the test results, the entire apparatus had to be maintained always in a clean condition. Nevertheless, at the start of each run, all of the tanks, tubes, and water lines were cleaned and flushed with distilled water. Then, the water storage tank was filled with distilled water of the required quality. The valves permitting discharge from the filter tubes were closed and the pump was started to fill the constant head tank and filter tubes with water from the water storage tank. Adjustments were made until it was certain that all air was excluded from the distribution lines and from underneath the septum.

The next step in the test procedure involved precoating the septums. The weight of diatomite to be used in the precoat was mixed in distilled water to form a slurry and was introduced into a filter tube through a funnel. The precoat funnel was inserted in each filter tube as shown in Fig. 2 so that the filter aid slurry could be added into each filter tube immediately above the filter septum without affecting either the recirculating water or the other filter tubes. As soon as the precoat slurry was added above the septum, the discharge valve at the base of that filter tube was opened slightly to allow a slow rate of flow through the septum to form a uniform precoat. In this way only a small amount of precoat filter aid passed through the septum during precoating. This filter aid was collected in a beaker as it discharged from the filter tube and returned back to the filter tube through the funnel. When the precoat had formed, the valve at the bottom of filter tube was opened completely and the flow through the filter aid was allowed to reach equilibrium under a constant head of 4.65 feet of water.

It was essential that no bubble of air be present under the precoated septum during subsequent observations. At times, the presence of small bubbles of air will reduce the flow rate as much as 40 per cent. If a bubble of air was present after precoating, it was removed by introducing a rubber tube through the outlet until it contacted the air bubble. The use of a small vacuum on the tube would serve to remove the air bubble completely.

As soon as the filter flow rate through the precoat had reached equilibrium, the flow rate was determined by measuring the time required to collect a known volume of the water discharging from the side outlet on the beaker. Flow rate measurements were made at intervals of 10 minutes initially to determine how much the flow rate reduced with time.

If a test were to be conducted using water containing specific cations and anions, solutions of these chemicals in a concentrated form were prepared prior to the test in 500 ml. volumetric flasks. The concentration in the flasks was determined by the concentration which would be used when the flask contents were mixed with the 15 gallons of distilled water in the CHP system. Chemical solutions were prepared in distilled water at room temperature. However, some of the solutions occassionally had to be heated to increase their solubility in the 500 ml flask (Table 4).

All test runs with the CHP apparatus were made with the water at room temperature, and a correction was applied to all flow or K_3 results to convert them to their respective values at a standard temperature of 20°C as described on page 20.

When a test was to be made to determine the permeability of a filter cake when filtering water containing dissolved chemicals, a flask containing the desired amount of dissolved chemical was poured into the water storage tank, the water was then recirculated until it was mixed uniformly with the 15 gallons of water already in the system. Once the chemical was uniformly distributed, the flow rate again was determined.

C. K_3 Filter

1. Introduction

Following the publication of Equation 3, a special filter was designed to permit collection of the data required for the direct determination of the impermeability coefficient K_3 for a filter aid as shown in Fig. 1. This filter is referred to as a "K_3 filter" and is shown schematically in Fig. 5 and in the photograph in Fig. 6.

The filter apparatus consists of two water storage tanks, a precoat tank, a small filter housing containing a filter septum, a flow measuring device, a head loss gage, a small recycle tank, and a pump to supply pressure. During a run with this apparatus, a fixed weight of diatomite, W_1, is precoated on the filter septum. Then the rate of flow through the precoat, Q_1, is varied and the head loss, h_1, is measured at each flow rate. These data collected with the water at a constant temperature are used to calculate the K_3 of the filter aid.

In the K_3 filter, there are three basic operations as there are for all diatomite filter plants:

(1) precoating, placing the diatomite onto the septum to form a precoat,

(2) filtering, passing of the water to be filtered through the precoat (normally, to remove suspended solids from the water), and

Fig. 5. Flow diagram of the K_3 filter

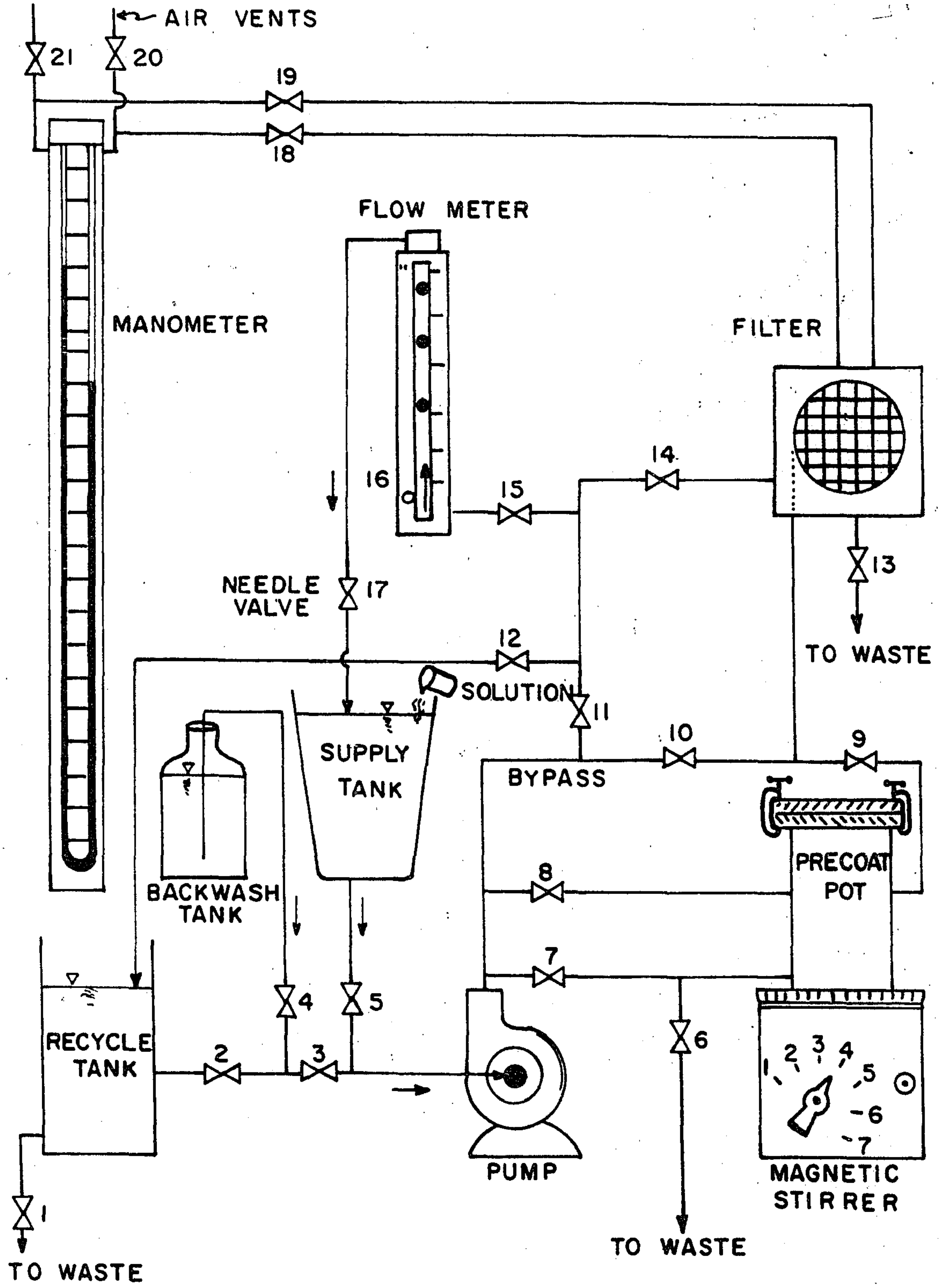
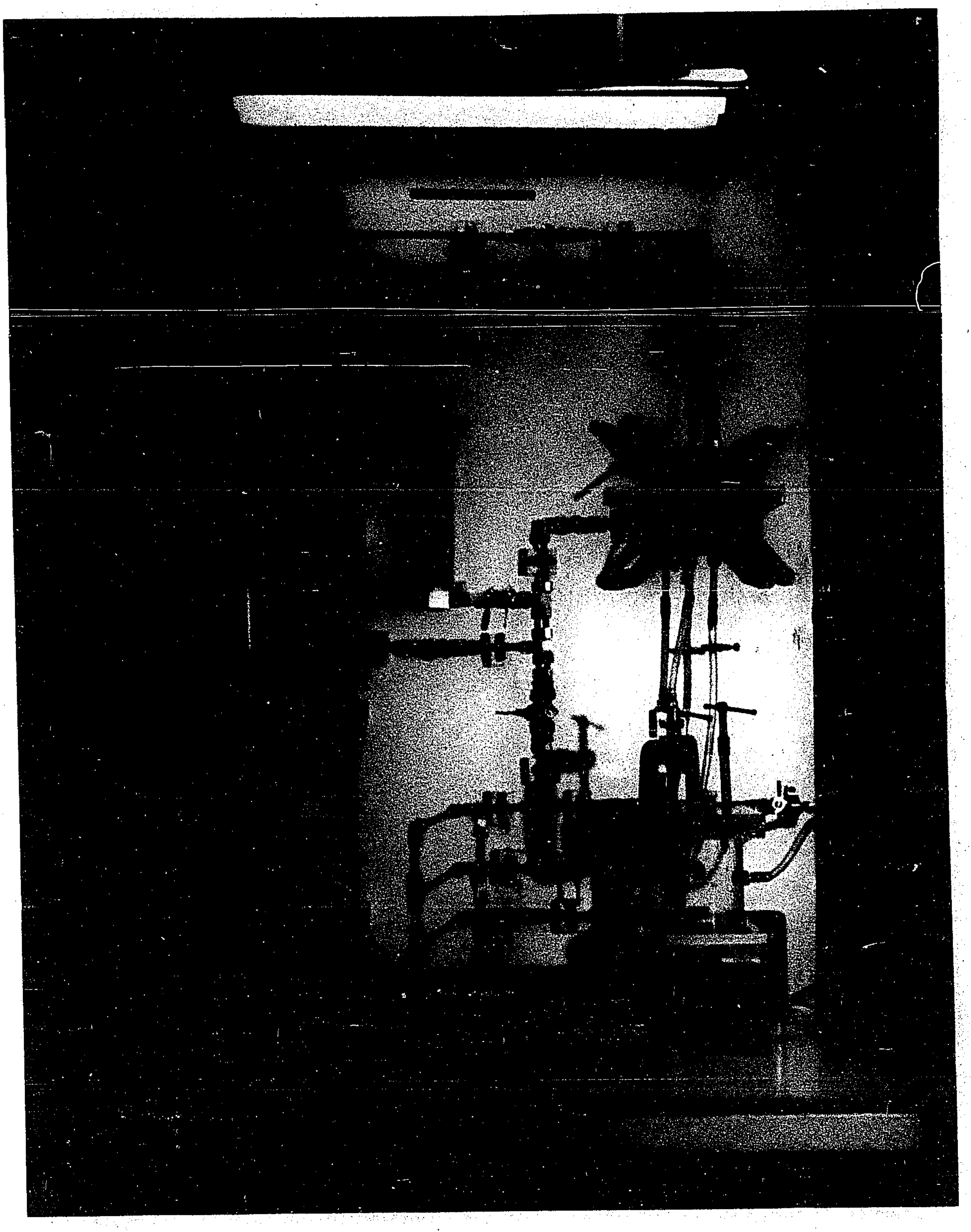

AIR VENTS
21
20
19
18
FLOW METER
MANOMETER
FILTER
16
15
14
13
TO WASTE
NEEDLE VALVE
17
12
SOLUTION
11
10
9
SUPPLY TANK
BYPASS
BACKWASH TANK
PRECOAT POT
8
7
4
5
6
RECYCLE TANK
2
3
PUMP
1
2
3
4
5
6
7
MAGNETIC STIRRER
1
TO WASTE
TO WASTE

Fig. 6. Overall view of the K_3 filter



(3) backwashing, the removing of the used filter cake from the septum and washing it and all other impurities in the system to waste.

2. Description of apparatus

To accomplish these operations, the K_3 filter is constructed in five basic sections:

a. A water supply section
b. A precoating section
c. A filtering section
d. A pressure differential section, and
e. A backwashing section

a. Water supply section The water supply section of the apparatus includes provision for storage of two types of water, precoat and/or backwash water and the test water to be filtered. The precoat and backwash water is stored in one or more five gallon Pyrex carboys. Water is drawn from these carboys through a 1/4 in. Tygon tubing connected to the water recirculation system at valve 4 (Fig. 5). The water to be filtered in the test is stored in a covered, commercial plastic garbage can with a capacity of about eight gallons. In order to maintain the water in this supply tank at a constant temperature, a heating-cooling system was installed. A centigrade thermometer was used to determine the water temperature and a thermostatically controlled copper coil heater was used to provide heat when the water temperature dropped below 20°C. To provide cooling of the water, a 20 ft. length of 3/8 in. round copper tubing was wrapped in a coil about 1 ft. diameter and spaced uniformly from top to the bottom of supply tank. Cold tap water was run through this copper coil continuously to provide cooling.

A small electric stirrer was used in the supply tank to provide a uniform mixture of the water in the tank. The heating-cooling system was adjusted until it was possible to maintain the water temperature at 20°C plus or minus 0.5°C. The supply tank was connected to the water distribution system at valve 5 by means of 1/2 in. tygon tubing. The supply tank was also provided with a drain.

b. Precoating section The precoating section, including the main flow distribution system, consisted of a small recycle tank, a pump to supply pressure, a precoat pot, and a small filter. The recycle tank consists of a 6 in. length of plastic tube which is 3 in. in inside diameter. The recycle tank is provided with a suction connection to a pump, and a drain valve 1 in. above the bottom of the recycle tank. The pump connection is located 1 1/2 in. above the bottom of the recycle tank.

The pump which supplies pressure for precoating, filtration and backwashing is an Eastern Industries Model A-1 stainless steel, centrifugal pump. The pump is driven by a 1/100 HP, 110 V, electric motor and will deliver 4.5 gallons per minute against no head and a shut-off pressure of 11 psi. The pump as installed in the system permitted a maximum rate of flow through the filter system of 4.08 gpm/ft^2.

All distribution lines not otherwise described were constructed of 1/4 in. O.D. copper tubing using compression fittings. All valves were 1/4 in. brass plug valves. All lines were constructed as short as possible and in either a horizontal or vertical position to prevent deposition of the filter aid in the distribution lines.

The precoat pot consists of a plastic tube 3 in. in inside diameter and 4 in. high. The precoat pot is equipped with a square lid (4 1/2 in. x 4 1/2 in.) which is sealed by means of a 3 1/2 in. diameter rubber O-ring to a square plate fastened to the top of the precoat pot. A 1/4 in. copper inlet (valve 7) from the pump enters the precoat pot immediately above the bottom. The precoat pot may be flushed to waste through this line by opening valve 6.

A 1/4 in. copper discharge line leading to the filter housing is connected 2 in. above the bottom of the precoat pot. A second inlet leading from valve 8 is located at the same level as precoat outlet. The precoat pot was fastened rigidly on top of a laboratory magnetic stirrer. A 1 in. long Teflon-covered magnetic stirring rod was used inside the precoat pot to provide mixing of the contents of the precoat pot.

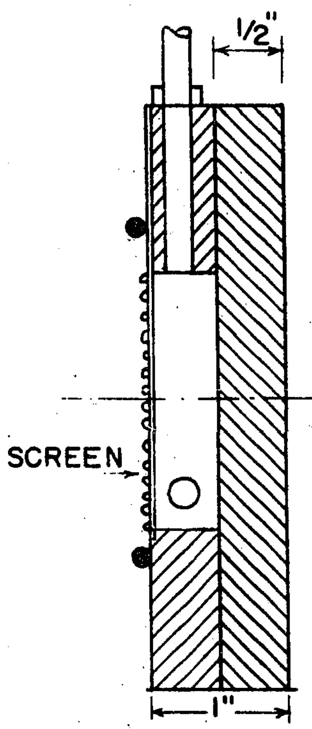
The K_3 filter was designed so that the filter septum would be fixed in a vertical plane. The filter is shown in detail in Fig. 7. The filter housing consisted of two separate plastic sections. The first or the inlet section of the filter consisted of three square plastic plates (4 1/2 in. x 4 1/2 in. x 1/2 in.) cemented together as shown in Fig. 7.

A 3 in. diameter circular hole was drilled in the center of the center plate. In addition, three 1/4 in. diameter holes were drilled in the 1/2 in. side, one at the top and two at the bottom as shown in Fig. 7. The upper hole was fitted and sealed with a copper tube connection to a manometer. One of the bottom holes was located off center and used as the water inlet. The tangential flow provided a rotation of suspended diatomite and served to aid in forming a uniform precoat. The other bottom hole was fitted with a copper tube leading to valve 13 (Fig. 5) and was used as a drain during backwash.

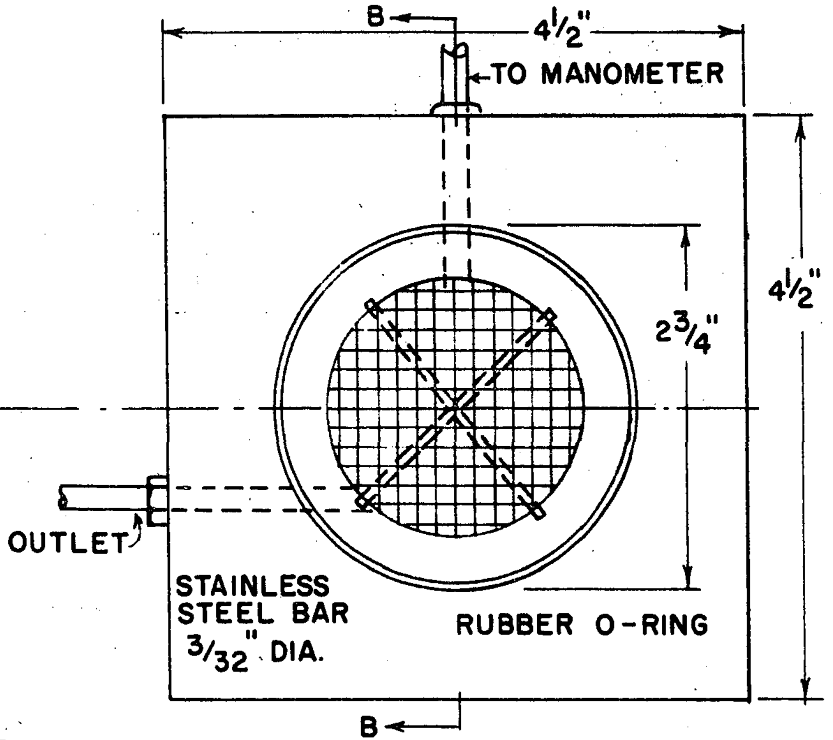
A 2 in. diameter circular hole was drilled in the center of the left plate shown in Section A-A of Fig. 7. The area represented by the area of this opening was the effective area of the filter septum. A 3 1/2 in. diameter rubber O-ring was mounted on the outside face of this plate to provide a water seal when this plate was clamped to the outlet section of the filter.

The outlet section of the filter was constructed from two square plastic plates (4 1/2 in. x 4 1/2 in. x 1/2 in.), cemented together as shown in Section B-B of Fig. 7. A 2 in.

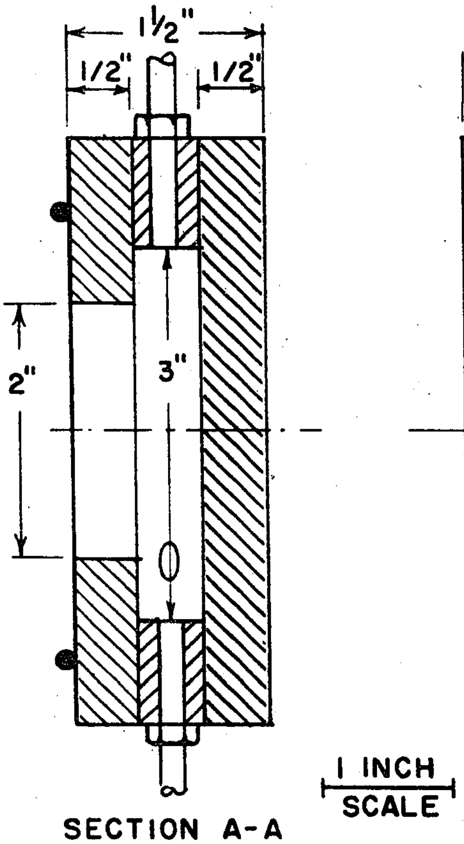
Fig. 7. Details of the filter used in the K_3 filter apparatus



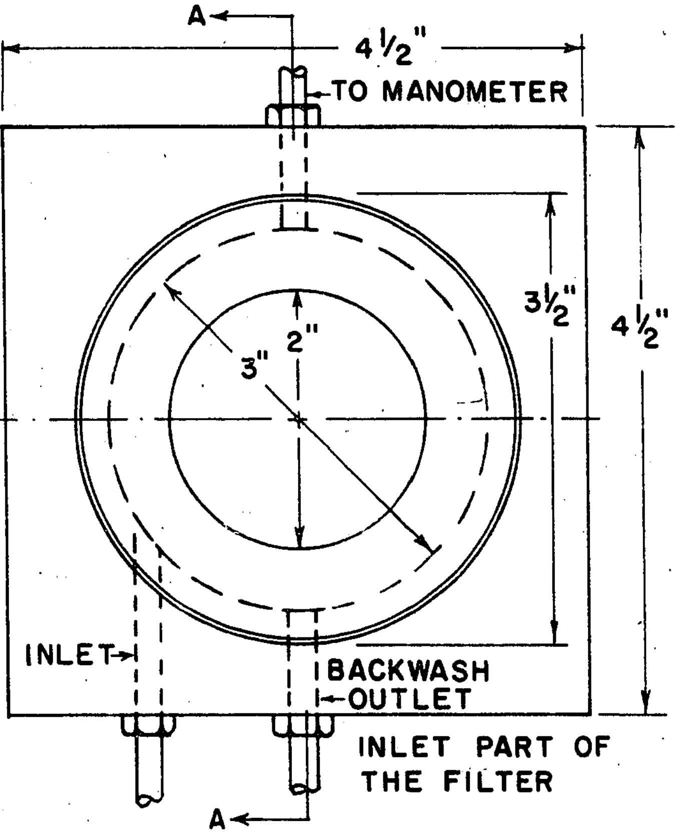
SECTION B-B



OUTLET PART OF THE FILTER



SECTION A-A



INLET PART OF THE FILTER

diameter hole was drilled in the center of the left plate (Section B-B) in such a way that it would be concentric with the two in. hole in the inlet portion of the filter when the two sections of the filter were clamped together. Two 1/4 in. holes were drilled at right angles to each other in the 1/2 in. side of the inner plate as shown in Section B-B. Both holes were fitted with 1/4 in. O.D. copper tubing, one of which was connected to a leg of the manometer and the other was connected to the flow meter as shown in Fig. 5.

A 2 3/4 in. rubber O-ring was mounted on the inner face of the inner plate to provide a water tight seal when the inlet and the outlet sections of the filter were joined together. A circular piece of stainless steel wire mesh approximately 3 in. in diameter was placed concentrically over the O-ring on the inner plate of the outlet section of the filter housing as shown in Section B-B, Fig. 7. The mesh used as the septum was similar to the mesh used in the CHP apparatus, page 29. The method of installation provided a filter area of 0.0218 sq. ft. The inlet and outlet sections of the filter housing were fitted together and held tightly by means of four C-clamps located at each corner of the housing (Fig. 6).

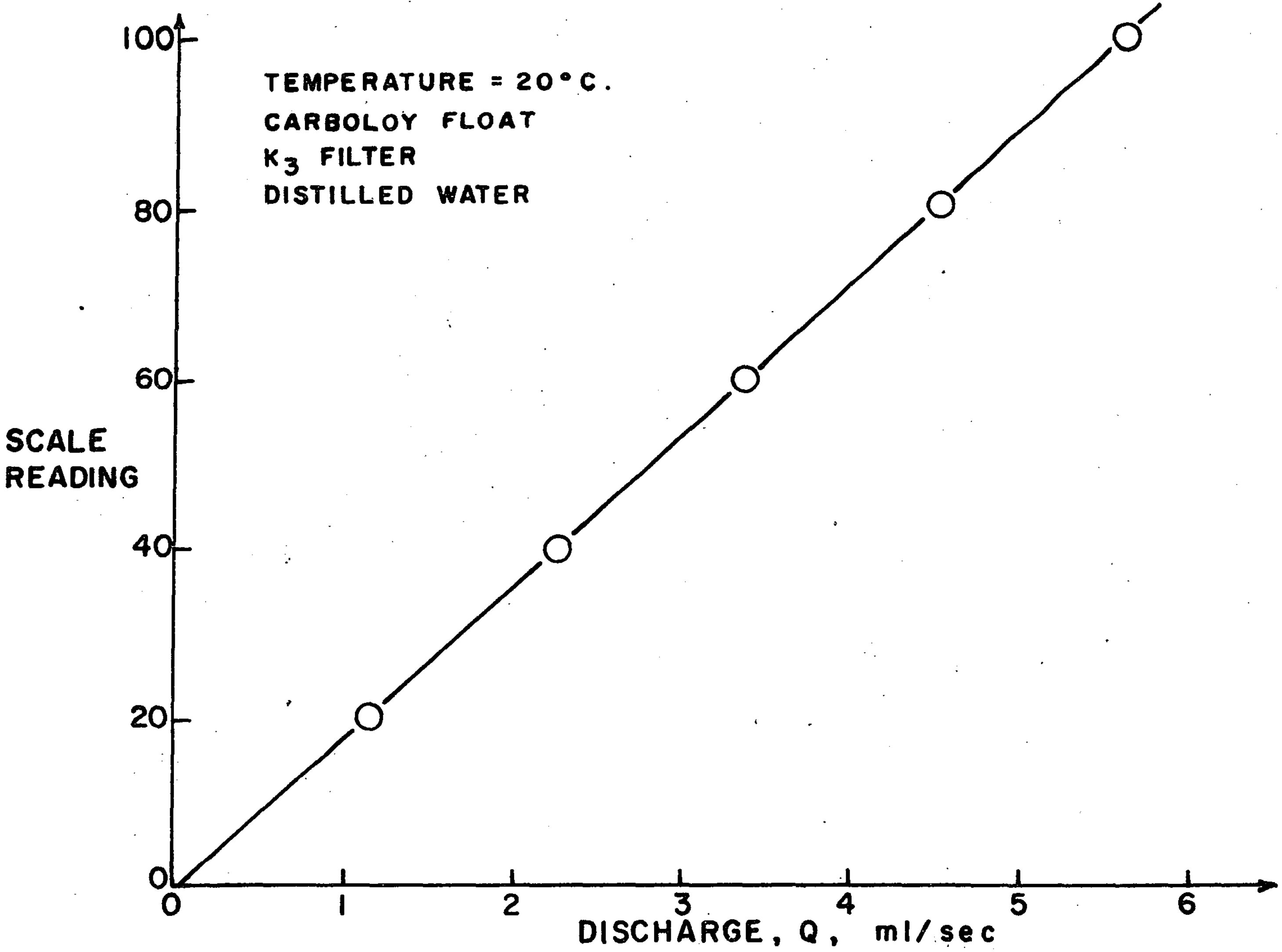
In the precoating operation, water was drawn from the backwash tank and went through the pump and entered the precoat pot through valve 8. The water left the precoat pot through valve 9 and entered the filter, passed through the filter septum, and left the filter housing through valve 14. The precoat water was then returned to the precoat recycle tank through valve 12 and was recycled through the system through valve 2. Once the system was full of water, the flow from the precoat and/or backwash storage tank was shut off.

c. Filtering section Once the filter had been precoated, the water was directed through the filtering section of the apparatus. The flow was then drawn from the water supply tank through valve 5 and moved through the pump and directly into the inlet to the filter through valves10. The water leaving the filter was directed through valves 14 and 15 directly to a flow measuring device. The rate of flow of filtrate was controlled by means of valve 16 and was measured with a Sho-Rate meter (Brooks Instrument Company, Inc.) tube R-2-15-C. The meter provided three flow measuring ranges by use of three floats, one of carboloy, one of stainless steel, and one of glass.

In this study, only the carboloy float was used. Fig. 8 shows the calibration curve developed to show the flow rate through the meter at 20°C versus the meter scale reading. A flow rate of 1.13 ml/sec (scale of 20) provided a flow rate of 0.823 gpm/sq ft. through the filter; a flow rate of 5.60 ml/sec (scale of 100) provided a flow rate of 4.08 gpm/sq ft.

The flow left the flow meter at the top and was returned

Fig. 8. Plot of discharge, Q, versus scale reading in percent determined in the calibration of the flow meter using the carboloy float


TEMPERATURE = 20°C.
CARBOLOY FLOAT
K3 FILTER
DISTILLED WATER
SCALE READING
100
80
60
40
20
0
0
1
2
3
4
5
6
DISCHARGE, Q, ml/sec

to the water supply tank through valve 17.

d. Pressure differential section The pressure drop across the filter cake was measured by means of a differential manometer connected to the upper taps on the inlet and outlet sides of the filter septum. A 2-foot long King Manometer, model BUB-24 (King Engineering Corp., Ann Arbor, Michigan) was used with No. 294 Red indicating liquid which had a specific gravity of 2.940 at 20°C. The indicating liquid is a bromide blend and is corrosive to iron and carbon steel. Pressure drops across the filter were read in inches of indicating fluid and converted into inches of water (Appendix C).

The manometer lines were provided with valves (18 and 19) to shut off the manometer from the system during precoating and backwashing operations. Each manometer lead was also provided with a vent line (valves 20 and 21) for removing all air from the manometer system.

e. Backwashing section During backwashing, water was drawn from the backwash tank through valves 4 and 3 and was delivered by the pump through valves 11 and 14 in reverse direction through the filter septum. Water was run to waste through valve 13. Water was also run through valve 8 into the precoat pot and out the precoat pot through valve 6.

The entire apparatus was mounted on a movable framework as shown in Fig. 6. The filter itself and all pipelines were mounted on a vertical backboard having the dimensions of 46 in. x 32 in. The recycle tank, the pump, and the precoat pot were mounted on a horizontal board whose dimensions were 18 in. x 32 in. The water supply and backwash tanks were mounted on another horizontal shelf behind the vertical backboard. The entire apparatus was mounted on four 4 in. wheels so that it could easily be moved from place to place. As constructed, the K_3 apparatus proved to be simple, convenient, fast and accurate.

3. Operating test procedures

Filter runs with the K_3 filter followed a uniform and convenient pattern. At the beginning of a run, the supply tank was filled with the specific water to be used in the test. The backwash tank was always kept filled with distilled water. Some of the distilled water was flushed through the entire system to purge air from the system and to wash out any residue solution and filter aid remaining from previous filter runs. Flushing air from the lines leading to the manometer was critical. This was accomplished by gradually opening the two valves (18 and 19) on the two lines to the manometer simultaneously. Then, the other two valves (20 and 21) which lead to the atmosphere were opened slightly until all the air was purged out. Then, valves 20 and 21 were closed and the whole system filled with water.

The precoating operation was performed as follows:

1. A predetermined amount of diatomite in slurry form was placed in the precoat pot, the lid was fixed tight to the pot, and the magnetic stirrer was turned on to keep the diatomite in suspension.

2. The recycle tank was filled with distilled water and the flow was cycled at the precoating flow rate as follows (Fig. 5): recycle tank - pump - bypass - filter - recycle tank. Then the flow was diverted through the precoat pot and the bypass was closed. Water was cycled in this manner until all diatomite was flushed from the precoat pot and onto the septum (about three minutes).

3. Then, the valves were adjusted to the filtering operation to give the following flow pattern (Fig. 5): supply tank - pump - bypass - filter - flow meter - supply tank. The valves which lead to the manometer were then opened. After completion of the above steps, precoating was complete, and the system ready for the filtering operation as soon as equilibrium conditions were established (two to five minutes).

If the rate of precoating was set too high, the precoat surface became scoured and took on an irregular spiral pattern. Too low a precoating flow rate permits diatomite to settle out in the inlet chamber making the cake thicker at the bottom than at the top. By experience, the right flow rate for formation of a uniform precoat could be estimated. In this filter, the velocity of the water approaching the filter element was not high enough to hold diatomite in suspension. Therefore, the flow was brought into the inlet chamber tangentially to impart a rotary motion to the diatomite suspension in this chamber. The suspension in the chamber would rotate with a velocity of 0.16 to 0.64 rps (17). This rotation can be observed when the cake is being formed and is sufficient to hold the diatomite in suspension without scouring the surface of the filter cake.

In collecting data for the determination of K_3 impermeability coefficient of the filter aid, the filtering operation with the K_3 filter was performed as follows:

1. After the precoat was formed and the system was in equilibrium, the rate of flow of distilled water through the precoat was adjusted successively to 5.60, 4.50, 3.35, 2.25 and 1.13 ml/sec, and the head loss corresponding to each flow rate was recorded. A sample data sheet is shown in Table 28 and a plot of the data collected in Figs. 15 and 16. If solutions of electrolytes were not to be used, the run was terminated and the filter was backwashed.

2. In those tests in which solutions of electrolytes were used, the head loss through the precoat filter aid was first determined with distilled water as in step one above. After the test with distilled water was completed, a predetermined quantity of the solution of the electrolyte under study was added to the water storage tank and allowed to circulate

through the filter for a period of seven minutes. This period was sufficient to provide a uniform distribution of the electrolyte in the water in the system and to provide opportunity for it to complete its reaction within the filter cake. After equilibrium conditions were again established with the electrolyte, the flow rates were adjusted successively to rates of 5.60, 4.50, 3.35, 2.25 and 1.13 ml/sec and the head loss corresponding to those flow rates was recorded. If larger concentrations of electrolytes were to be tested, an additional volume of the electrolyte solution was added to the water storage tank, mixed for seven minutes and again the flow rates were adjusted in reverse order, and the corresponding head losses were recorded. Additional electrolyte solutions were added in a similar manner until data had been collected for the desired range of electrolyte concentration. At the end of the test, the filter was backwashed and all solution and filter aid wasted. The filter was then rinsed several times to eliminate all electrolyte and filter aid contamination of the K_3 filter system.

V. LABORATORY APPROACH

A. General

All of the tests conducted in this investigation were made to determine the effect of cations and anions in solution on the permeability of diatomite filter aid. All of the tests were made using a commercial grade of diatomite filter aid, Celite-535, a product of the Johns-Manville Corporation. All tests were made using filter aid from a single 50 lb. sack of the commercial material.

During the early phase of the study, all tests were made with the CHP apparatus. Later the CHP apparatus was abandoned, and a new group of tests were conducted with the K_3 filter. The laboratory tests were conducted in six different series. The term "series" as used in this thesis designates a number of runs conducted with one specific objective. The series conducted in the study may be summarized as follows:

CHP filter

Series	Runs	Purpose of Series
C	179-197 223-267	Verification of apparatus with distilled water.
B	43-142	(not included in this thesis) K_4 studies.
A	1-42 143-178 198-222 268-624	Effect of solutions of salts on permeability

K_3 filter

Series	Runs	Purpose of Series
D	625-674	Verification of apparatus with distilled water.
E	675-738	Effect of different tap waters on filter cake permeability
F	739-903	Effect of solution of salts on filter cake permeability.

B. Constant Head Permeameter

1. Series "C", Reproducibility of data and weight of precoat

Before the CHP apparatus could be used to determine the effect of solution of salts on the filter cake permeability, it was necessary to conduct a large number of runs to demonstrate that the apparatus gave reproducible results. Accordingly, the series "C" tests were made to determine the effect of weight of precoat and the time of filtration on the filter cake permeability.

In this test, the CHP filter was precoated with either 5 or 10 grams of filter aid. The filter aid was added through the funnel at a distance about 2 feet above the septum and was allowed to settle onto the filter septum at the bottom of the filter tube. Distilled water was then recycled through the precoat continuously for period of three hours under a constant head of 4.65 feet of water. Periodically, the filtration rate was determined by timing the collection of a known volume of filtrate.

The quantity of filter aid used as precoat was weighed out with an analytical balance to a precision of plus or minus 0.005 gram. In the CHP tests, no attempt was made to keep the water temperature constant, water temperature varied between 20° - 29°C in different runs, but seldom more than 2°C in a group of similar runs. In a few runs, a cooling coil was used in the bottom storage tank and the water temperature dropped during a test (from 31°C to 17°C as in the case of KOH solution). All results were corrected to provide flow rates at a constant temperature of 20°C by use of the relationship shown in Appendix C.

During early runs, each test was repeated from three to six times and an average results of all tests under the same conditions was determined. The average result was plotted to show the decrease in the rate of flow through the filter cake expressed in gpm/sq ft. at 20°C versus time of filtration (Fig. 9). During the early runs, the rate of flow was observed to decrease sharply during the first hour of filtration. During the next two hours of filtration with distilled water containing no suspended solids, the rate of flow decreased linearly with time. A similar observation was made by Phillips who reported "that if distilled water flow through diatomite at a constant rate of flow, the pressure loss across the filter increases even though the distilled water carries no suspended particles" (18).

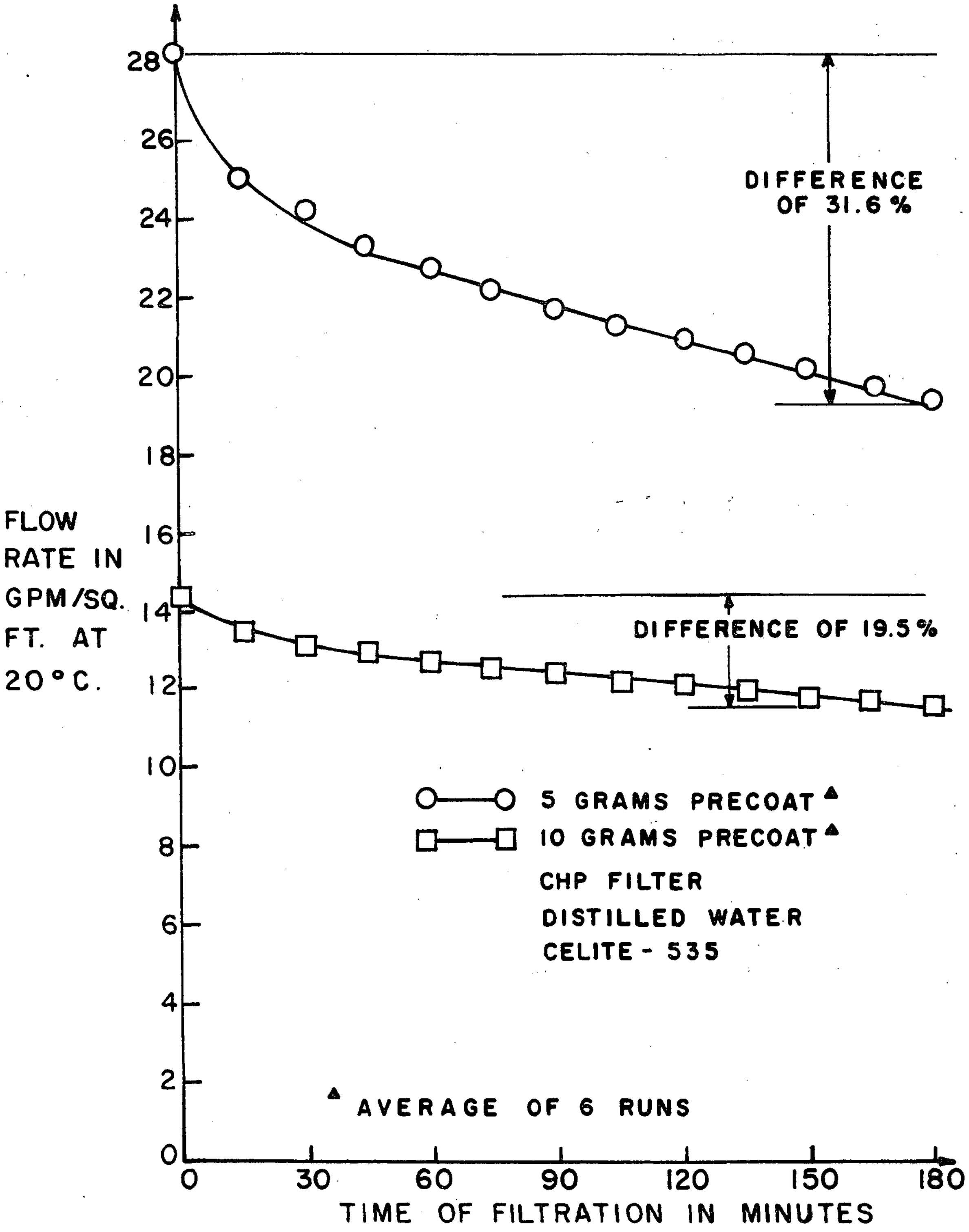
Fig. 9 shows the change in flow rate through the CHP filter using 5 and 10 grams of Celite-535 as precoat. After three hours of filtration, the rate of flow through the 5 grams of precoat decreases about 32 per cent and through the 10 grams of precoat it decreases about 19.5 per cent. During filtration in the CHP filter, several factors will produce the effect observed, in which the flow rate decreases with time of filtration. Since the water passed through the precoat contains no solids to clog the pores, the reduction in flow rates must have occured due to basic changes in precoat permeability. Such changes could be due to one or more of the following reasons:

1. The realignment of the filter aid particles to provide an optimum alignment of particles for flow.
2. The continuous compaction of filter aid with time due to the difference in pressure on the upstream and downstream sides of the filter.
3. The breakdown of the more fragile diatomite particles under the mechanical compression of the pressure differential across the filter.

All of these factors will tend to reduce the cake thickness, the characteristics of the pore spaces, and will reduce the cake porosity and cause a reduction in flow rate. Similar reductions in flow rates have been studied previously (1, 16).

The method used for precoating resulted in a somewhat

Fig. 9. Effect of weight of precoat on the rate of flow through the CHP filter after different times of filtration of distilled water

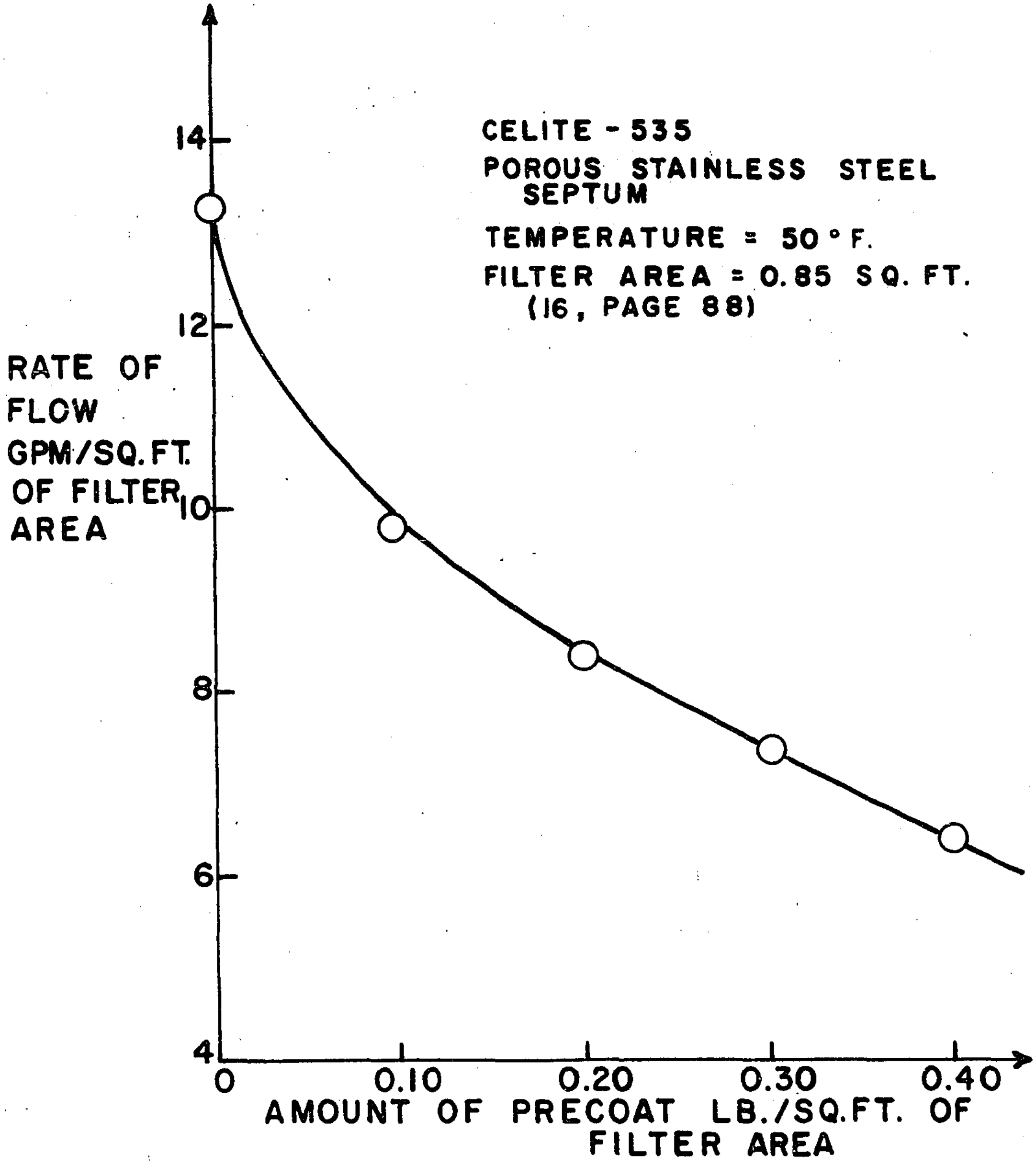

FLOW RATE IN GPM/SQ. FT. AT 20°C.
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
30
60
90
120
150
180
TIME OF FILTRATION IN MINUTES
DIFFERENCE OF 31.6 %
DIFFERENCE OF 19.5 %
○—○ 5 GRAMS PRECOAT ▲
□—□ 10 GRAMS PRECOAT ▲
CHP FILTER
DISTILLED WATER
CELITE - 535
▲ AVERAGE OF 6 RUNS

nonuniform precoat. The concentrated precoat slurry was added by means of a funnel about two feet above the filter septum. As a result, the heavier filter aid particles settled out on the septum first, and the finer particles which have a somewhat smaller settling velocity collected in higher concentration at the surface of the cake. In all tests, however, the standard method of precoating was used and the variation in precoat character was undoubtedly fairly constant in all tests.

The data shown in Fig. 9 represent an average curve determined from six separate runs under identical conditions. No individual results varied more than 3 per cent from the average. Thus, even though there was a change in cake permeability with time, it was concluded that the effect of solutions of chemicals could be qualitatively evaluated by determining the departure of the flow rate from the expected trend shown in Fig. 9.

Several tests were conducted to determine a desirable standard weight of precoat to be used in all tests. Fig. 10 shows the effect of the amount of precoat on the rate of flow through a stainless steel septum used in previous studies of the precoat and backwash characteristics of the diatomite filters (16). With no precoat, the rate of flow through the filter septum under a standard head of 4.65 feet of water was 13.3 gpm/sq ft. With this septum, a straight line rate of flow versus weight of precoat does not begin until 0.15 lb/sq

Fig. 10. Effect of amount of precoat on rate of flow through a precoat of Celite-535 on a porous stainless steel septum of filter area 0.85 sq ft at 50°F (16, page 88)


CELITE - 535
POROUS STAINLESS STEEL SEPTUM
TEMPERATURE = 50 ° F.
FILTER AREA = 0.85 SQ. FT.
(16, PAGE 88)
RATE OF FLOW GPM/SQ. FT. OF FILTER AREA
14
12
10
8
6
4
0
0.10
0.20
0.30
0.40
AMOUNT OF PRECOAT LB./SQ.FT. OF FILTER AREA

ft of filter aid has been used as precoat. With larger amounts of precoat, the addition of successive equal amounts of precoat will give equal increases in the thickness of precoat and equal decreases in the rate of flow. With a precoat amount less than 0.15 lb/sq ft, the addition of equal increments of precoat give unequal thickness of precoat and a nonuniform change in flow rate with increase in precoat weight. Baumann concluded (16) that the weight of precoat at which the straight line relationship begins represents the minimum weight of precoat needed to give a complete and uniform layer of filter aid over the entire septum area. Similar results have been reported for twenty different types of septum materials including porous mesh screen of the type used in this study (16). In most cases using wire mesh, a minimum precoat weight of about 0.05 lb/sq ft was required.

In this study, the use of five grams of precoat provided an average precoat weight of 0.27 lb/sq ft (Appendix C). Accordingly, in this study the standard weight of precoat was significantly greater than the amount needed to effectly precoat the septum. Fig. 9 shows the changes in flow rate through 5 (0.27 lb/sq ft) and 10 (0.54 lb/sq ft) grams of precoat. After one hour of filtration through the smaller precoat, the flow rate was 22.80 gpm/sq ft and through the larger precoat was 12.80 gpm/sq ft. Thus, these data indicate that the flow rate could be controlled very effectively by varying the weight of precoat if desired. In all subsequent tests a weight of precoat of 0.27 lb/sq ft was used.

2. Series "A", Runs with chemicals in solution

The series "A" tests with the CHP apparatus were made to determine the effect of solutions of fifteen different salts on the permeability of 5 grams of precoat after one hour of filtration using distilled water. The salts used in this study are tabulated in Table 4 which shows their solubility, molecular weight, and melting points as recorded in the Physical Chemistry Handbook (11).

The first tests using ions in solution were made using solutions of Na_2SO_4 in uniform concentrations of 100 ppm. This concentration involved the solution of 5.68 grams of sodium sulfate in 15 gallons of distilled water and provided a molal concentration of 0.71×10^{-3} (Appendix C). A concentration of 100 ppm of sodium sulfate provided a total of 0.726×10^{23} ions in CHP system (Appendix C).

In order to have some basis for standardization, all salts were tested using 0.726×10^{23} ions as the initial concentration of the salt in solution. Table 5 shows the grams, ppm, and molality of each salt required to provide 0.726×10^{23} ions in the 15 gallons of water in the CHP system. The amounts shown in Table 5 were always used to provide the initial salt concentration. Whole number multiples of these concentrations were used to provide higher concentrations of

Table 4. Physical constants of inorganic compounds (11)

Name	Formula	Mol.	Melting point, C°	Solubility in grams per 100 ml of	
				Cold water	Hot water
Sodium Chloride	$NaCl$	58.54	801	35.7 at 0°C	39.1 at 100°C
Calcium Chloride	$CaCl_2$	110.99	772	59.5 at 0°C	159 at 100°C
Aluminum Chloride	$AlCl_3$	133.36		S	V.S.
Aluminum Sulfate	$Al_2(SO_4)_3$	342.14	770	313 at 0°C	98.1 at 100°C
Potassium Sulfate	K_2SO_4	174.26		6.8 at 0°C	24.1 at 100°C
Sodium Sulfate	Na_2SO_4	142.06	884	4.7 at 0°C	42.7 at 100°C
Magnesium Sulfate	$MgSO_4$	120.39	150	71 at 20°C	91 at 40°C
Ferrous Sulfate	$FeSO_4$	151.92	640	15.6 at 0°C	48.6 at 50°C
Sodium Hydroxide	$NaOH$	40.01	318	42 at 0°C	347 at 100°C
Potassium Hydroxide	KOH	56.10	360	97 at 0°C	178 at 100°C
Potassium Carbonate	K_2CO_3	138.20	891	112 at 20°C	156 at 100°C
Sodium Carbonate	Na_2CO_3	106	851	7.1 at 0°C	45.5 at 100°C
Sodium Bicarbonate	$NaHCO_3$	84.01	$-CO_2$, 270	6.9 at 0°C	16.4 at 60°C
Potassium Bicarbonate	$KHCO_3$	100.11	150	22.4 at 0°C	60 at 60°C
Ferric Chloride	$FeCl_3$	162.23	37	91.2 at	∞

Table 5. Quantities of unhydrated salts, required to provide 0.726×10^{23} ions in 15 gallons of water

Salts	0.726×10^{23} ions gm	ppm	$m \times 10^{-3}$
NaCl	3.52	62	1.06
$CaCl_2$	4.46	78.5	0.71
$AlCl_3$	4.03	71	0.53
$Al_2(SO_4)_3$	8.20	143	0.42
K_2SO_4	7.00	123	0.71
Na_2SO_4	5.68	100	0.71
$MgSO_4$	7.25	127.5	1.06
$FeSO_4$	9.20	162	1.06
NaOH	2.40	42	1.05
KOH	3.38	59.5	1.06
K_2CO_3	5.56	98	0.71
Na_2CO_3	4.27	75.5	0.71
$NaHCO_3$	5.07	89.5	1.06
$KHCO_3$	6.05	106	1.06

these salts in solution.

In conducting the tests with dissolved ions, the filter was precoated with 5 grams of Celite-535 and distilled water was filtered through the precoat for one hour. From four to six samples containing the number of grams of the given salt shown in Table 5 were prepared at the beginning of the test in solution form. At the end of one hour of filtration with distilled water, one sample containing 0.726×10^{23} ions was added to the storage tank and brought to equilibrium. After fifteen minutes of filtration with the ions in solution (75 minutes of total filtration), the flow rate through the filter cake was determined. At the same time, the effluent water temperature and pH were recorded. This flow rate might be the same, greater than, or less than the flow rate which would have been predicted from Fig. 9 where only distilled water was being filtered. If higher salt concentrations were being studied, a second sample of the chemical in solution was added to double the number of ions now in the system. Again, after 15 minutes of mixing and filtration with higher chemical concentration, (90 minutes of total filtration) the flow rate was again determined. The process was repeated in a similar manner until the flow rate had been determined with the highest concentration of chemical to be used.

Data for a typical run are plotted in Fig. 13. In this figure, the curve without salt represents the portion of distilled water curve from Fig. 9 for the period of filtration from 60 to 180 minutes. If the salt had no effect on the permeability of the precoat, this is the result that should have been obtained in the test. The second curve shows the actual rate of flow which was measured through the precoat when different solutions of the salt were filtered through the precoat. Qualitatively, the curve with salt lays above the curve with distilled water and it may be concluded that the addition of the salt serves to increase the filter cake permeability. Similarly, if the curve lay below the curve with distilled water, the addition of salt would serve to decrease the filter cake permeability.

C. K_3 Filter

1. <u>Series "D", Reproducibility of data</u>

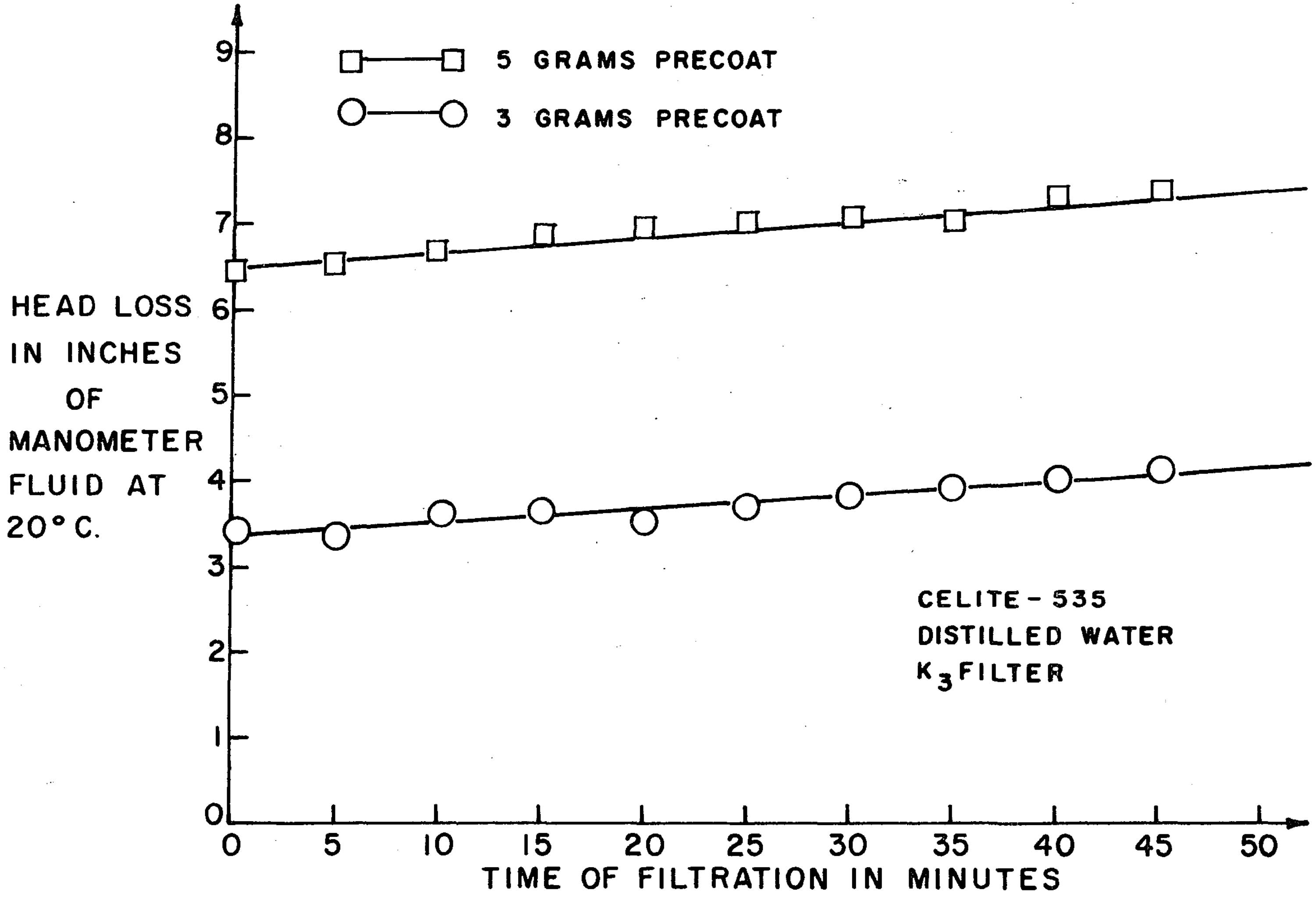
The series "D" tests with the K_3 filter were designed to determine the reproducibility of the K_3 values under standardized conditions. The K_3 value with any water was determined by making three separate runs using precoat weights of 3, 4 and 5 grams, equivalent to precoat weight of 0.3, 0.4, and 0.5 lb/sq ft.

Since the rate of flow through a precoat on the CHP filter was observed to decrease with time, a test was made to determine the change in head loss across a given weight of precoat in the K_3 filter with time of filtration. Accordingly, in three separate runs, the K_3 filter was precoated with 3, 4, and 5 grams of precoat and water was filtered at a rate of 5.60 ml/sec for 45 minutes. The head loss was read in inches of manometer fluid at 20°C every five minutes. Fig. 11 shows the variation of head loss versus time from two of the three runs. In each case, the head loss increased linearly with time of filtration.

These tests were conducted at the highest flow rate to be used in K_3 filter and indicate a result similar to that obtained with the CHP filter. The results indicate that if the entire K_3 data determination required less than five minutes, the error in head loss recorded would be negligible. In fact, the K_3 data required can be collected in less than two minutes when distilled water is used. When tests were conducted in which solutions of various ion concentrations were passed through the same precoat, approximately 10 to 15 minutes were required to complete the test.

To observe the effect of time of filtration on the actual value of K_3, the K_3 filter was precoated with six grams of Celite-535. Distilled water was filtered through this cake at a rate of 5.60 ml/sec for 30 minutes. At zero time of filtration, the flow through the filter cake was adjusted successively to rates of 5.60, 4.50, 3.35, 2.25, and 1.13 ml/sec and the head loss was recorded as in Table 27. As soon as the head loss data were collected at these flow rates,

Fig. 11. Effect of the time of filtration at a rate of 5.60 ml/sec (distilled water) on the head loss through two different weights of Celite-535 using the K_3 filter


5 GRAMS PRECOAT
3 GRAMS PRECOAT
HEAD LOSS IN INCHES OF MANOMETER FLUID AT 20° C.
0
1
2
3
4
5
6
7
8
9
TIME OF FILTRATION IN MINUTES
0
5
10
15
20
25
30
35
40
45
50
CELITE - 535
DISTILLED WATER
K3 FILTER

the flow rate was returned to 5.60 ml/sec and allowed to continue at this rate for 10 minutes. At the end of this time, the flow was again adjusted to the five previous rates and the head loss was again recorded. This procedure was repeated after 20 and 30 minutes of filtration. The data collected after each period of filtration were used to determine a value of K_3 as shown in Fig. 15. The K_3 values shown in Table 27 indicate a slight tendency for values of K_3 to increase with time of filtration. However, the differences are less than 2 per cent after 30 minutes of filtration. These data again indicate that compaction effects have not been a significant factor affecting the K_3 value of a filter aid. The normal procedure in making the calculation of K_3 using data collected on the K_3 filter is shown in Table 28 and in Fig. 15 and Fig. 16. Each test for the determination of K_3 was repeated using several weights of filter aid in the precoat. In Table 28, for example, weights of 3, 4, and 5 grams were used.

The results using each weight of precoat were plotted to show head loss in inches of manometer fluid at 20°C versus filtration rate in ml/second. The straight line providing the best fit through each set of data provides a measure of K_3 (the slope of the line). The value of K_3 in standard units was calculated as shown in Appendix C.

The data in Table 29 may be combined to form a single graph by plotting the data as shown in Fig. 16. Here, the head loss in inches of manometer fluid at 20°C was plotted against the product of QW. The straight line of best fit through these data provided an average value of $K_3 = 0.530 \frac{ft^5 . \ min}{lb. \ gal}$. The average of the three individual runs (Fig. 15) provided values of K_3 of 0.535, 0.538, and 0.523 with an average value of $K_3 = 0.532 \frac{ft^5 . \ min}{lb. \ gal}$. The maximum variation of any value from the mean was less than two per cent. Accordingly, the average values of K_3 reported in this thesis were determined by plotting the data as shown in Fig. 16. These values of K_3 are assumed to be accurate to the second decimal place.

2. Series "E", Tests with various tap waters

The K_3 filter and the technique for calculating K_3 were developed for the purpose of establishing a standard method for expressing the permeability of diatomite (3). However, K_3 results using distilled water and tap water are different. The authors hinted, although they did not expressly state, that all K_3 determination should be made using distilled water (3). In order to determine whether the different mineral contents of typical tap waters would significantly affect the K_3 of a filter aid, the K_3 of Celite-535 was determined using five different waters as follows:

1. Distilled water
2. Tap water from the City of Ames
3. Tap water from the City of Des Moines
4. Tap water from Iowa State University
5. Tap water from the City of Ames passed through a standard household water softener.

The distilled water used in all tests was prepared in the Sanitary Engineering Laboratories of the University. It had a normal pH ranging from 6.5 to 8.0 and a water conductivity from 4×10^{-6} to 5×10^{-6} ohms^{-1}.

The tap water from the City of Ames is derived from shallow wells and is softened by the lime-soda ash process to about 90 ppm of hardness. Table 6 shows a typical mineral analysis of this tap water.

The tap water from Des Moines is drawn from the Raccoon River through a filter gallery and is softened by the lime-soda ash process. Table 7 shows a typical mineral analysis of Des Moines tap water.

The tap water from Iowa State University is drawn from shallow wells and is aerated and filtered for iron removal, but it is unsoftened. A typical mineral analysis of the University tap water is shown in Table 8.

In one test, tap water from the city of Ames was collected after it had passed through an automatic home water softener, which effectively reduced the hardness to zero by replacing the calcium and magnesium cations with sodium.

3. Series "F", Tests with chemical solutions

This series of tests was conducted to determine the effect of various concentration of solutions of the following chemicals on the K_3 of the filter aid:

1.	Aluminum sulfate	$Al_2(SO_4)_3$
2.	Ferric chloride	$FeCl_3$
3.	Aluminum chloride	$AlCl_3$
4.	Sodium sulfate	Na_2SO_4
5.	Calcium chloride	$CaCl_2$
6.	Potassium hydroxide	KOH

The physical constants pertaining to these chemicals are summarized in Table 4. In these tests, different concentrations of these chemicals were chosen at random and used in the determination of K_3. Plots of the variation of K_3 of Celite-535 were made against the concentration of salts in solution as shown in a typical diagram in Fig. 18.

Table 6. Mineral analysis of Ames tap water on November 11, 1963

pH:	9.6	
Dissolved solids:	275	ppm
Total solids:	220	ppm
Alkalinity as $CaCO_3$:	60	ppm
Non-carbonate hardness:	43	ppm
Total hardness:	86	ppm
Calcium, Ca as $CaCO_3$:	43	ppm
Magnesium as $CaCO_3$:	40	ppm
Potassium, K:	3.2	ppm
Sodium, Na:	30	ppm
Iron, Fe:	.05	ppm
Manganese, Mn:	.05	ppm
Silica, SiO_2:	13.4	ppm
Nitrate, NO_3 as N:	1.6	ppm
Fluoride, F:	1.0	ppm
Chloride, Cl:	17.0	ppm
Sulphate, SO_4:	93.4	ppm
Bicarbonate, HCO_3:	20	ppm
Carbonate, CO_3:	21	ppm

Table 7. Mineral analysis of Des Moines tap water on November 9, 1963

pH:	10.53	
Dissolved solids:	197	ppm
Total solids:	197	ppm
Alkalinity as $CaCO_3$:	56	ppm
Non-carbonate hardness:	43	ppm
Total hardness:	99	ppm
Calcium, Ca as $CaCO_3$:	37.4	ppm
Magnesium, Mg as $CaCO_3$:	62.1	ppm
Potassium, K:	37.8	ppm
Sodium, Na:	10.1	ppm
Iron, Fe:	.05	ppm
Manganese, Mn:	< .03	ppm
Silica, SiO_2:	12	ppm
Nitrate, NO_3 as N:	0.01	ppm
Fluoride, F:	1.05	ppm
Chloride, Cl:	16.5	ppm
Sulphate, SO_4:	72.1	ppm
Bicarbonate, HCO_3:	None	
Carbonate, CO_3:	34.8	ppm

Table 8. Mineral analysis of the University tap water on November 10, 1963

Total residue:	537	ppm
Alkalinity as $CaCO_3$:	320	ppm
Aluminum, Al:	0.05	ppm
Calcium, Ca:	114.0	ppm
Chloride, Cl:	11.0	ppm
Copper, Cu:	0.25	ppm
Fluoride, F:	0.40	ppm
Iron, Fe:	0.05	ppm
Magnesium, Mg:	61.0	ppm
Manganese, Mn:	0.20	ppm
Nitrate, NO_3 as N:	0.70	ppm
Phosphate, PO_4:	0.15	ppm
Potassium, K:	2.50	ppm
Silica, SiO_2:	12.0	ppm
Sodium, Na:	19.5	ppm
Sulphate, SO_4:	210.0	ppm

VI. TEST RESULTS

A. Constant Head Permeameter

1. Series "C", Results

Series "C" tests were made to determine the effect of the weight of precoat and the time of filtration on the filter cake permeability in the CHP filter. This series has been discussed previously on pages 56 to 65 of this thesis.

The averages of the data collected in these runs are tabulated in Tables 9 and 10. A typical curve for the data tabulated in these two tables are plotted in a single diagram in Fig. 9. Table 9 includes the average of the data for six separate runs using 5 grams of Celite-535 as a precoat in the CHP filter. Table 10 also includes the averages of the data from six separate runs, but using 10 grams of Celite-535 as a precoat in the CHP filter. In both tables, the rates of flow were determined from the average time required for collecting a certain volume of filtrate (Appendix C). Temperatures, recorded for each separate run, were averaged arithmatically as shown in Tables 9 and 10. A correction factor was applied for conversion of the flow rate at the tabulated temperature to the standard temperature of $20^{\circ}C$ (Appendix C). Corrected flow rates and corresponding K_3 values at the standard temperature of $20^{\circ}C$ are tabulated in Tables 9 and 10. (Appendix C). Fig. 12 shows graphically variation in the K_3

Table 9. Variation in K_3 of a 5-gram Celite-535 precoat with time in the CHP filter

Time of filtration, minutes	Rate of flow, gpm/sq ft	Average temp., C^{o}	Correction factor, $\frac{(\eta_{20})}{\eta_t}$	Flow at $20^{o}C$, gpm/sq ft	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
0	33.73	27.75	1.195	28.23	0.60
15	29.96	28.00	1.202	24.93	0.68
30	29.12	28.00	1.202	24.23	0.71
45	28.72	28.10	1.205	23.40	0.73
60	27.51	28.25	1.209	22.80	0.75
75	27.33	28.50	1.215	22.30	0.76
90	26.45	28.58	1.217	21.80	0.78
105	26.23	28.87	1.225	21.41	0.79
120	25.76	29.00	1.228	21.00	0.81
135	25.50	29.12	1.232	20.60	0.82
150	25.04	29.30	1.236	20.26	0.84
165	24.53	29.38	1.239	19.80	0.86
180	23.84	29.40	1.239	19.24	0.88

Table 10. Variation in K_3 of a 10-gram Celite-535 precoat with time in the CHP filter

Time of filtration, minutes	Rate of flow, gpm/sq ft	Average temp., C^o	Correction factor, $\frac{(\eta_{20})}{\eta_t}$	Flow at 20^{o}C, gpm/sq ft	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
0	17.19	27.75	1.195	14.38	0.60
15	16.25	28.0	1.202	13.52	0.63
30	15.91	28.0	1.202	13.23	0.64
45	15.71	28.10	1.205	13.04	0.65
60	15.54	28.25	1.209	12.85	0.66
75	15.29	28.50	1.215	12.58	0.67
90	15.19	28.58	1.217	12.48	0.68
105	15.02	28.87	1.225	12.26	0.69
120	14.94	29.00	1.228	12.16	0.70
135	14.82	29.12	1.232	12.03	0.705
150	14.76	29.30	1.231	11.94	0.71
165	14.64	29.38	1.239	11.82	0.72
180	14.35	29.40	1.239	11.58	0.73

values for a 5-gram Celite-535 precoat with time of filtration in the CHP filter.

2. Series "A", Results

This series was conducted to determine the effect of solutions of fourteen different salts on the permeability of 5 grams of filter aid used as a precoat in CHP filter. This series of tests has been described in the previous section (pages 65 to 69). Solutions of salts were added to the distilled water after one hour of filtration through the precoat of Celite-535. From four to six different concentrations of each chemical have been filtered through a single precoat in evaluating the effect of the different salt concentrations on the permeability of the cake.

The results of these tests are tabulated in Tables 12 to 25. The chemicals used in this series are grouped as shown in Table 11.

In Tables 12 to 25, the times of filtration and the salt concentrations used have been tabulated. Flow rates that would have been observed without the salt at any time of filtration were taken from Fig. 9. Temperatures have been averaged for all the runs which have been conducted with a certain chemical and are tabulated in the above tables. Values of pH recorded are approximate. Every chemical in Table 11 has been used in at least three tests for the purpose of providing the best representation of its effect on the K_3 value

Fig. 12. Plot showing variation in K_3 of 5-gram Celite-535 precoat with time of filtration at the standard temperature of 20°C in the CHP filter

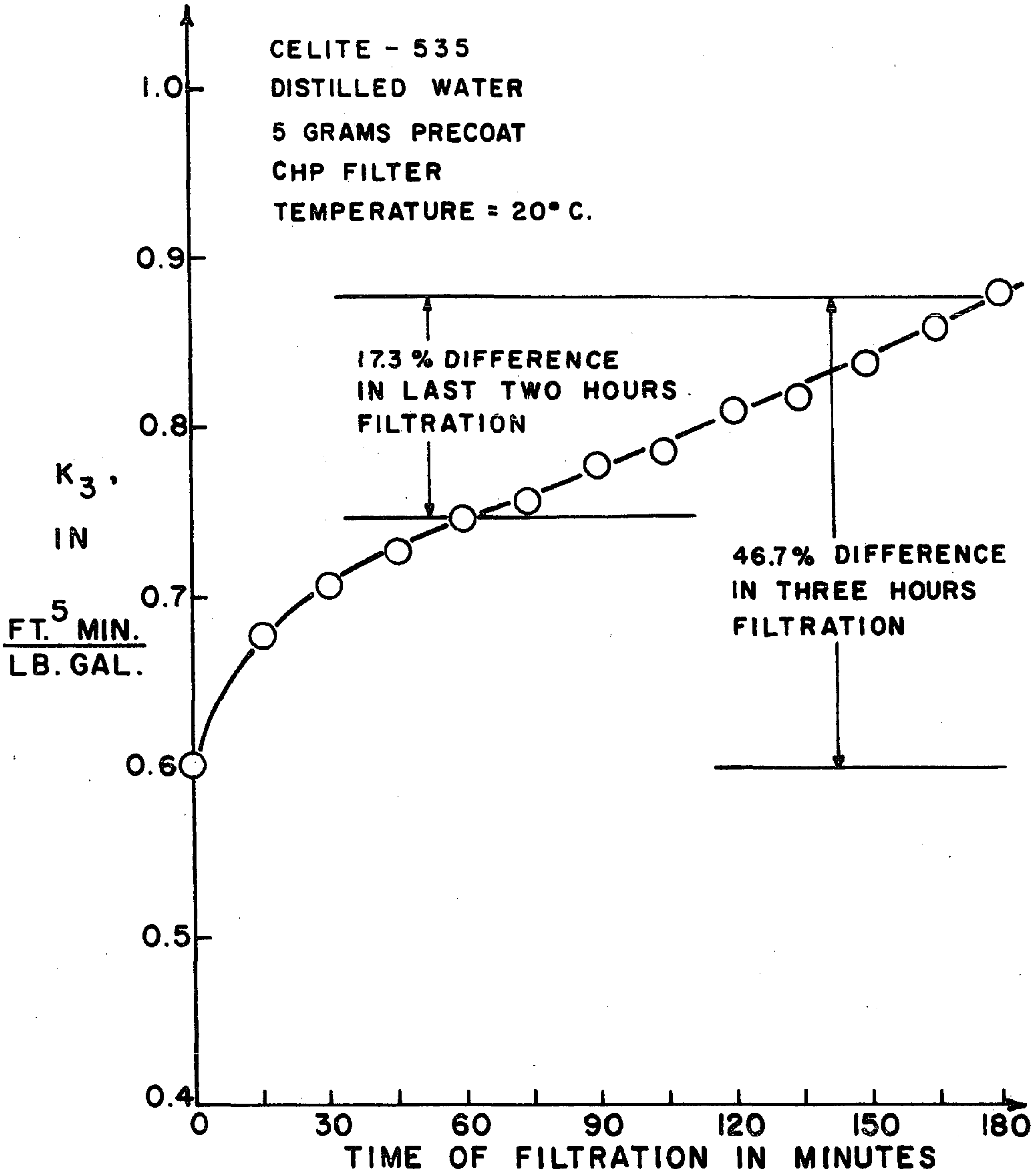

CELITE - 535
DISTILLED WATER
5 GRAMS PRECOAT
CHP FILTER
TEMPERATURE = 20° C.
17.3 % DIFFERENCE IN LAST TWO HOURS FILTRATION
46.7 % DIFFERENCE IN THREE HOURS FILTRATION
K_3, IN $\frac{FT.^5 MIN.}{LB. GAL.}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
30
60
90
120
150
180
TIME OF FILTRATION IN MINUTES

Table 11. Location of data from the Series "A" tests conducted with CHP filter

Family	Salt solution	Results in table no.	Results in fig. no.
Chloride	Sodium Chloride	12	13
	Calcium Chloride	13	
	Aluminum Chloride	14	
Sulfate	Aluminum Sulfate	15	
	Potassium Sulfate	16	
	Sodium Sulfate	17	
	Magnesium Sulfate	18	
	Ferrous Sulfate	19	
Hydroxide	Sodium Hydroxide	20	
	Potassium Hydroxide	21	
Carbonate	Potassium Carbonate	22	13
	Sodium Carbonate	23	
Bicarbonate	Sodium Bicarbonate	24	
	Potassium Bicarbonate	25	

Table 12. Effect of the concentration of NaCl on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration,	Flow rate without salt at 20°C (Fig. 9)	Salt concentration	Average temp., T	pH	Calculated flow rate at T°C	Temperature correction factor	Flow rate with salt at 20°C	K_3 with salt
min	gpm/sq ft	m x 10^{-3}	°C		gpm/sq ft	$\frac{\eta_{20}}{\eta_T}$	gpm/sq ft	$\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.80	0	27.8	6.98	27.4	1.197	22.8	0.745
75	22.3	1.06	28.2	6.98	27.5	1.207	22.7	0.750
90	21.8	2.12	28.5	7.15	27.7	1.215	22.7	0.750
105	21.4	4.24	28.8	7.06	27.6	1.223	22.6	0.753
120	21.0	8.48	29.0	7.00	27.0	1.228	22.0	0.773
135	20.6	16.96	29.1	6.91	26.3	1.231	21.3	0.798

Table 13. Effect of the concentration of $CaCl_2$ on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0	25.6	7.17	26.0	1.139	22.80	0.745
75	22.3	0.707	25.8	7.10	25.0	1.145	21.78	0.781
90	21.8	1.414	25.9	7.27	23.9	1.147	20.77	0.820
105	21.4	2.828	26.2	7.43	22.1	1.155	19.07	0.891
120	21.0	5.656	27.1	7.77	19.5	1.179	16.46	1.033
135	20.6	11.312	27.4	8.33	13.4	1.186	11.25	1.510

Table 14. Effect of concentration of $AlCl_3$ on the K_3 of a Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.80	0	26.5	7.10	26.41	1.16	22.80	0.745
75	22.30	0.53	27.0	4.34	28.30	1.18	23.95	0.710
90	21.80	1.06	27.0	4.19	28.80	1.18	24.36	0.698
105	21.40	2.12	27.3	4.11	28.50	1.18	24.15	0.705
120	21.00	4.24	27.3	3.97	28.80	1.18	24.43	0.695
135	20.60	8.48	27.5	3.84	28.60	1.19	24.23	0.702

Table 15. Effect of the concentration of $Al_2(SO_4)_3$ on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0	28.5	6.02	27.7	1.215	22.80	0.745
75	22.3	0.425	28.9	4.16	26.8	1.225	21.89	0.777
90	21.8	0.850	28.9	3.96	27.0	1.225	21.95	0.775
105	21.4	1.700	29.1	3.74	28.0	1.231	22.67	0.750
120	21.0	3.400	29.1	3.50	28.7	1.231	23.24	0.732
135	20.6	6.800	29.3	3.26	28.8	1.236	23.36	0.726

Table 16. Effect of the concentration of K_2SO_4 on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb.gal}$
60	22.8	0	26.0	6.78	26.3	1.150	22.80	0.745
75	22.3	0.707	26.2	6.60	26.3	1.154	22.75	0.748
90	21.8	1.414	26.5	6.61	26.2	1.163	22.49	0.756
105	21.4	2.828	27.0	6.66	26.1	1.176	22.17	0.767
120	21.0	5.656	27.3	6.58	26.1	1.184	22.00	0.773
135	20.6	11.312	26.8	6.57	25.9	1.195	21.60	0.788

Table 17. Effect of the concentration of Na_2SO_4 on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0	28.5	6.35	27.6	1.21	22.8	0.745
75	22.3	0.7	28.5	6.18	25.0	1.21	20.6	0.826
90	21.8	1.4	28.5	6.08	23.2	1.21	19.2	0.886
105	21.4	2.8	28.5	6.07	22.0	1.21	18.2	0.935
120	21.0	5.6	28.5	6.07	20.8	1.21	17.2	0.992
135	20.6	11.2	28.5	6.16	19.0	1.21	15.7	1.081

Table 18. Effect of the concentration of $MgSO_4$ on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration,	Flow rate without salt at 20°C (Fig. 9)	Salt concentration	Average temp., T	pH	Calculated flow rate at T°C	Temperature correction factor	Flow rate with salt at 20°C	K_3 with salt
min	gpm/sq ft	m x 10^{-3}	°C		gpm/sq ft	$\frac{\eta_{20}}{\eta_T}$	gpm/sq ft	$\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0	27.75	6.97	27.30	1.195	22.8	0.745
75	22.3	1.06	27.75	7.07	26.20	1.195	21.9	0.777
90	21.8	2.12	27.62	6.97	25.4	1.192	21.2	0.803
105	21.4	4.24	27.62	7.00	24.9	1.192	20.8	0.818
120	21.0	8.48	27.62	6.90	24.4	1.192	20.4	0.835

Table 19. Effect of the concentration of $FeSO_4$ on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with $_3$salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0	28.7	6.77	27.90	1.222	22.80	0.745
75	22.3	1.06	28.5	5.22	2.86	1.215	2.35*	7.25
90	21.8	2.12	28.5	4.97	1.92	1.215	1.58*	10.80
105	21.4	4.24	28.0	4.88	1.66	1.202	1.38*	12.30

[*] A yellow precipitate of iron was noticed on the top of the diatomite precoat each time, with increasing density and color with increasing salt concentration.

Table 20. Effect of the concentration of NaOH on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0	22.0	7.36	24.0	1.049	22.80	0.745
75	22.3	1.05	23.0	10.56	20.1	1.074	18.67	0.913
90	21.8	2.10	23.7	10.92	19.4	1.090	17.79	0.956
105	21.4	4.20	24.3	11.23	19.2	1.107	17.37	0.982
120	21.0	8.40	25.0	11.57	17.8	1.125	15.75	1.080
135	20.6	16.80	25.2	11.80	14.5	1.129	12.77	1.333

Table 21. Effect of the concentration of KOH on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0.00	18.8	6.73	22.2	0.97	22.8	0.745
75	22.3	1.06	20.0	10.52	18.3	1.00	18.3	0.930
90	21.8	2.12	20.7	11.00	18.4	1.02	18.0	0.945
105	21.4	4.24	21.5	11.35	18.7	1.04	18.0	0.945
120	21.0	8.48	22.0	11.67	18.9	1.05	18.0	0.945
135	20.6	16.96	22.3	12.00	18.1	1.06	17.1	0.995

Table 22. Effect of the concentration of K_2CO_3 on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb.gal}$
60	22.8	0	24.6	7.00	25.4	1.115	22.80	0.745
75	22.3	0.707	26.0	10.00	24.2	1.150	21.00	0.810
90	21.8	1.414	26.8	10.20	24.6	1.172	21.00	0.810
105	21.4	2.828	26.3	10.40	24.6	1.158	21.20	0.803
120	21.0	5.656	26.3	10.62	24.8	1.158	21.40	0.795
135	20.6	11.372	26.2	10.78	24.0	1.154	20.60	0.826

Table 23. Effect of the concentration of Na_2CO_3 on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0.00	27.0	7.28	26.7	1.17	22.8	0.745
75	22.3	0.71	26.8	9.99	26.4	1.17	22.5	0.756
90	21.8	1.42	26.7	10.21	26.5	1.17	22.6	0.753
105	21.4	2.84	26.5	10.41	26.2	1.16	22.5	0.756
120	21.0	5.68	26.5	10.55	26.0	1.16	22.4	0.760
135	20.6	11.36	26.5	10.70	25.7	1.16	22.1	0.770

Table 24. Effect of the concentration of $NaHCO_3$ on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration,	Flow rate without salt at 20°C (Fig. 9)	Salt concentration	Average temp., T	pH	Calculated flow rate at T°C	Temperature correction factor	Flow rate with salt at 20°C	K_3 with salt
min	gpm/sq ft	m x 10^{-3}	°C		gpm/sq ft	$\frac{\eta_{20}}{\eta_T}$	gpm/sq ft	$\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0.00	25.2	6.86	25.8	1.13	22.8	0.745
75	22.3	1.06	25.2	7.85	24.8	1.13	21.9	0.777
90	21.8	2.12	25.8	8.16	24.1	1.15	20.9	0.815
105	21.4	4.24	26.2	8.58	22.5	1.15	19.5	0.873
120	21.0	8.48	26.3	8.75	21.5	1.16	18.5	0.920
135	20.6	16.96	26.0	8.78	20.6	1.15	17.9	0.951

Table 25. Effect of the concentration of $KHCO_3$ on the K_3 of a 5-gram Celite-535 precoat in the CHP filter

Time of filtration, min	Flow rate without salt at 20°C (Fig. 9) gpm/sq ft	Salt concentration m x 10^{-3}	Average temp., T °C	pH	Calculated flow rate at T°C gpm/sq ft	Temperature correction factor $\frac{\eta_{20}}{\eta_T}$	Flow rate with salt at 20°C gpm/sq ft	K_3 with salt $\frac{ft^5 \cdot min}{lb \cdot gal}$
60	22.8	0	25.5	6.97	26.0	1.137	22.80	0.745
75	22.3	1.06	25.8	7.85	26.4	1.143	23.00	0.740
90	21.8	2.12	25.8	8.12	27.0	1.143	23.45	0.725
105	21.4	4.24	25.5	8.32	26.7	1.137	23.36	0.728
120	21.0	8.48	25.8	8.43	27.0	1.143	23.54	0.723
135	20.6	16.96	25.8	8.44	27.1	1.143	23.70	0.717

Fig. 13. Plot of rate of flow of different electrolyte solutions at different concentrations through 5-gram of Celite-535 versus time of filtration (data collected on the CHP filter)

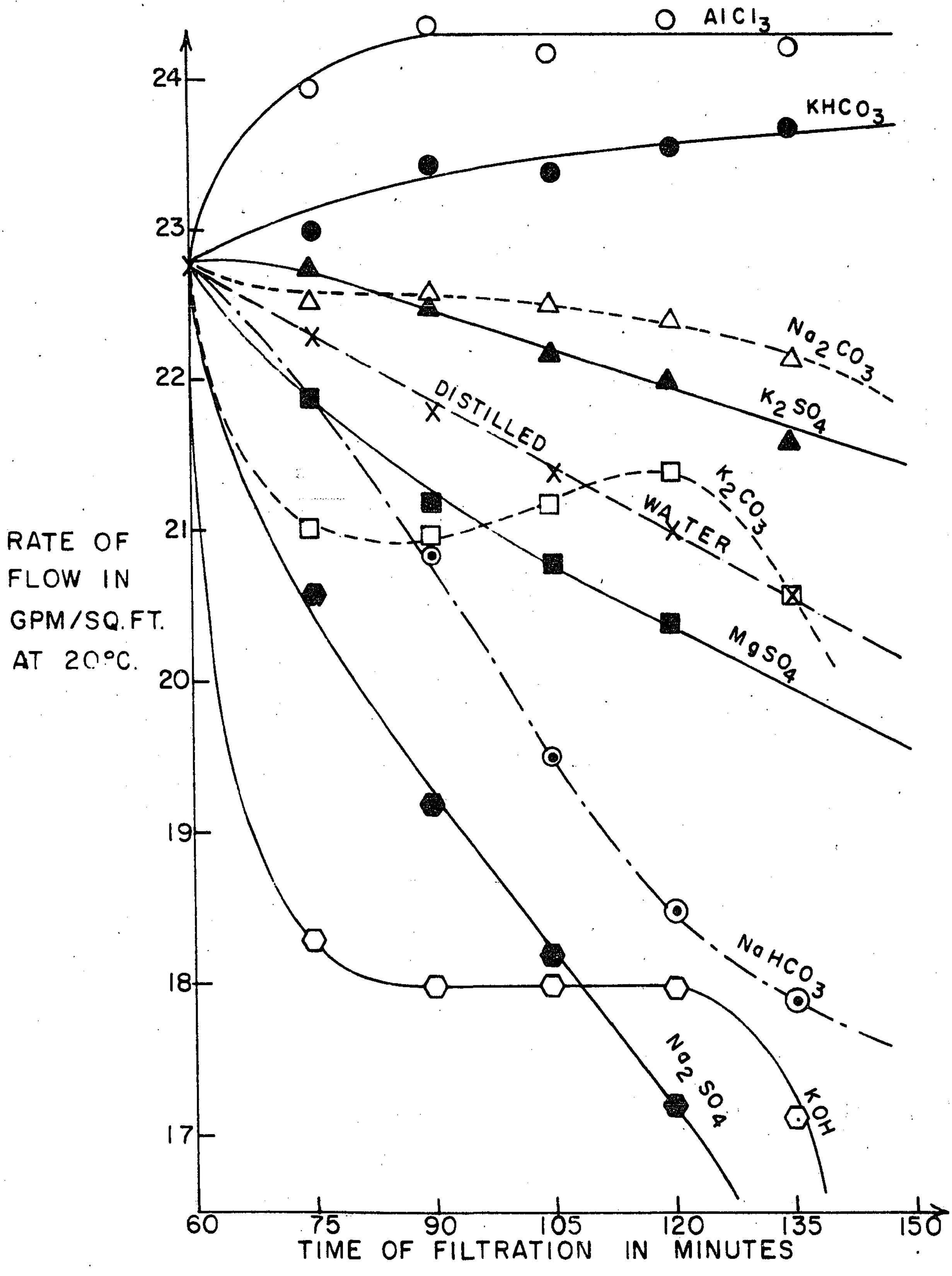
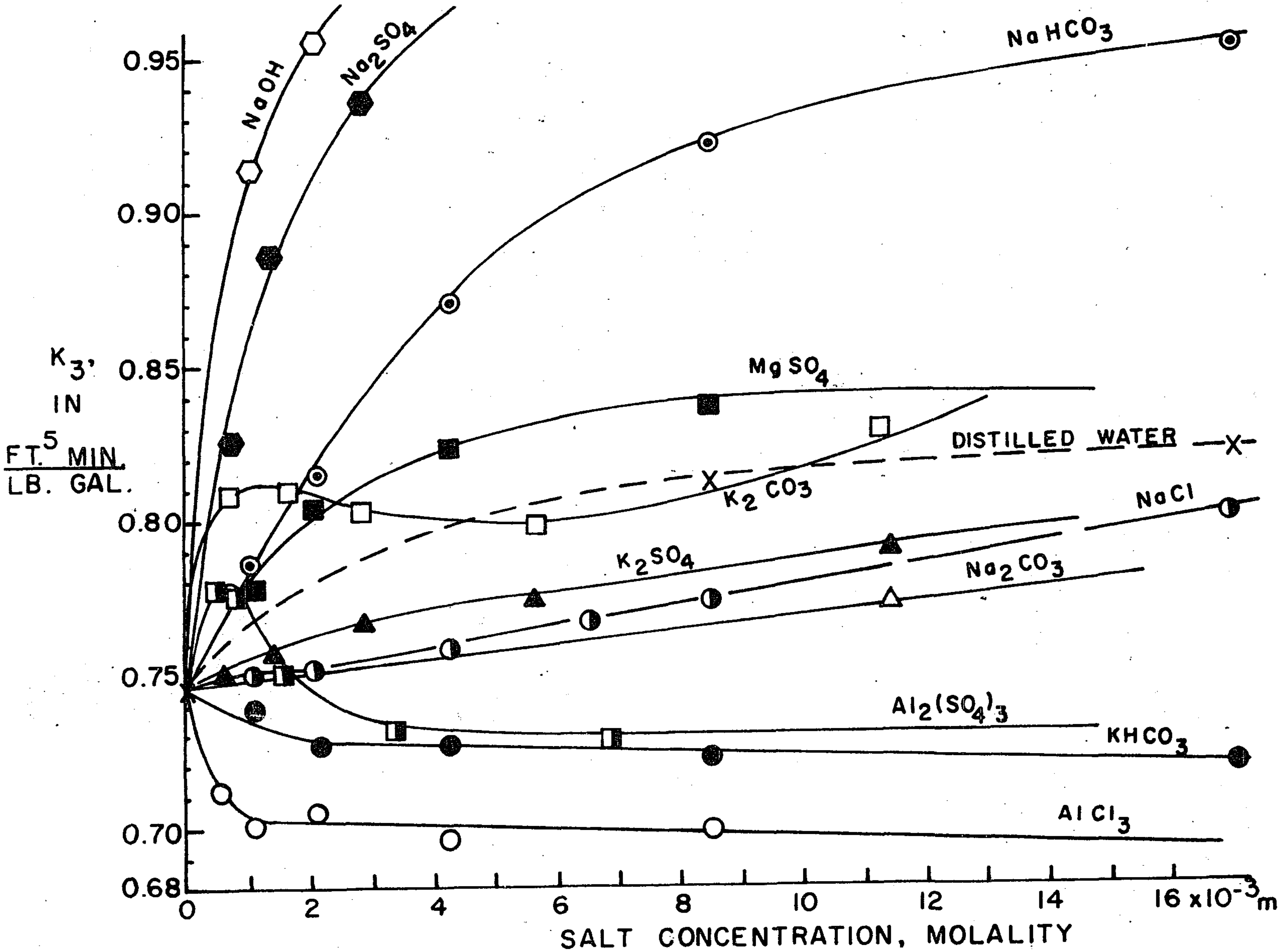

AlCl3
KHCO3
Na2CO3
K2SO4
DISTILLED WATER
K2CO3
MgSO4
NaHCO3
Na2SO4
KOH
RATE OF FLOW IN GPM/SQ.FT. AT 20°C.
24
23
22
21
20
19
18
17
60
75
90
105
120
135
150
TIME OF FILTRATION IN MINUTES

Fig. 14. K_3 of Celite-535 in standard units versus salt concentration at standard temperature of 20°C (from data collected on the CHP filter)


K_3' IN $\frac{FT.^5\ MIN.}{LB.\ GAL.}$
0.95
0.90
0.85
0.80
0.75
0.70
0.68
0
2
4
6
8
10
12
14
16 x10^{-3}m
SALT CONCENTRATION, MOLALITY
NaOH
Na_2SO_4
$NaHCO_3$
$MgSO_4$
DISTILLED WATER
K_2CO_3
NaCl
K_2SO_4
Na_2CO_3
$Al_2(SO_4)_3$
$KHCO_3$
$AlCl_3$

of the filter aid. The average flow rates have been determined for individual runs in the normal way as described in Appendix C are tabulated in each table. The flow rates at a standard temperature of 20°C are tabulated in these tables after the introduction of the correction factors for temperature (Appendix C). Finally, the corresponding K_3 values in standard units have been calculated from the corresponding flow rates at 20°C as described in Appendix C.

Fig. 13 shows a compilation of some of the data in a single figure which shows the range of flow rates versus the time of filtration observed in the CHP filter with both distilled water and salt solutions. Fig. 14 also shows a compilation of some of the data in a single figure which shows the values of K_3 versus salt concentration.

B. K_3 Filter

1. Series "D", Results

The series "D" tests were made to determine what factors affect the reproducibility of test results with the K_3 filter. In one group of runs, water was filtered through a given weight of precoat and the head loss was recorded at various times of filtration. Typical results of such runs are included in Table 26 and are plotted in Fig. 11. These tests were discussed on page 69 of this thesis.

A second group of runs were made to show the effect of time of filtration on the actual value of K_3 which was calculated from the test results. Table 27 shows the results of such a test using 6 grams of Celite-535 filter aid as a precoat. These results were discussed on pages 70 and 73 of this thesis.

2. Series "E", Results

The series "E" tests were conducted to determine the effect of using several different tap waters in the determination of the standard value of K_3 using the K_3 filter. The data collected in these runs are tabulated in Tables 28 to 32. A typical set of data are plotted in Fig. 15 and Fig. 16. Each table includes the data for two or more separate runs with different weights of precoat. The results from each of these runs could be plotted as shown in Fig. 15 to provide a measure of K_3. The K_3 value for each run may be determined from the slope of the graph of head loss versus discharge as described in Appendix C. Each table includes data showing the rate of flow, the product of rate of flow and the precoat weight, and the head loss observed in each run.

The K_3 shown in the table represents the K_3 determined by a plot for data of that specific run only. In addition two other values of K_3 are included in each table. The mean value of K_3 is the arithmetic average for each K_3 determined in the individual runs. The combined data K_3 value also shown in each table represents the value of K_3 which is obtained when

Table 26. Results of series "D" tests showing variation in head loss with time of filtration when distilled water was filtered at 5·60 ml/sec through two weights of C-535 precoat using the K_3 filter

Time of filtration, min	Head loss through* 3 grams precoat	Head loss through* 5 grams precoat
0	3.4	6.5
5	3.4	6.6
10	3.6	6.7
15	3.6	6.9
20	3.6	7.0
25	3.7	7.0
30	3.8	7.1
35	3.9	7.1
40	4.0	7.3
45	4.1	7.4

*Head loss in inches of manometer fluid at 20°C.

all the data collected from all runs with a given water are combined to produce a single curve of head loss versus the product of discharge and precoat weight as shown in Fig. 16. The variation in the value of K_3 has been discussed previously on page 74.

Table 27. Results of series "D" tests using Celite-535 in the determination of K_3 using the K_3 filter

Precoat weight, gms	Time of filtration min	Discharge, Q, ml/sec	Head loss,* h, inches	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
6	0	5.60	7.5	0.52
		4.50	6.0	
		3.35	4.4	
		2.25	3.0	
		1.13	1.5	
6	10	5.60	7.5	0.52
		4.50	6.1	
		3.35	4.4	
		2.25	3.0	
		1.13	1.6	
6	20	5.60	7.6	0.53
		4.50	6.1	
		3.35	4.4	
		2.25	3.1	
		1.13	1.6	
6	30	5.60	7.6	0.54
		4.50	6.2	
		3.35	4.5	
		2.25	3.1	
		1.13	1.6	

*Head loss in inches of manometer fluid at 20°C.

Table 28. Results of series "E" tests using Celite-535 with distilled water in determination of K_3 using the K_3 filter, November 7, 1963

Precoat weight, W gms	Discharge Q, ml/sec	Product of Q · W gm x ml/sec	Head* loss, h inches	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
3	5.60	16.80	4.10	0.535
	4.50	13.50	3.30	
	3.35	10.05	2.40	
	2.25	6.75	1.60	
	1.13	3.39	0.80	
4	5.60	22.4	5.40	0.538
	4.50	18.0	4.50	
	3.35	13.40	3.20	
	2.25	9.00	2.10	
	1.13	4.50	1.10	
5	5.60	28.00	6.54	0.523
	4.50	22.50	5.20	
	3.35	16.75	3.60	
	2.25	11.25	2.60	
	1.13	5.65	1.30	
			Mean	0.532
Combined Data (Fig. 16)				0.530

---

*Head loss in inches of manometer fluid at 20°C.

Table 29. Results of series "E" tests using Celite-535, with Ames tap water in determination of K_3 using the K_3 filter, November 11, 1963

Precoat weight, W gms	Discharge Q, ml/sec	Product of Q • W gm x ml/sec	Head* loss, h inches	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
3	5.60	16.80	4.5	0.576
	4.50	13.50	3.6	
	3.35	10.05	2.5	
	2.25	6.75	1.7	
	1.13	3.39	0.8	
4	5.60	22.40	5.9	0.580
	4.50	18.00	4.7	
	3.35	13.40	3.5	
	2.25	9.00	2.3	
	1.13	4.52	1.1	
6	5.60	33.60	8.3	0.540
	4.50	27.00	6.6	
	3.35	20.10	4.7	
	2.25	13.50	3.1	
	1.13	6.78	1.6	
			Mean	0.565
Combined Data				0.565

---

*Head loss in inches of manometer fluid at 20°C.

Table 30. Results of series "E" tests using Celite-535 with Des Moines tap water in determination of K_3 using the K_3 filter, November 9, 1963

Precoat weight, W gms	Discharge Q, ml/sec	Product of Q • W gm x ml/sec	Head loss,* h inches	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
4	5.60	22.40	5.9	
	4.50	18.00	4.7	
	3.35	13.40	3.3	0.570
	2.25	9.00	2.2	
	1.13	4.52	1.2	
5	5.60	28.00	7.6	
	4.50	22.50	6.0	
	3.35	16.75	4.4	0.580
	2.25	11.25	3.0	
	1.13	5.65	1.4	
			Mean	0.575
Combined Data				0.580

*Head loss in inches of manometer fluid at 20°C.

Tests were conducted to determine the effect of five different waters on values of K_3 of Celite-535. The results obtained with the different waters are summarized in Table 33 and are shown graphically in Fig. 17.

Table 31. Results of series "E" tests using Celite-535 with College tap water in determination of K_3 using the K_3 filter, November 10, 1963

Precoat weight, W gms	Discharge Q, ml/sec	Product of Q · W gm x ml/sec	Head* loss, h inches	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
3	5.60	16.80	4.6	
	4.50	13.50	3.7	
	3.35	10.05	2.6	0.595
	2.25	6.75	1.7	
	1.13	3.39	0.7	
4	5.60	22.40	6.3	
	4.50	18.00	5.0	
	3.35	13.40	3.5	0.616
	2.25	9.00	2.5	
	1.13	4.52	1.3	
6	5.60	33.60	9.5	
	4.50	27.00	7.7	
	3.35	20.10	5.4	0.620
	2.25	13.50	3.6	
	1.13	6.28	1.8	
			Mean	0.610
Combined Data				0.610

*Head loss in inches of manometer fluid at 20°C.

Table 32. Results of series "E" tests using Celite-535 with Ames-Zeolite softened tap water in determination of K_3 using the K_3 filter

Precoat weight, W gms	Discharge Q, ml/sec	Product of Q • W gm x ml/sec	Head* loss, h inches	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
4	5.60	22.40	5.8	
	4.50	18.00	4.5	
	3.35	13.40	3.2	0.555
	2.25	9.00	2.2	
	1.13	4.52	1.1	
5	5.60	28.00	6.6	
	4.50	22.50	5.3	
	3.35	16.75	3.8	0.525
	2.25	11.25	2.7	
	1.13	5.65	1.3	
			Mean	0.540
Combined Data				0.540

*Head loss in inches of manometer fluid at 20°C.

3. Series "F", Results

This series was conducted to find the effect of salt concentration on the permeability of the filter aid used as a precoat. The permeability of the filter aid was measured by determining the K_3 in the K_3 filter as described on page 73 . The results of these tests are tabulated in Tables 34 to 39. In each table, several runs were made with a constant precoat weight in which the concentration of salt in solution

Fig. 15. Determination of the K_3 of diatomite from data collected on the K_3 Filter (Separate data)

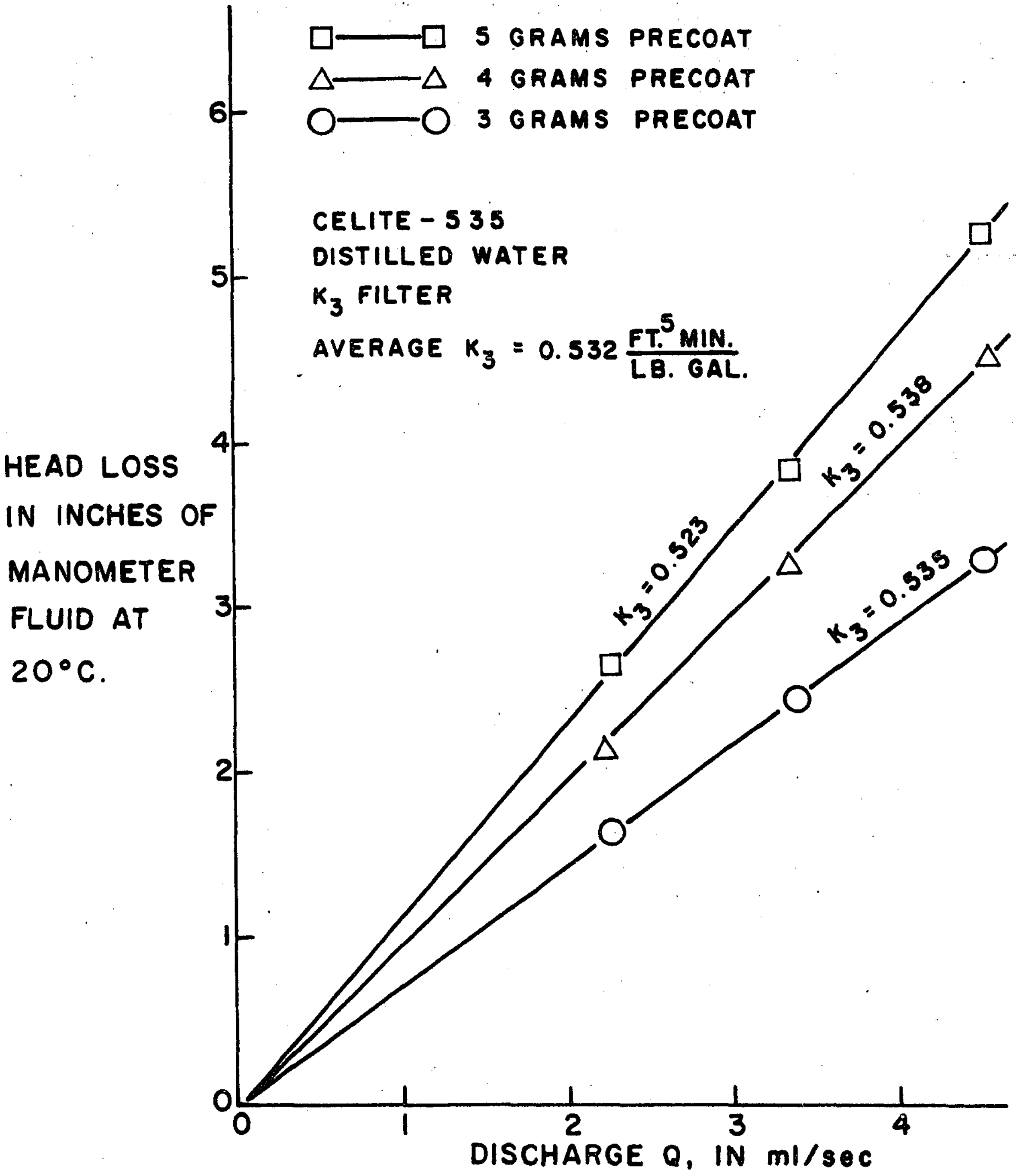

□——□ 5 GRAMS PRECOAT
△——△ 4 GRAMS PRECOAT
○——○ 3 GRAMS PRECOAT
CELITE - 535
DISTILLED WATER
K_3 FILTER
AVERAGE $K_3 = 0.532 \frac{FT.^5 MIN.}{LB. GAL.}$
$K_3 = 0.523$
$K_3 = 0.538$
$K_3 = 0.535$
HEAD LOSS IN INCHES OF MANOMETER FLUID AT 20°C.
0
1
2
3
4
5
6
DISCHARGE Q, IN ml/sec

Fig. 16. Determination of the K_3 of diatomite from data collected on the K_3 Filter (Combined data)

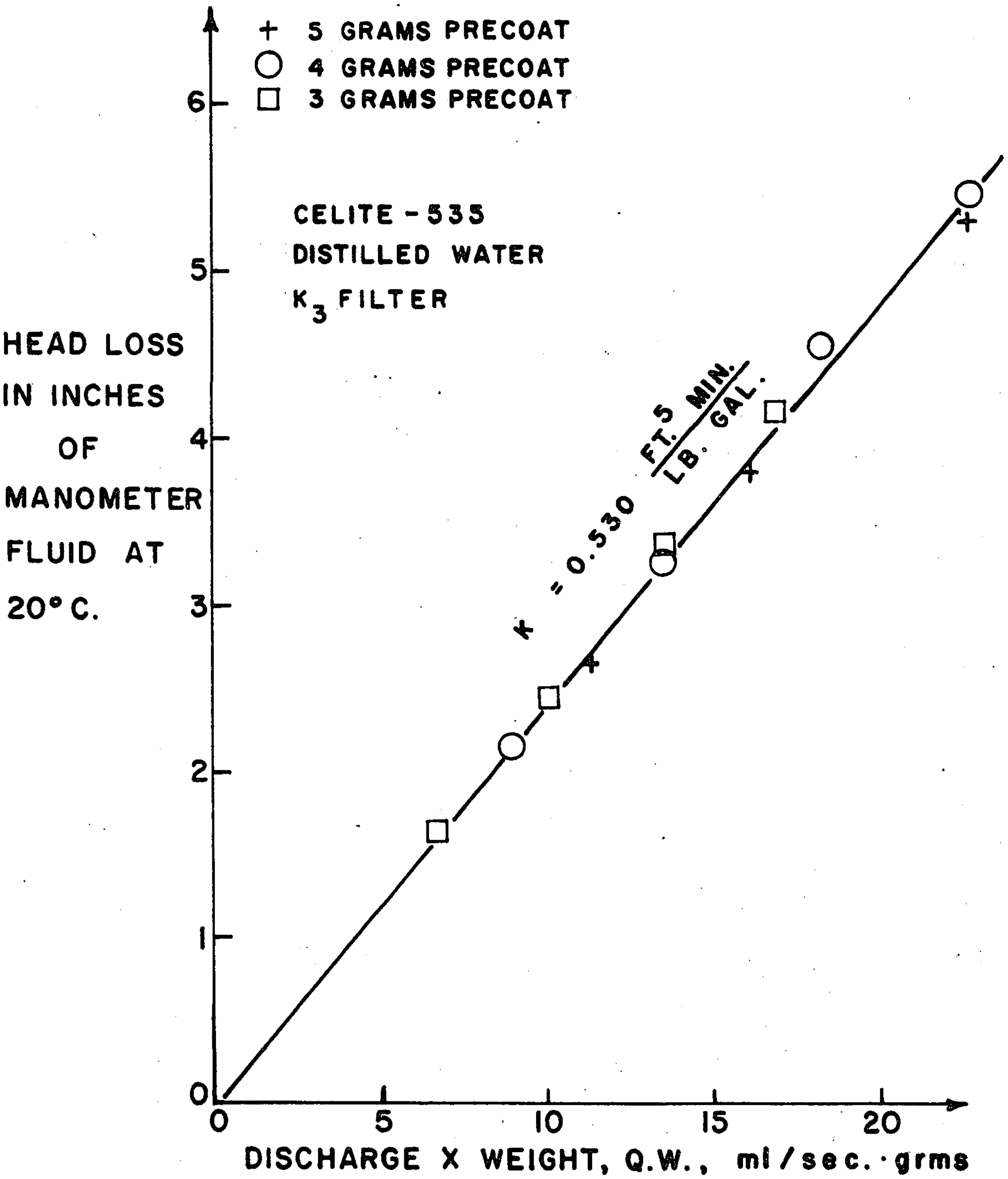

+ 5 GRAMS PRECOAT
○ 4 GRAMS PRECOAT
□ 3 GRAMS PRECOAT
CELITE - 535
DISTILLED WATER
K_3 FILTER
HEAD LOSS IN INCHES OF MANOMETER FLUID AT 20° C.
$k = 0.530 \frac{\text{FT.}^5\text{ MIN.}}{\text{LB. GAL.}}$
0
1
2
3
4
5
6
0
5
10
15
20
DISCHARGE X WEIGHT, Q.W., ml / sec. · grms

Fig. 17. Bar graph showing relative values of K_3 of Celite-535 using different waters at a standard temperature of 20°C

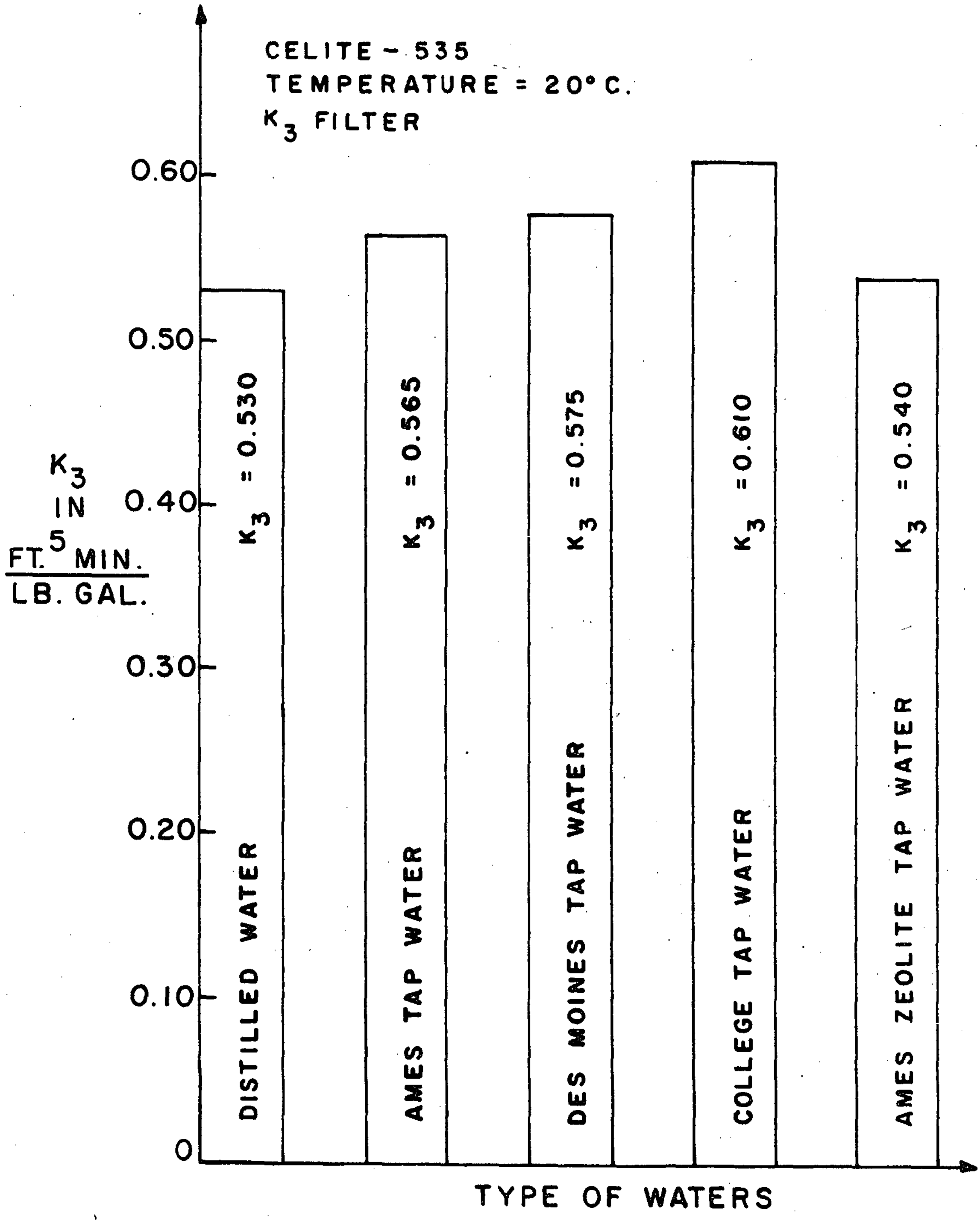

CELITE - 535
TEMPERATURE = 20°C.
K_3 FILTER
K_3 IN $\frac{FT.^5 MIN.}{LB. GAL.}$
0.60
0.50
0.40
0.30
0.20
0.10
0
DISTILLED WATER K_3 = 0.530
AMES TAP WATER K_3 = 0.565
DES MOINES TAP WATER K_3 = 0.575
COLLEGE TAP WATER K_3 = 0.610
AMES ZEOLITE TAP WATER K_3 = 0.540
TYPE OF WATERS

Table 33. Effect of type of water used on the value of K_3 of Celite-535 at a standard temperature of 20°C

Source of water	Table no.	pH	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
Distilled water	28	7.1	0.530
Ames tap water	29	9.6	0.565
Des Moines tap water	30	10.5	0.575
College tap water	31	8.5	0.610
Ames-Zeolite softened tap water	32	7.5	0.540

was increased from run to run (pages 53 - 54). The data for each run were plotted in a typical graph (Fig. 15) and used to determine the value of K_3.

Fig. 18 shows a compilation of all of the data in a single figure which shows the value of K_3 versus the salt concentration. Table 40 shows a summary of where the data are to be found for each salt used in this series.

The results shown in Fig. 18 indicate that the use of water containing KOH, $CaCl_2$ and Na_2SO_4 gave higher values of K_3 than tests conducted with the use of distilled water. With the salt concentrations used, K_3 continues to increase with increasing concentration of salts.

Table 34. Results of series "F" tests using $Al_2(SO_4)_3$ solutions in determination of K_3 of Celite-535 using the K_3 filter

Precoat weight gms	Salt concentration $m \times 10^{-3}$	Discharge Q, ml/sec	Head* loss h inches	K_3 $\frac{ft^5 \cdot min}{lb.gal}$
4	0	5.60	5.3	0.523
		4.50	4.1	
		3.35	3.0	
		2.25	2.0	
		1.13	1.0	
4	1.82	5.60	4.9	0.476
		4.50	3.9	
		3.35	2.9	
		2.25	1.9	
		1.13	0.9	
4	3.64	5.60	4.8	0.470
		4.50	3.8	
		3.35	2.9	
		2.25	1.9	
		1.13	1.0	
4	7.28	5.60	4.9	0.490
		9.50	4.0	
		3.35	2.9	
		2.25	2.0	
		1.13	1.04	
4	14.56	5.60	5.0	0.500
		4.50	4.0	
		3.35	3.0	
		2.25	2.0	
		1.13	1.0	

*Head loss in inches of manometer fluid at 20°C.

Table 35. Results of series "F" tests using $FeCl_3$ solutions in determination of K_3 of Celite-535 using the K_3 filter

Precoat weight gms	Salt concentration m x 10^{-3}	Discharge Q, ml/sec	Head* loss h inches	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
4	0	5.60	5.6	
		4.50	4.4	
		3.35	3.1	0.523
		2.25	2.0	
		1.13	1.1	
4	4.56	5.60	5.10	
		4.50	4.1	
		3.35	2.8	0.480
		2.25	1.9	
		1.13	1.0	
4	13.65**	5.60	5.6	
		4.50	4.4	
		3.35	3.1	0.520
		2.25	2.1	
		1.13	1.1	

*Head loss in inches of manometer fluid at 20°C

**No further solution was added to the tank, due to the distinct formation of a yellow layer on the surface of the cake.

Table 36. Results of series "F" tests using $AlCl_3$ solutions in determination of K_3 of Celite-535 using the K_3 filter

Precoat weight gms	Salt concentration $m \times 10^{-3}$	Discharge Q, ml/sec	Head* loss h inches	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
6	0	5.60	8.4	0.530
		4.50	6.6	
		3.35	4.8	
		2.25	3.3	
		1.13	1.6	
6	2.145	5.60	8.15	0.517
		4.50	6.45	
		3.35	4.72	
		2.25	3.22	
		1.13	1.60	
6	4.29	5.60	8.0	0.500
		4.50	6.3	
		3.35	4.7	
		2.25	3.2	
		1.13	1.5	
6	8.58	5.60	7.40	0.485
		4.50	6.00	
		3.35	4.40	
		2.25	3.04	
		1.13	1.55	
6	14.75	5.60	7.1	0.473
		4.50	5.9	
		3.35	4.4	
		2.25	3.0	
		1.13	1.4	

*Head loss in inches of manometer fluid at 20°C.

Table 37. Results of series "F" tests using Na_2SO_4 solutions in determination of K_3 of Celite-535 using the K_3 filter

Precoat weight gms	Salt concentration $m \times 10^{-3}$	Discharge Q, ml/sec	Head* loss h inches	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
6	0	5.60	8.4	0.530
		4.50	6.8	
		3.35	5.0	
		2.25	3.3	
		1.13	1.7	
6	2.81**	5.60	8.5	0.565
		4.50	6.8	
		3.35	5.1	
		2.25	3.6	
		1.13	1.8	
6	5.62**	5.60	8.5	0.570
		4.50	6.8	
		3.35	5.2	
		2.25	3.7	
		1.13	1.8	
6	11.25***	5.60	8.8	0.590
		4.50	7.0	
		3.35	5.4	
		2.25	3.6	
		1.13	2.0	

*Head loss in inches of manometer fluid at 20°C.

**Cake imperfectly formed (may cause slight decrease in K_3).

***New cake.

Table 38. Results of series "F" tests using Celite-535 with $CaCl_2$ solutions in determination of K_3 using the K_3 filter

Precoat weight gms	Salt concentration m x 10^{-3}	Discharge Q, ml/sec	Head* loss h inches	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
6	0	5.60	8.4	
		4.50	6.8	
		3.35	5.2	0.530
		2.25	3.5	
		1.13	1.8	
6	2.83	5.60	8.2	
		4.50	6.7	
		3.35	5.0	0.552
		2.25	3.4	
		1.13	1.8	
6	5.66	5.60	8.4	
		4.50	6.8	
		3.35	5.2	0.563
		2.25	3.5	
		1.13	1.8	
6	11.32	5.60	8.6	
		4.50	7.0	
		3.35	5.3	0.580
		2.25	3.6	
		1.13	1.9	
6	22.64	5.60	9.8	
		4.50	8.1	
		3.35	6.2	0.663
		2.25	4.4	
		1.13	2.2	

*Head loss in inches of manometer fluid at 20°C.

Table 39. Results of series "F" tests using Celite-535 with KOH solution in determination of K_3 using the K_3 filter

Precoat weight gms	Salt concentration $m \times 10^{-3}$	Discharge Q, ml/sec	Head* loss h inches	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
4	0	5.60	5.6	
		4.50	4.4	
		3.35	3.3	0.52
		2.25	2.2	
		1.13	1.1	
4	4.24	5.60	5.8	
		4.50	4.5	
		3.35	3.3	0.580
		2.25	2.3	
		1.13	1.2	
4	8.48	5.60	6.0	
		4.50	4.7	
		3.35	3.5	0.61
		2.25	2.4	
		1.13	1.3	
4	16.96	5.60	6.5	
		4.50	5.2	
		3.35	3.9	0.790
		2.25	2.7	
		1.13	1.4	

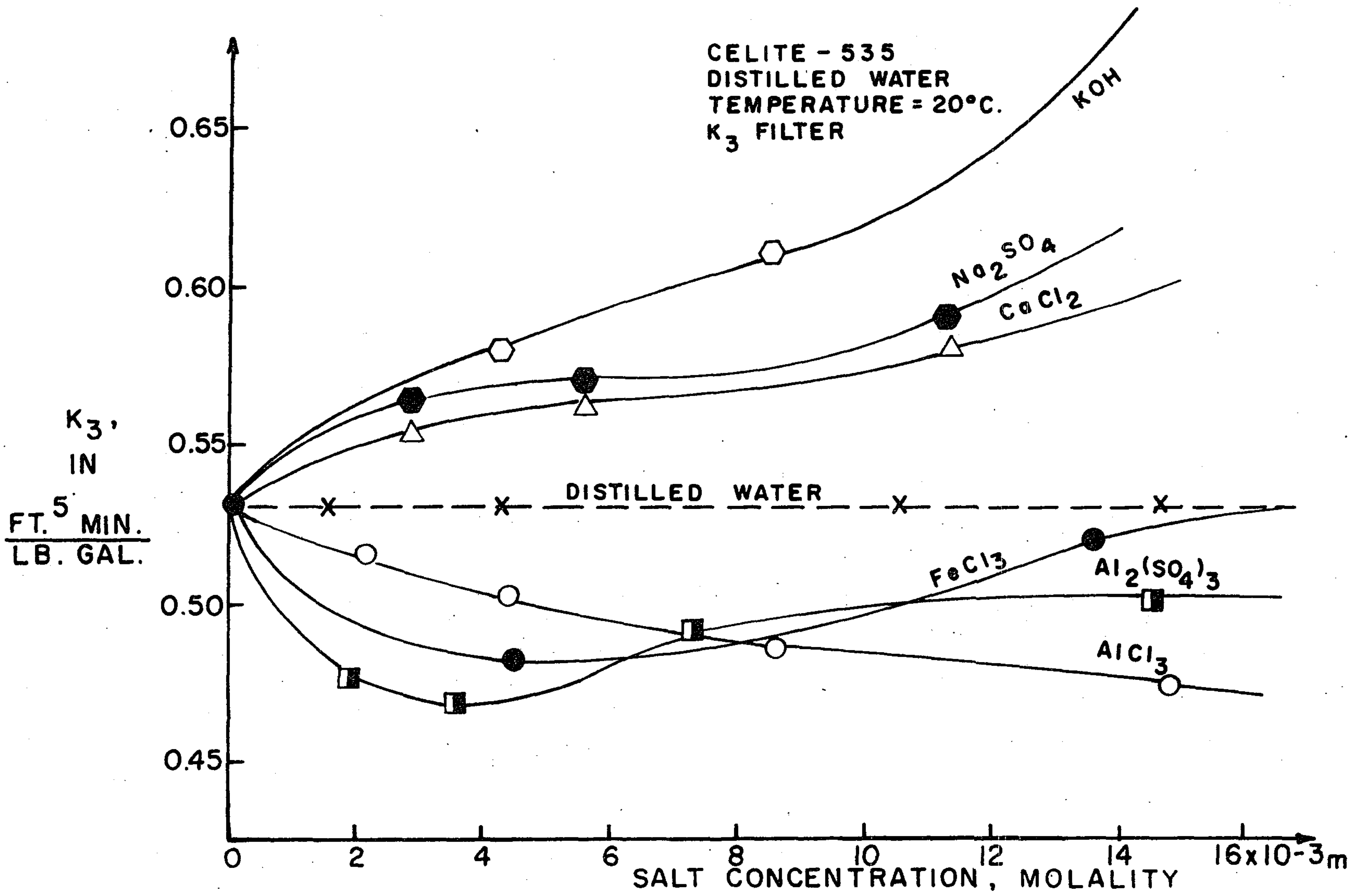
*Head loss in inches of manometer fluid at 20°C.

Table 40. Summary of the tables and figures of the "F" series results conducted with K_3 filter

Salt solution	Results in table no.	Results in fig. no
Aluminum Sulfate	34	18
Ferric Chloride	35	
Aluminum Chloride	36	
Sodium Sulphate	37	
Calcium Chloride	38	
Potassium Hydroxide	39	

The results in Fig. 18 again indicate that the other three chemicals, $Al_2(SO_4)_3$, $FeCl_3$, and $AlCl_3$ gave smaller values of K_3 than tests conducted with the use of distilled water. However, with $Al_2(SO_4)_3$, the K_3 values started to increase from its lowest value of 0.470 $\frac{ft^5 \cdot min}{lb \cdot gal}$ at a salt concentration of about 4×10^{-3}m to 0.5000 $\frac{ft^5 \cdot min}{lb \cdot gal}$ at a salt concentration of about 15×10^{-3}m, then levels off. But with $FeCl_3$, the K_3 value reaches its minimum of $K_3 = 0.480 \frac{ft^5 \cdot min}{lb \cdot gal}$ at about 5×10^{-3}m, then increases with the increase of salt concentration to about that of distilled water of

Fig. 18. K_3 values of Gelite-535 in standard units versus salt concentration at standard temperature of 20°C (from data collected on the K_3 filter)


CELITE - 535
DISTILLED WATER
TEMPERATURE = 20°C.
K_3 FILTER
KOH
Na_2SO_4
$CaCl_2$
DISTILLED WATER
$FeCl_3$
$Al_2(SO_4)_3$
$AlCl_3$
K_3, IN $\frac{FT.^5 MIN.}{LB. GAL.}$
0.65
0.60
0.55
0.50
0.45
0
2
4
6
8
10
12
14
16×10^{-3}m
SALT CONCENTRATION, MOLALITY

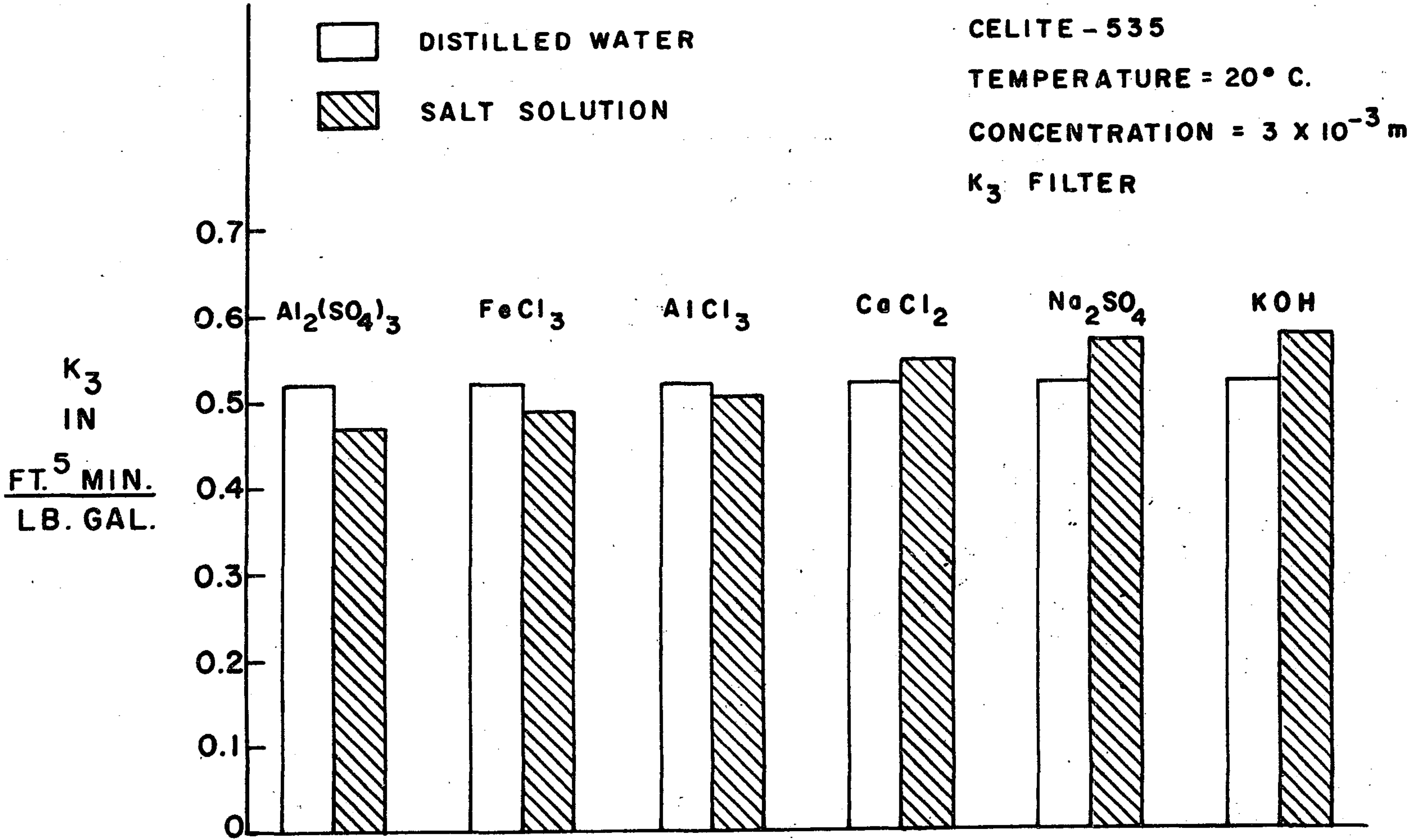
$K_3 = 0.520 \frac{ft^5 \cdot min}{lb \cdot gal}$.

A typical range of K_3 values obtained with a standard salt concentration of 3×10^{-3} m is shown in Table 41 and in Fig. 19. These values were obtained by reading the appropriate K_3 values from Fig. 18 at the above salt concentration.

Table 41. Relative values of K_3 of Celite-535 using different chemical solutions at a fixed concentration and a temperature of 20°C

Solutions	Concentration $m \times 10^{-3}$	Concentration ppm	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
$Al_2(SO_4)_3$	3	1000	0.470
$FeCl_3$	3	485	0.485
$AlCl_3$	3	400	0.508
Distilled water			0.520
$CaCl_2$	3	334	0.555
Na_2SO_4	3	427	0.565
KOH	3	170	0.575

Fig. 19. Bar graph showing relative K_3 values of Celite-535 for different electrolyte solutions at a standard concentration of 3×10^{-3}m (using the K_3 filter)


DISTILLED WATER
SALT SOLUTION
CELITE - 535
TEMPERATURE = 20° C.
CONCENTRATION = 3 X 10^{-3} m
K_3 FILTER
K_3 IN $\frac{FT.^5 MIN.}{LB. GAL.}$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$Al_2(SO_4)_3$
$FeCl_3$
$AlCl_3$
$CaCl_2$
Na_2SO_4
KOH

VII. DISCUSSION OF TEST RESULTS

A. General

Tests were conducted in this investigation to determine the effect of cations and anions in solution on the permeability of diatomite filter aid. Celite-535 from a single 50 lb. shipment from the Johns-Manville Corporation was selected as the commercial grade of diatomite filter aid used in all tests.

Test runs were conducted with both a Constant Head Permeameter (CHP) and a K_3 filter. Early efforts were directed to making standard permeability determinations using typical CHP apparatus. Then, after publication of the theory of diatomite filtration, the use of the K_3 permeability coefficient was found to offer significant advantages in saving time, material, and providing increased accuracy of test results. As a result, the K_3 filter was designed, built and operated later in this study in the investigation of the effects of dissolved ions on the permeability of diatomite filter aid.

B. CHP Filter Results

All of the electrolytes which were studied in different runs with the CHP filter were found to affect the permeability of the filter aid (Figs. 13 and 14):

1. Some of the chemicals in solution increased the permeability of the filter aid, or decreased the K_3 values, from those observed using distilled water at any time of filtration.

2. Another group of chemicals in solution decreased the permeability of the filter aid, or increased the K_3 values, from those observed with distilled water at any time of filtration.

Now questions may be asked as to how these chemicals affect the filtration results. These observed effects of the salts in solution on the filter cake permeability could be due to one or more of the following reasons:

a. The salts in solution may change the net particle charge with a resulting change in the dispersion of the diatomite particles in the filter cake.

b. The salts in solution may change the nature of the diatomite surface.

c. The salts in solution may change the thickness of the fixed layer of water around each particle of diatomite.

The degree to which the salts which have been studied affect the permeability of filter aid using the CHP filter can be seen in the results of Fig. 14. For example, at a salt concentration of 10×10^{-3}m in Fig. 14, the following chemicals in solution increase the filtration rates and decrease the corresponding values of K_3 from those obtained with distilled water: (arranged in increasing order of their effect on K_3)

$AlCl_3$
$KHCO_3$
$Al_2(SO_4)_3$
Na_2CO_3
$NaCl$
K_2SO_4

Similarly, the following chemicals in solution decrease the filtration rates and increase the corresponding values of K_3 from those obtained with distilled water: (arranged in increasing order of their effect on K_3)

K_2CO_3
$MgSO_4$
$NaHCO_3$
KOH
Na_2SO_4
$NaOH$
$CaCl_2$

Table 42 shows the calculated K_3 values for Celite-535 filter aid when the salt solution filtered has an arbitrary concentration of 10×10^{-3}m.

Table 42. K_3 values of Celite-535 with different electrolyte solutions using the CHP filter and a 5-gram precoat.

Salt solution	Salt concentration		K_3,
	m x 10^{-3}	ppm	$\frac{ft^5 \cdot min}{lb \cdot gal}$
$AlCl_3$	10	1340	0.700
$KHCO_3$	10	1000	0.725
$Al_2(SO_4)_3$	10	3400	0.732
Na_2CO_3	10	1060	0.766
NaCl	10	585	0.775
K_2SO_4	10	1730	0.785
H_2O (distilled)	Standard Value		0.810
K_2CO_3	10	1380	0.815
$MgSO_4$	10	1200	0.835
$NaHCO_3$	10	845	0.930
KOH	10	560	0.945
Na_2SO_4	10	1400	1.060
NaOH	10	400	1.120
$CaCl_2$	10	1100	1.370

C. K_3 Filter Results

Tests conducted with the K_3 filter, basically were divided into three different serieses, namely "D" "E" and "F". The first series of runs, or Series "D", were conducted to determine the reproducibility of the K_3 values as determined under the standard conditions. These results are discussed on page 105.

In the series "E" runs, it was found that different tap waters gave different values of K_3 for a Celite-535. The variation in K_3 values were from $K_3 = 0.530 \frac{ft^5 \cdot min}{lb \cdot gal}$ (for distilled water) to $K_3 = 0.610 \frac{ft^5 \cdot min}{lb \cdot gal}$ (for college tap water) (Table 33). These variation in K_3 values, is most probably be due to the variation in the mineral composition of these waters (Tables 6, 7, and 8).

In the series "F" tests, the effects of several chemicals ($Al_2(SO_4)_3$, $FeCl_3$, $AlCl_3$, Na_2SO_4, $CaCl_2$, and KOH) were investigated on the permeability of Celite-535 used as precoat in the K_3 filter. Figure 18 shows a compilation of the data in a single figure for K_3 values versus salt concentration of all the above mentioned chemicals.

The results in this figure indicate that the K_3 values for Celite-535 determined using solutions up to concentration of 8×10^{-3}m of the above electrolytes will be in the following order: $Al_2(SO_4)_3$, $FeCl_3$, $AlCl_3$, H_2O (distilled water),

$CaCl_2$, Na_2SO_4, and KOH (K_3 values are in increased order). On the other hand, for salts concentrations of 10 x 10^{-3}m and over (Fig. 18), the order of the above chemicals as far as K_3 values are concerned were as follow: $AlCl_3$, $Al_2(SO_4)_3$, $FeCl_3$, H_2O (distilled water), $CaCl_2$, Na_2SO_4, and KOH.

It is interesting to note that the pattern of their order as far as their effects on the K_3 values for Celite-535 are concerned is about the same when comparing with the results found with the CHP filter. An explanation of how these chemicals affect the permeability of filter aid will be included in the next section.

VIII. INTERPRETATION OF TEST RESULTS

The zeta potential of the particles in a filter media will change if an electrolyte solution is passed through the filter media (6, 9). Under a constant pressure, the rate of filtration will also change (9).

Any change in the electrolyte concentration at the surface of the particles in a colloidal suspension may change the ion distribution in the hydrated layer around the particle. As the distribution of the ions changes, the ζ-potential of the particle will also change. The thickness of the hydrated layer depends upon the concentration of the electrolyte (6). An expansion or shrinkage of this hydrated layer will lead to a change in pore space. The well known Debye-Hückel Theory may be applied to estimate the average thickness of the hydrated layer at the surface of a particle. If we assume that the average thickness of the double layer (related to the thickness of the hydrated layer) is d and the ionic strength of the electrolyte solution is μ;

$$d = \frac{K}{\mu\ 1/2} \qquad (6)$$

For water at 25°C, the constant K is equal to 3×10^{-8}cm (5). Therefore, according to this equation, the thickness of the hydrated layer around the diatomite particles may be calculated easily for any electrolyte solution of known concentration. It is apparent in Equation 6 that as the ionic strength (Appendix A) increases, the double layer shrinks in toward the diatomite particle (6). As the ionic strength increases the zeta potential will also tend to fall (5, 6, 9).

According to the Debye-Hückel Theory, the thickness of the hydrated layer around diatomite particles for different electrolyte solutions should be a function of their ionic strength (5). The higher the ionic strength of the electrolyte solution, the smaller will be the thickness of the hydrated layer and the higher will be the permeability of the filter media.

If we compare the different values of K_3 for Celite-535 determined using different concentrations of $AlCl_3$ solutions in the K_3 filter (Table 36), we find that as the ionic strength of the electrolyte solution increased, the permeability of the diatomite also increased and the K_3 values decreased. These results are shown in the Table 43.

Fig. 20 shows a plot of K_3 values in standard units on an arithmetic scale versus the square root of ionic strength for ($AlCl_3$) solution on a logarithmic scale. This relationship between K_3 and ionic strength is linear whether the plot is for K_3 values versus square root of ionic strength, μ 1/2, or if it is for K_3 values versus the reciprocal of the square root of ionic strength, $\mu^{-1/2}$, as appeared in the Debye-Hückel

Table 43. Effect of the ionic strength of solutions of $AlCl_3$ on the values of K_3 of Celite-535 using the K_3 filter

Precoat weight gms	Salt concentration $m \times 10^{-3}$	(Ionic strength)$^{1/2}$ $\mu^{1/2}$	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
6	0.000	0	0.530
	2.145	0.1135	0.517
	4.290	0.1604	0.500
	8.580	0.2269	0.485
	14.750	0.2975	0.473

equation. These results would seem to indicate the change in K_3 is due to the fact that increasing salt concentrations reduce the thickness of the double layer.

On the other hand, increasing the concentration of some electrolytes (increasing the ionic strength-Appendix A) will decrease the permeability of the filter media contrary to what will be predicted from the Debye-Hückel equation. For example, if we consider the K_3 values of Celite-535 determined using solutions of ($NaHCO_3$) at different ionic strengths (Table 24), we find that, as the ionic strength of the electrolyte solution increased, the permeability of the diatomite decreased and consequently the K_3 values increased. These results are tabulated in Table 44.

Fig. 20. Effect of the ionic strength of solutions of $AlCl_3$ on the values of K_3 of Celite-535 using the K_3 filter, 20°C

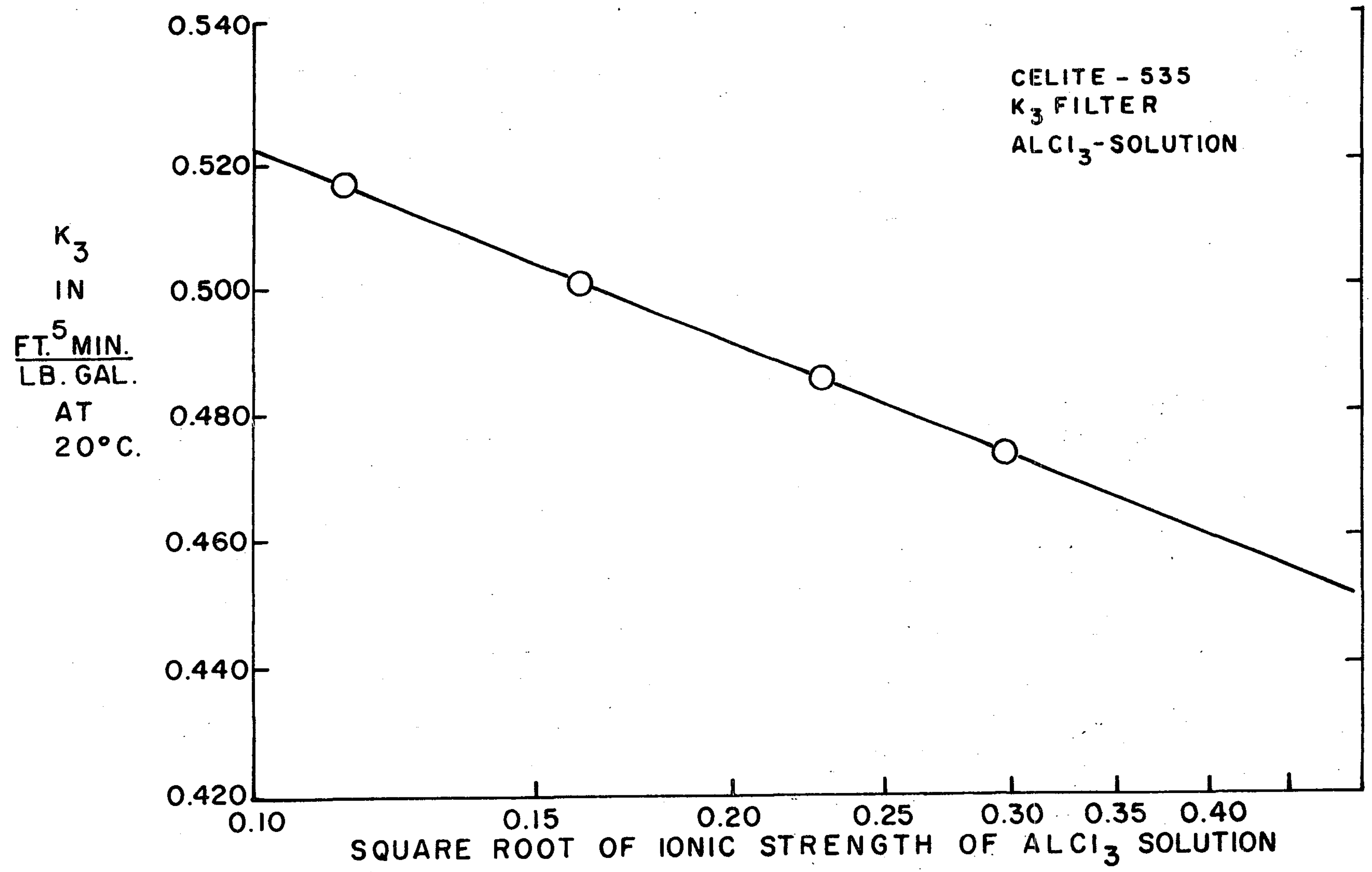

CELITE - 535
K_3 FILTER
$AlCl_3$-SOLUTION
K_3 IN $\frac{FT.^5 MIN.}{LB. GAL.}$ AT 20°C.
0.540
0.520
0.500
0.480
0.460
0.440
0.420
0.10
0.15
0.20
0.25
0.30
0.35
0.40
SQUARE ROOT OF IONIC STRENGTH OF $AlCl_3$ SOLUTION

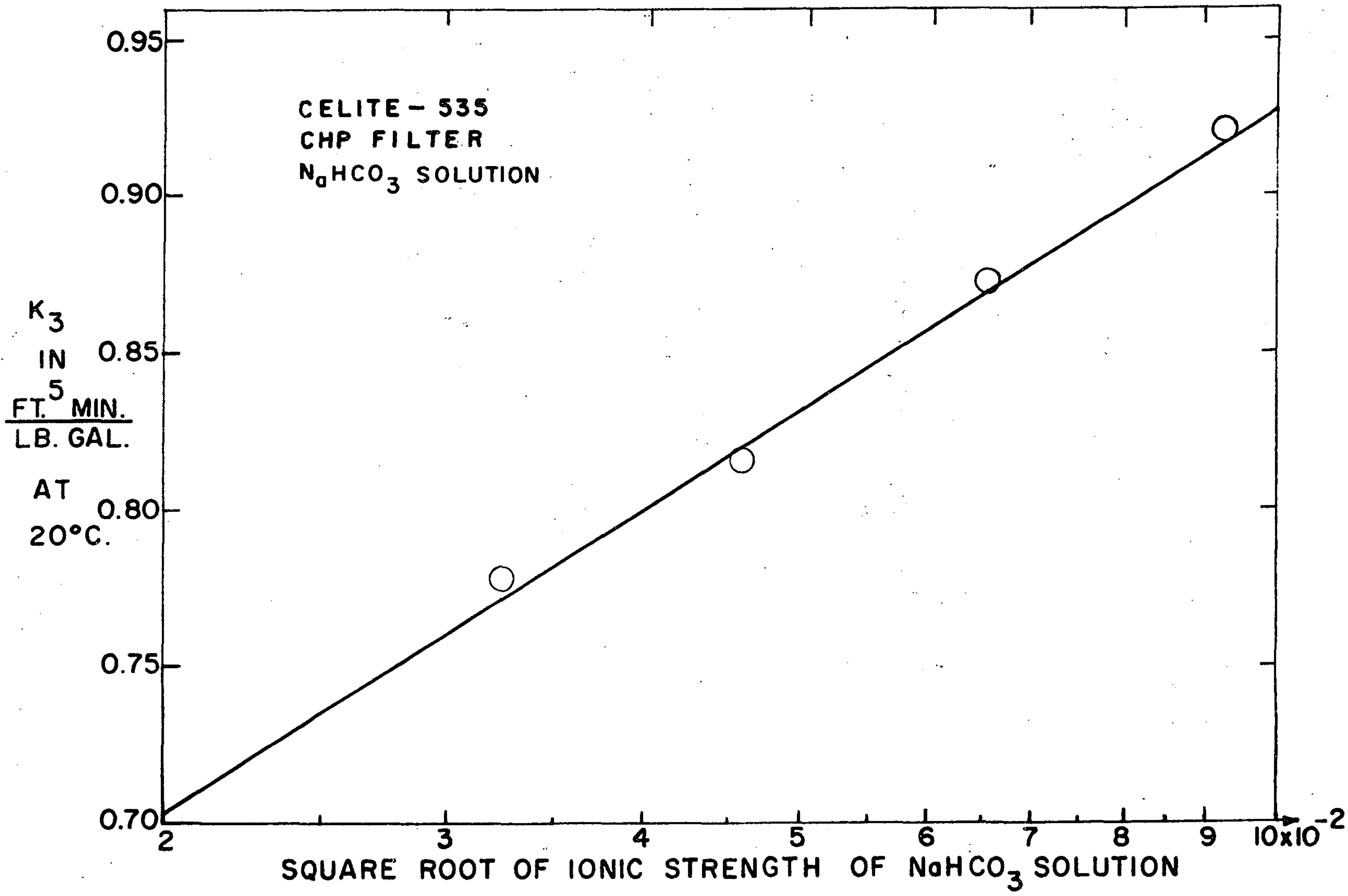
Table 44. Effect of the ionic strength of solutions of $NaHCO_3$ on the value of K_3 of Celite-535 using the CHP filter, at 20°C

Precoat weight gms	Salt concentration $m \times 10^{-3}$	(Ionic strength)$^{1/2}$ $\mu^{1/2}$ $\times 10^{-2}$	K_3 $\frac{ft^5 \cdot min}{lb \cdot gal}$
5	0	0	0.745
	1.06	3.26	0.777
	2.12	4.60	0.815
	4.24	6.51	0.873
	8.48	9.21	0.920

Fig. 21 shows the variation of K_3 of Celite-535 on an arithmetic scale versus the square root of ionic strength of different solutions of ($NaHCO_3$) on a logarithmic scale. Again, we find the relationship between K_3 and ionic strength is straight line, but in a direction opposite to what would be predicted by the Debye-Hückel Theory.

Another explanation of the observations resulting from this study is that based on the concepts explaining the formation of the hydrate envelope around diatomite particles. The hydrate envelope refers to the layer of oriented molecules of water situated next to the diatomite particles. The following layers, at an increasing distance from the diatomite particles, lose their orientation and pass into ordinary water.

Fig. 21. Effect of the ionic strength of solutions of $NaHCO_3$ on the values of K_3 of Celite-535 using the CHP filter, 20°C


CELITE – 535
CHP FILTER
Na_aHCO_3 SOLUTION
K_3 IN $\frac{FT.^5 MIN.}{LB. GAL.}$ AT 20°C.
0.95
0.90
0.85
0.80
0.75
0.70
2
3
4
5
6
7
8
9
10x10^{-2}
SQUARE ROOT OF IONIC STRENGTH OF $NaHCO_3$ SOLUTION

Thus, near the diatomite particle there is a firmly bound layer of adsorptional water and a diffuse layer of loosely bound water. The degree of hydration of the diatomite particles, or the amount of bound water associated with the diatomite particle, depends on the magnitude of the particle charge, the condition of the particle surface and also the nature and properties of the adsorbed ions.

As the valency of the cation becomes greater, the diffusional layer is compressed and the size of the hydration envelope decreases. As a result, it will increase the pore space available for free passage for water. Therefore, we would expect higher flow rates through diatomite precoat from filtering solutions of aluminum and ferric salts than from solutions of calcium, sodium, or potassium salts. In fact, this concept seems to be confirmed generally by the data collected on the K_3 filter. The K_3 filter tests results indicate that the value of K_3 of Celite-535 will be in the following order of magnitude when solutions incorporating the listed cations are used to determine filter aid impermeability (Fig. 18):

$$K^+ > Na^+ > Ca^{++} > H^+ \text{ (distilled water)} > Fe^{+++} > Al^{+++}.$$

Of interest here is the work of other investigators in their study of the effect of the type of adsorbed ions on aqueous films and on the water retaining capacity of Clay (14).

Although clay is different from diatomite, there is a great deal of similarity between their mineral analyses. The only significant variation is in relatively minute differences in the two groups (13, 14).

The materials studied by these investigators, were Chasov Yar (CY) Clay and Prosyamov (P) Kaolin. In their investigation of the effect of the nature of the absorbed cations on the amount of water retained in aqueous films in clay masses under different pressures, they prepared Na^+, Ca^{++}, Al^{+++} and H^+ clays. The results of their experiments are shown in Fig. 22 and Fig. 23 which show the relationships between applied pressure and the content of residual water in the specimens after the clay samples were compressed under increasing external pressures. The test results indicate that the higher the valency of the cation (hydrogen is an exception) the lower will be pressure at which the region of constant moisture content is found. From their results, it has been found that, as the valency of the cation becomes greater, the diffusional layer is compressed and the size of the hydration envelope decreases.

Under constant pressure, the amount of water held by 1 gram of clay is greatest when the clay is saturated with Na^+ cations and least when it is saturated with Al^{+++} cations (Fig. 22). In general, the cations saturating clay may be arranged in the following series showing decreasing (from left

Fig. 22. Amount of water held by CY-Clay in relation to the pressure and the nature of the exchange cation (14, page 87)

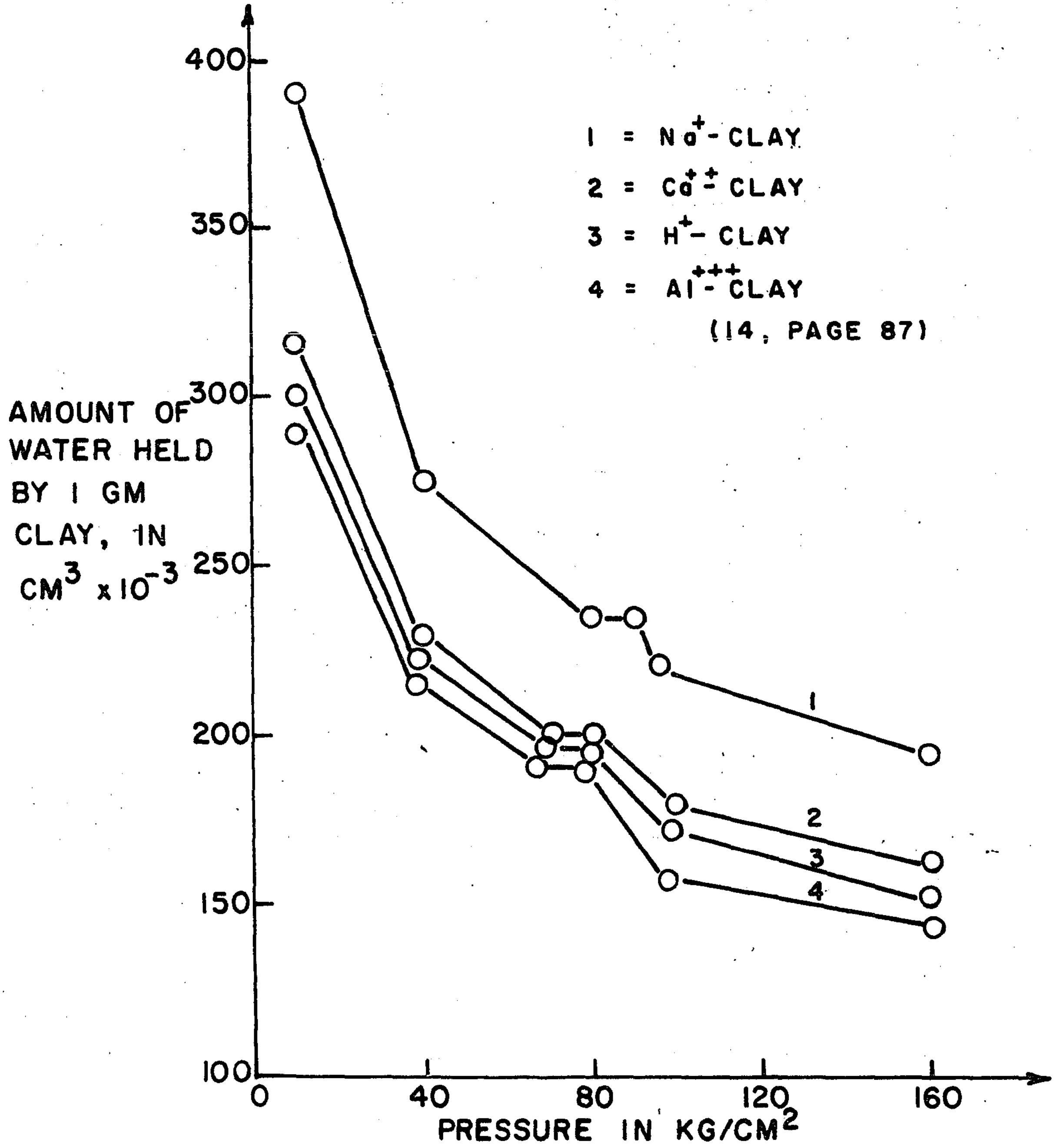
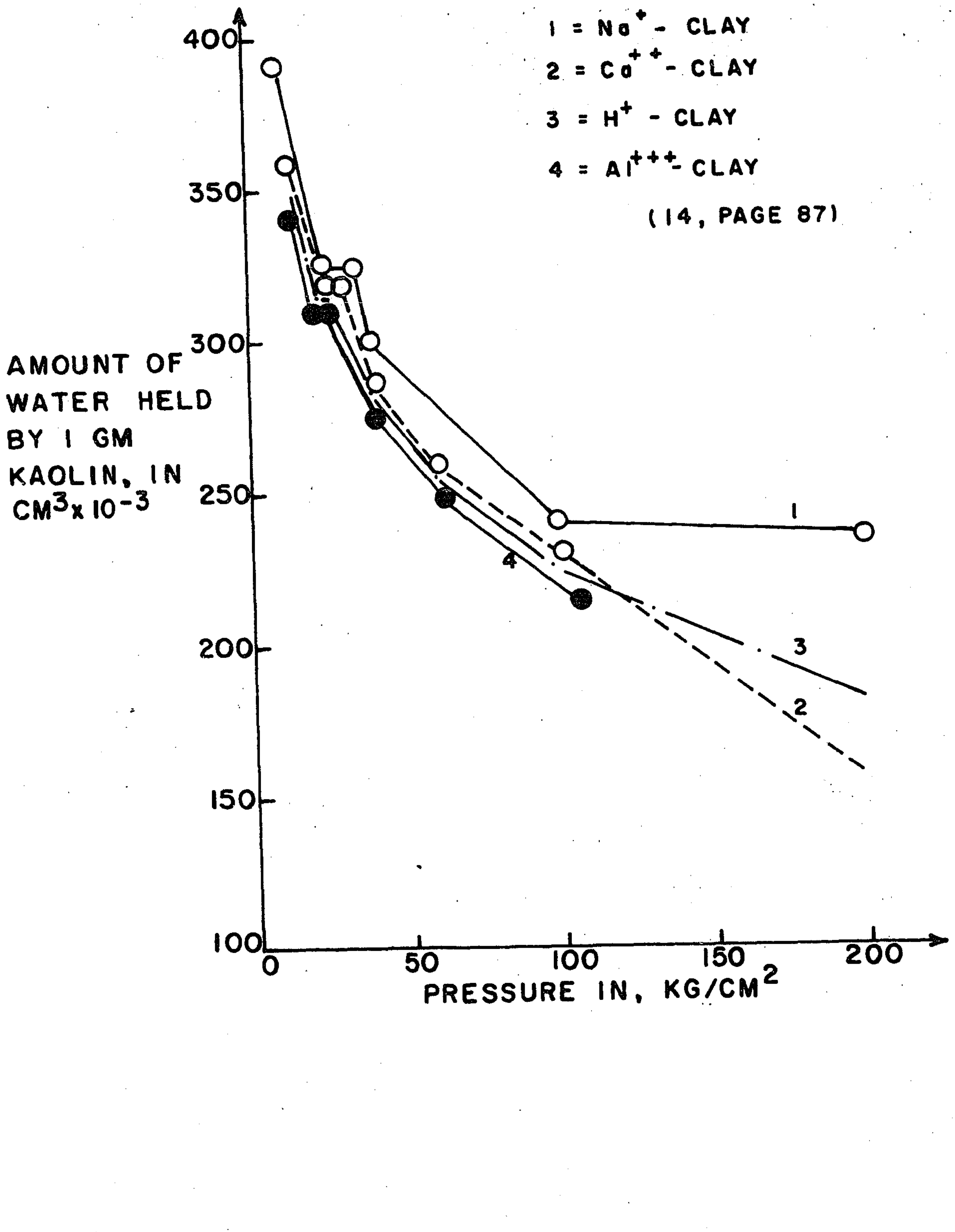

1 = Na⁺-CLAY
2 = Ca⁺⁺-CLAY
3 = H⁺-CLAY
4 = Al⁺⁺⁺-CLAY
(14, PAGE 87)
AMOUNT OF WATER HELD BY 1 GM CLAY, IN CM³ x 10⁻³
400
350
300
250
200
150
100
0
40
80
120
160
PRESSURE IN KG/CM²
1
2
3
4

Fig. 23. Amount of water held by P-Kaolin in relation to the pressure and the nature of the exchange cation (14, page 87)


1 = Na⁺ - CLAY
2 = Ca⁺⁺ - CLAY
3 = H⁺ - CLAY
4 = Al⁺⁺⁺ - CLAY
(14, PAGE 87)
AMOUNT OF WATER HELD BY 1 GM KAOLIN, IN CM³ x 10⁻³
400
350
300
250
200
150
100
0
50
100
150
200
PRESSURE IN, KG/CM²
1
2
3
4

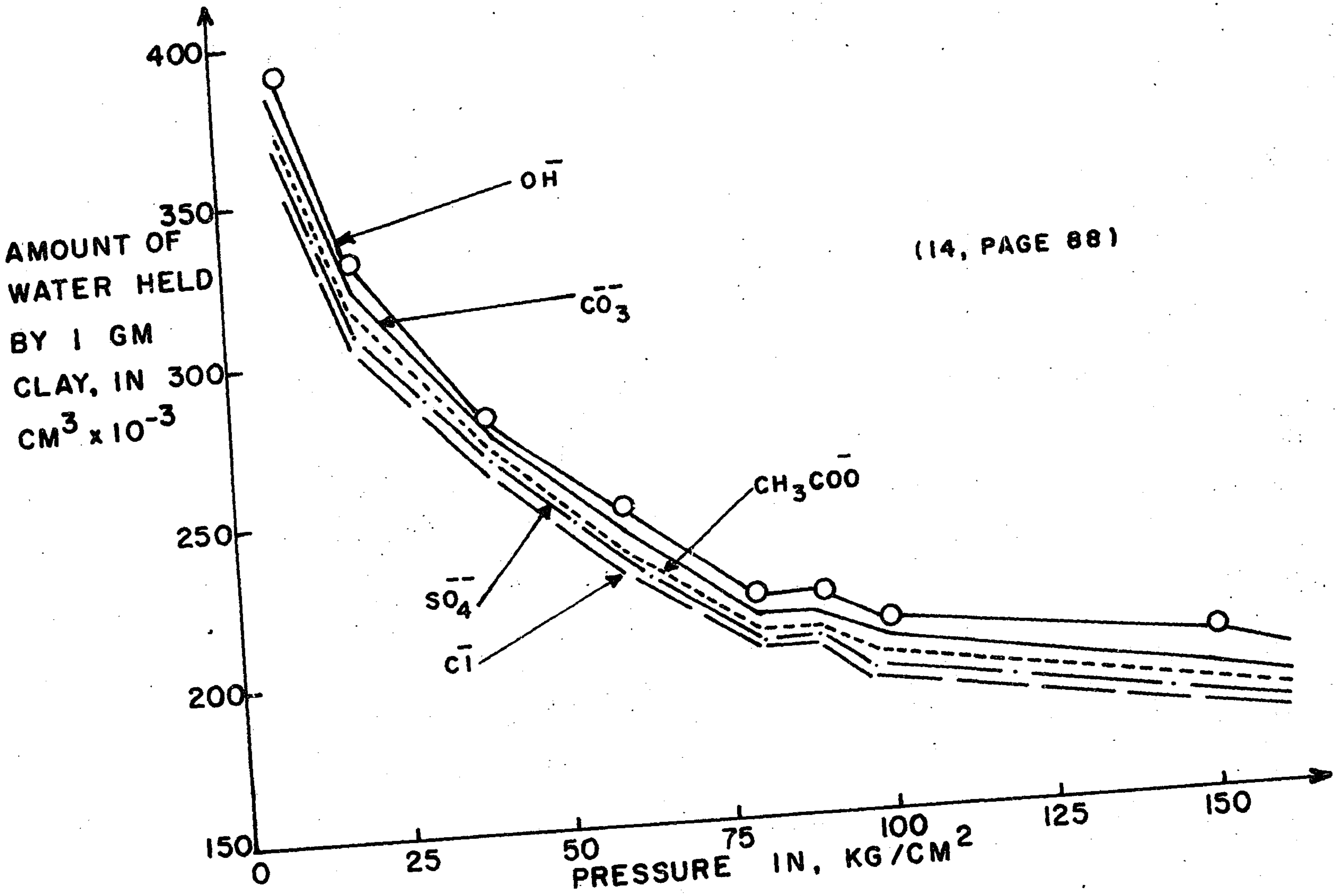
to right) amounts of water held by the clay: $Na^+ > Ca^{++} > H^+ > Al^{+++}$ for CY-Clay (Fig. 22) and $Na^+ > Ca^{++} > H^+ > Al^{+++}$ for P-Kaolin (Fig. 23) for pressures of less than 120 Kg/cm^2. For pressures greater than 120 Kg/cm^2, the order was $Na^+ > H^+ > Ca^{++} > Al^{+++}$ (Fig. 23) for P-Kaolin.

The results obtained in this study on the effect of cations on the amount of water held by the diatomite particle gave the same order with both the CHP filter and the K_3 filter. In decreasing order of the K_3 values of Celite-535, the cations were as follows: $Na^+ > Ca^{++} > H^+$ (distilled water) $> Al^{+++}$ (Fig. 18).

In a similar manner, the Russians studied (14) the effect of the adsorbed anions on the amount of water held by 1 gram of clay. The anions produced results in the following order according to decreasing amounts of water held by 1 gram of clay under constant pressure (Fig. 24): $OH^- > CO_3^{--} > CH_3COO^- > SO_4^{--} \geq Cl^-$. These results indicate that the greatest amount of water is held by clay in the adsorption of OH^- ions.

In this study, the effect of the anions on the amount of water held by a diatomite particle can be shown (Table 42). One method of making such a comparison would be to show the variation in K_3 when the same molal concentration of different sodium salts is used in the test apparatus. For example, the following results are extracted from Table 42:

Fig. 24. Amount of water held by Na-clay in relation to the pressure and nature of the anion (14, page 88)


AMOUNT OF WATER HELD BY 1 GM CLAY, IN CM^3 x 10^{-3}
400
350
300
250
200
150
0
25
50
75
100
125
150
PRESSURE IN, KG/CM^2
$O\bar{H}$
$C\bar{\bar{O}}_3$
$CH_3CO\bar{O}$
$S\bar{\bar{O}}_4$
$C\bar{l}$

(14, PAGE 88)

Salt	Concentration $m \times 10^{-3}$	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
Na_2CO_3	10	0.766
NaCl	10	0.775
$NaHCO_3$	10	0.930
Na_2SO_4	10	1.060
NaOH	10	1.120

Thus, the effect of the anion (in order of decreasing effect of the sodium salts on the value of K_3) would be in the following order: $OH^- > SO_4^{--} > HCO_3^- > Cl^- > CO_3^{--}$. Here, the CO_3^{--} appears to be out of place. In a similar manner, the effect of the anion in potassium salts was in the following order (Table 42): $OH^- > CO_3^{--} > SO_4^{--} > HCO_3^-$. These results do not indicate any departures from the trends reported by others (14).

We can conclude, therefore, that the different salt concentrations will result in the retention of different thicknesses of the bound water layer around the diatomite particles in the filter cake. The cations and anions will increase the K_3 of a filter cake due to changes in pore space available for flow in the following order:

Cation order	Anion order	K_3
Al^{+++}	Cl^-	lowest
Fe^{+++}	HCO_3^-	
H^+	SO_4^{--}	
Ca^{++}	CO_3^{--}	
Na^+	OH^-	
K^+		highest

IX. SUMMARY

A. Constant Head Permeameter

The K_3 value of diatomite filter aids, a measure of filter cake impermeability, can be determined by making a run filtering distilled water containing no suspended solids and no body feed through a thick layer of precoat. Using a constant head permeameter, the head loss is held constant and, Q, the rate of flow is observed through various weights of precoat.

The data collected can be plotted to show head loss through the precoat diatomite in feet of water, h, versus QW_1. Since

$$h_1 = K_3 Q W_1, \qquad (7)$$

the slope of the straight line drawn through the origin and the data collected with the CHP filter will represent the value of K_3.

Using five grams of Celite-535 filter aid as precoat, the K_3 value at 20°C changes from $K_3 = 0.600 \frac{ft^5 \cdot min}{lb \cdot gal}$ to $K_3 = 0.880 \frac{ft^5 \cdot min}{lb \cdot gal}$ during three hours of filtration, an increase of 47 per cent (Table 9). Using ten grams of precoat, the K_3 value changes from 0.595 to 0.730 $\frac{ft^5 . min}{lb \cdot gal}$ in three hours of filtration, a variation of 23 per cent

(Table 10).

The preliminary results indicated two things:

1. The weight of precoat will affect the K_3 value calculated using results determined with the CHP apparatus. It was observed that the K_3 value of 10 grams of precoat was slightly smaller than the K_3 value of 5 grams of precoat under exactly the same conditions (Tables 9 and 10).

2. The rate of flow through the CHP filter was observed to decrease (with an increase in K_3) with time (Fig. 9). However, tests made under exactly similar conditions indicated that the change in K_3 with time was always similar and the comparison of K_3 values determined with different qualities of water could be made, if the comparison was made always after the same period of filtration. All K_3 comparisons using different waters with the CHP apparatus were made using 5 grams of precoat and after equal periods of filtration.

Although the K_3 values are not identical with the K_3 values determined with the K_3 filter, they can be used to demonstrate the qualitative effects of solutions of various salts on the K_3 impermeability coefficient of diatomite. (The CHP filter will give a slightly higher value of K_3 than the K_3 filter with the same water).

In Series "A" runs, increasing concentrations of electrolyte solutions were added to the distilled water in the system at the end of one hour filtration with distilled water and every fifteen minutes thereafter. The rate of flow through the precoat was determined with distilled water at the end of one hour of filtration and with the solutions of the electrolyte 15 minutes after the addition of the electrolyte. The value of K_3 was determined with each concentration of electrolyte (Tables 12 to 25).

In these tests, the following salts in solution were found to increase the filtration rates and decrease the corresponding K_3 values over those obtained with distilled water: (In increasing order of K_3) $AlCl_3$, $Al_2(SO_4)_3$, $KHCO_3$, Na_2CO_3, NaCl and K_2SO_4 (Fig. 13 and Fig. 14). Similarly, the following salts were found to decrease the filtration rates and increase the corresponding K_3 values over those obtained with distilled water: (in increasing order of K_3) K_2CO_3, $MgSO_4$, $NaHCO_3$, KOH, Na_2SO_4, NaOH and $CaCl_2$ (Fig. 13 and Fig. 14).

The test results with the CHP filter served to indicate qualitatively and quantitatively the role which different chemical solutions will play in affecting the K_3 value of filter aid as determined with the CHP filter. However, initial experience with the CHP filter indicated that it had several basic inadequacies in design:

1. The large volume of distilled water required, 15 gallons, was difficult to prepare of consistent quality. Relatively large amounts of chemicals were required. The

large storage container and constant head tank offered significant opportunity for dust and other contaminants to enter the system.

2. With 5 grams of precoat and a constant head of 4.65 feet of water, the flow rate initially was about 28 gpm/sq ft and decreased with time. This flow rate is approximately 10-30 times the flow rate which would normally be used through a diatomite precoat. Thus, the filter cake was more compacted and gave higher values of K_3 than would be obtained in normal filtration practice.

3. From four to five hours was required to complete each test, and the results of K_3 with each salt concentration had to be based on the slope of a straight line through the origin and one additional point.

In view of possible errors which might result from these causes, a record apparatus, the K_3 filter, was used to collect similar data to verify the results from the CHP filter.

B. K_3 Filter

The use of the K_3 filter greatly simplified the determination of K_3 for diatomite filter aid. In each case, the value of K_3 was determined as follows: In successive runs, the apparatus was used to determine the head loss across several weights of precoat when the filtration rate was varied from 1 to about 4 gpm/sq ft. The data were used to make a plot of h_1 versus QW_1 (Fig. 15). The slope of the line through as many as fifteen to twenty points provided a reproducible measure of K_3. The results of K_3 by all methods gave the same results with less than 1 per cent error.

The K_3 apparatus has several distinct advantages over the CHP filter:

1. The volume of water was smaller (7 gallons) and was stored in covered plastic containers.

2. The flow rates used, 1 to 4 gpm/sq ft, were similar to those used in normal diatomite filtration practice.

3. The temperature of the water could be maintained constant through a single run.

4. A complete run using solution of salts took about one half hour.

The series "D" tests were conducted to determine the reproducibility of the results from K_3 filter. All methods of determining quantitative values of K_3 gave similar results. Several runs were made to determine the change in value of K_3 in the K_3 filter after various periods of filtration. The K_3 value through 6 grams precoat was observed to increase from 0.520 to 0.540 $\frac{ft^5 \cdot min}{lb \cdot gal}$ after 30 minutes of continuous filtration at the highest flow rates used in the apparatus. Since all tests were completed in less than this time, the values of K_3 were unaffected by the changes in the cake arrangement with time of filtration.

The series "E" tests were conducted to determine the effect of using several different tap waters for the determination of K_3 value of Celite-535 with the K_3 filter. The value of K_3 as determined with each water may be summarized as follows (Fig. 17):

Types of water	K_3, $\frac{ft^5 \cdot min}{lb \cdot gal}$
(1) Distilled water	0.530
(2) Ames-Zeolite softened tap water	0.540
(3) Ames tap water	0.565
(4) Des Moines tap water	0.580
(5) College tap water	0.610

The mineral compositions of the tap waters are shown in Tables 6 to 8. Since none of these waters contain solids in suspension, the differences in the values of K_3 must be due to the differences in the cations and anions in solution in water. In each case, the value of K_3 was increased using tap water with a maximum increase of about 15 per cent. These waters contain significant concentrations of calcium, sodium and magnesium salts which were found in the K_3 filter to similarly increase the K_3 value of filter aid.

The series "F" tests were used to evaluate the effect of salts in solution on the value of K_3 determined with the K_3

filter. The value of K_3 of the precoat was first determined with distilled water. A solution of salt was added to the water and the solution was then used to determine the K_3 of the same cake.

This series of tests indicated that solution of $Al_2(SO_4)_3$, $FeCl_3$, and $AlCl_3$ will provide a value of K_3 that is smaller than that observed with distilled water. Solutions of Na_2SO_4, $CaCl_2$ and KOH will provide a higher value of K_3 than those obtained for distilled water. These results are almost similar to those obtained with the CHP filter.

Working with the same six chemicals, Oulman (17) reported the following "Ferric and aluminum salts reverse the zeta potential of diatomite from negative to positive, while sodium and magnesium give more negative zeta potential of diatomite than its value when determined with deionized water". In this study, the determination of the K_3 value of C-535 using water containing ferric and aluminum salts in solution provided a lower value of K_3 than the use of distilled water. The use of sodium, calcium and potassium in solution in the water provided a higher value of K_3 than it would have been obtained with distilled water.

X. CONCLUSIONS

As a result of this study, the following conclusions may be drawn:

1. The K_3 filter as described in this thesis may be used to provide a measure of the K_3 impermeability coefficient of diatomite filter aids. The K_3 impermeability coefficient represents a hydraulic characteristic of filter aids in the following equation:

$$h_1 = K_3 Q W_1 \tag{7}$$

where

h_1 = head loss through the precoat diatomite in feet of water
Q = rate of flow (gpm/ft^2)
W_1 = weight of precoat (lb/ft^2)
K_3 = permeability coefficient for the clean precoat ($ft^5 \cdot min/lb \cdot gal$)

2. For comparison between laboratories, the value of K_3 should always be determined using distilled water. Tests using 4 typical hard and softened well waters indicated that K_3 value of Celite-535 would vary as much as 15 per cent from the value obtained with distilled water.

3. The presence of various cations and anions affect the thickness of the hydrated layer of bound water around the

particles of diatomite in the precoat. Thus, the amount of pore space available for flow will be changed as the cations and anions in the solution change and will change the permeability of the filter aid. The thickness of the hydrated layer may be changed by a factor of up to 100 times when salts are added to distilled water (6).

4. Tests with various salt solutions in this study indicated that with a salt molality of 10 x 10^{-3} the value of K_3 could be decreased by as much as 14 per cent or increased by as much as 69 per cent (Table 42).

5. The presence of cations and anions will increase the K_3 of a filter cake due to changes in pore space available for flow in the following order:

Cation order	Anion order	K_3
Al^{+++}	Cl^-	lowest
Fe^{+++}	HCO_3^-	
H^+	SO_4^{--}	
Ca^{++}	CO_3^{--}	
Na^+	OH^-	
K^+		highest

XI. RECOMMENDATIONS

The author wishes to make two recommendations:

1. Use K_3 filter to evaluate the quantitative effects of dissolved cations and anions in both natural and laboratory prepared water on the permeability of a diatomite filter aid.

2. In trying to explain discrepancies of filtering results under similar conditions in various parts of the country, investigators should consider the effect of cations and anions on the thickness of the hydrated layer of bound water around the particles of diatomite in the precoat and the resulting effect on the filter aid permeability.

XII. BIBLIOGRAPHY

1. Baumann, E. R. A study of the effect of mechanical compression on the particle size and permeability of diatomite filter aids. Section D of final report to Engineer Research and Development Laboratories, Fort Belvoir, Virginia, contract W-44-009 eng. 453. University of Illinois, Department of Civil Engineering, Division of Sanitary Engineering. [Mimeographed report.] Urbana, Illinois. 1950.

2. Baumann, E. R. The design and operation of diatomite precoat filters for water. Unpublished Ph.D. thesis. Urbana, Illinois, Library, University of Illinois. 1954.

3. Baumann, E. R., Cleasby, J. L. and LaFrenz, R. L. A theory of diatomite filtration. Journal of the American Water Works Association 54: 1109-1119. 1962.

4. Baumann, E. R. and LaFrenz, R. L. Optimum economical design for municipal diatomite filter plants. Journal of the American Water Works Association 55: 48-52. 1963.

5. Brey, Wallace S., Jr. Principles of physical chemistry. New York, N. Y., Appleton-Century-Crofts, Inc. 1958.

6. Bull, H. B. and Gortner, R. A. Studies on electrokinetic potentials. VI, Journal of Physical Chemistry 35: 309-330. 1931.

7. Dillingham, J. H. Hydraulic characteristics of some diatomite filter aids. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1963.

8. Gardner, D. G. Effect of certain ion combinations commonly found in potable water on rate of filtration through roasted and ground coffee. Coffee Brewing Institute, Pub. No. 31. March, 1958.

9. Grigorov, O. N. and Novikova, N. A. Filtration capacity and electrokinetic potential of capillary systems. Colloid Journal (U.S.S.R.). In English translation. 17: 259-265. 1955.

10. Hildebrand, Joel H. and Powell, Richard E. Principles of chemistry. Sixth ed. New York, N. Y., The Macmillan Company. 1956.

11. Hodgman, Charles D., Weast, Robert C. and Selby, Samuel M. Handbook of Chemistry and Physics. 37th ed. Cleveland, Ohio, Chemical Rubber Publishing Co. 1955-1956.

12. Hudson, H. E., Jr. Factors affecting filtration rates. Journal of the American Water Works Association 48: 1138-1154. 1956.

13. Johns-Manville Products, Celite Division. Filter aids and mineral filters. DS series 450. The Company. New York, N.Y. (ca. 1952).

14. Kukolev, G. V. and Syrkin, Ya. M. Effect of the type of sorbed ions on the splitting pressure in aqueous films and on the water retaining capacity of clay and kaolin. Colloid Journal (U.S.S.R.) In English translation. 17: 85-91. 1955.

15. LaFrenz, R. L. Design of municipal diatomite filters for iron removal. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1961.

16. Martin, Deward M. and Baumann, E. Robert. A study of several factors affecting the precoat, backwash, and the hydraulic characteristics of a diatomite filter. Section A of final report to Engineer Research and Development Laboratories, Fort Belvoir, Virginia, contract W-44-009 eng. 453. University of Illinois, Department of Civil Engineering, Division of Sanitary Engineering. [Mimeographed report.] Urbana, Illinois. 1950.

17. Oulman, C. S. Streaming potentials in diatomite filtration. Unpublished Ph.D. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1963.

18. Phillips, Eugene, Jr. Recommended practices for the design and operation of diatomite water filters. Unpublished M.S. thesis. Ames, Iowa, Library, Iowa State University of Science and Technology. 1957.

XIII. ACKNOWLEDGMENTS

The author wishes to acknowledge the aid and suggestions of his major professor, Dr. E. Robert Baumann, for his guidance, for providing space, laboratory facilities, materials, chemicals and his assistance during the course of this study. The research was supported in part by Research Grant WP-00196 from the U.S. Public Health Service, Division of Water Supply and Pollution Control.

XIV. APPENDIX A: DEFINITION OF TERMS

A. General

1. Filter aids

A filter aid is a material that is used as a filtering medium. It may be used in the form of a precoat on the filter septum to serve as the primary filtering medium. It also may be added continuously as body feed during a filter run in proportion to the suspended solids in the water in order to form a porous layer of filter aid containing entrapped suspended solids on top of the precoat.

A filter aid should be a finely divided porous material consisting of hard, strong particles that are virtually incompressible when massed together into a cake under pressure. Many different materials are used as filter aids such as: diatomite (also referred to as moler, kieselguhr, Fuller's earth, diatomaceous earth), finely divided carbon, wood pulp fibers, etc. There are many different grades of filter aids depending on their particular particle size and flow characteristics (18). The most widely used filter aid for the filtration of potable water supplies, and the only type which has been used in this study, is diatomite. The other types of filter aids mentioned above are used mainly for specific filtering operations in the chemical industry.

2. Ion

An ion is defined as a charged atom or chemical radical. For example: $Ca(OH)_2 \rightarrow Ca^{++} + 2OH^-$. Both the ($Ca^{++}$) and

(OH^-) are ions in solution. The positive ions are called cations and the negative ions are called anions.

Ions may be present in the solutions in either a free or a solvated state. In addition ions may be adsorbed on constituent ions of the surface of a particle in contact with the solution, because of various attractive forces between the ion and the ionic surface.

Ions may be monovalent, divalent or polyvalent depending upon the number of electrons they have gained or lost. For example: Na^+ and Cl^- are monovalent ions, Ca^{++} and SO_4^{--} are divalent ions and Al^{+++} is a trivalent ion.

3. Ionic strength

Ionic strength is a measure of the concentration and valence of ions in solution. The ionic strength is computed in the following manner: the concentration of each ionic species in the solution is multiplied by the square of the charge on that ion type, and the results are added together and divided by two. Thus, each ion is assigned a weight proportional to the square of its charge.

$$\mu = 1/2 \sum_i C_i \; Z_i^2 = 1/2 \; (C_1 Z_1^2 + C_2 Z_2^2 + \ldots + C_u Z_u^2)$$

where:

μ = the ionic strength

C_i = the ionic concentration

Z_i = the number of electronic charges on the ion.

For example, with $AlCl_3$ concentration of 2.145×10^{-3}m (Table 43)

$$\mu = 1/2\ (C_1Z_1{}^2 + C_2Z_2{}^2)$$

where

$C_1 = Al^{+++}$ concentration $= 2.145 \times 10^{-3}$m

$C_2 = Cl^{-}$ concentration $= 3 \times 2.145 \times 10^{-3}$m

$Z_1 = 3$ (number of electronic charge on Al^{+++})

$Z_2 = 1$ (number of electronic charge on Cl^{-})

Therefore,

$$\mu = 1/2\ (2.145 \times 10^{-3} \times 3^2 + 3 \times 2.145 \times 10^{-3} \times 1^2)$$

$$= \underline{0.01287} \text{ or } \underline{12.87 \times 10^{-3}}$$

and

$$\mu^{1/2} = 1.135 \times 10^{-1} \text{ or } 0.1135 \text{ (Table 43)}$$

Similarly, with $NaHCO_3$ concentation of 1.06×10^{-3}m (Table 44)

$$\mu = 1/2(C_1Z_1{}^2 + C_2Z_2{}^2)$$

Here

$C_1 = Na^{+}$ concentration $= 1.06 \times 10^{-3}$m

$C_2 = HCO_3{}^{-}$ concentration $= 1.06 \times 10^{-3}$m

$Z_1 = 1$ (number of electronic charge on Na^{+})

$Z_2 = 1$ (number of electronic charge on $HCO_3{}^{-}$)

Then,

$$\mu = 1/2\ (1.06 \times 10^{-3} \times 1^2 + 1.06 \times 10^{-3} \times 1^2)$$

$$= \underline{10.6 \times 10^{-4}}$$

and

$$\mu^{1/2} = 3.26 \times 10^{-2} \text{ (Table 44)}$$

4. Molality

Molality is defined as the number of moles of solute present with each kilogram of solvent (5).

5. Precoat

The initial layer of filter aid deposited on the septum at the beginning of a run is called the precoat.

6. Salts

Substances which crystallize in ionic lattices, except those whose negative ion is OH^-, are usually called salts, by analogy with NaCl, common salt. Most of them are more or less soluble in poler solvents such as water, whose molecules are able to attract the ions of the salt crystal sufficiently to overcome the forces holding them in lattice. When the water molecule reaches the surface of a salt crystal, it tends to orient with its negative part towards the positive atom of the salt and its positive part towards the negative atom of the salt (10). This weakens the force between the charged atoms of the crystal so that, if it is not too strong, the charged atoms may be detached from the crystal and wander off into solution each surrounded by an envelope of oriented water molecules. These charged atoms in solution are but weakly attracted to each other and can move about in the solution more or less independently. They are accordingly called ions (10).

7. Solution

The term solution may be applied to any homogeneous mixture (5). In this thesis the term solution refers to a homogeneous mixture of a salt in water.

8. Zeta potential

When a colloidal particle is suspended in water, a thin liquid layer called the fixed layer surrounds the colloid and moves through the water with the colloid. The electrical potential difference between the outer edge of the fixed layer and point of electroneutrality in the water surrounding the particle is referred to as the electrokinetic or zeta potential (7).

XV. APPENDIX B: K_3 FILTER OPERATION

The K_3 filter is simple to operate and incorporates sufficient valves and lines to permit a high degree of flexibility in its operation. With practice, an operator can soon dispense with detailed instructions concerning the filter operation. A preliminary set of instructions to be followed in four distinct cycles -- precoating, transition, filtering, and backwashing is desireable. The following table will summarize which valves are opened and which valves are closed during a given cycle, Fig. 5.

1. Precoating operation

Valves open: 2, 3, 8, 9, 14 and 12

Valves closed: 1, 4, 5, 6, 7, 10, 11, 15, 16, 17, 18, 19, 20 and 21

2. Transition step to filtering operation

Valves open: 2, 3, 5, 8, 9, 10, 14, 15, 16 and 17, as soon as flow is taking place through the flow meter, close 3, 8 and 9.

Valves closed: 1, 2, 3, 4, 6, 7, 8, 9, 11, 12, 13, 18, 19, 20, and 21.

3. Filtering operation

Valves open: 5, 10, 14, 15, 16, 17, 18 and 19, partially open 20 and 21 to get rid of air bubbles, then close them.

Valves closed: 1, 2, 3, 4, 6, 7, 8, 9, 11, 12, 13, 20 and 21

4. Backwashing operation:

Valves open: 1, 3, 4, 6, 13, and 14

Valves closed: 2, 5, 7, 8, 9, 10, 12, 15, 16, 17, 18, 19, 20 and 21. After a few minutes operation, open valve 10 to wash the front face of the screen and then close it.

XVI. APPENDIX C: SAMPLE CALCULATIONS

A. Constant Head Permeameter

1. Filter area: The filter consisted of a circular septum 2.718 inch in diameter.

$$A = \frac{\pi d^2}{4} = \frac{3.14 \times (2.718)^2}{4} = 0.0402 \text{ sq ft}$$

2. Rate of filtration at T°C: The rate of filtration was expressed in gallons per minute per square foot of filter area.

$$\text{Rate} = \frac{\text{volume}}{\text{Time} \times \text{area}}$$

Example: Series "C" run using five grams of diatomite precoat. During check on flow rate, 0.107 ft^3 of filtrate was collected in an average time of 35.43 seconds.

$$\text{Rate} = \frac{(0.107 \text{ ft}^3)\ (60 \text{ second/min})\ (7.48 \text{ gal})}{(35.43 \text{ sec.})\ (0.0402 \text{ sq ft})\ (\text{ft}^3)}$$

$$= 33.73 \text{ gpm/sq ft}$$

Average temp. = 27.75°C (recorded)

3. Rate of filtration at 20°C:

Viscosity of water at 27.75°C, η_T = 0.8407 centipoise

Viscosity of water at 20°C, η_{20} = 1.0050 centipoise

$$\text{Correction factor} = \frac{\eta_{20}}{\eta_T} = \frac{1.0050}{0.8407} = 1.195$$

$$\text{Therefore, flow rate at } 20^\circ\text{C} = \frac{33.73}{1.195} = 28.23 \text{ gpm/sq ft}$$

4. K$_3$ computation from flow rate:

$$h_1 = K_3 Q W_1$$

Where: Q = flow rate in gpm/sq ft

W_1 = precoat diatomite in lb/sq ft

h_1 = head loss in feet of water

Since: h_1 = 4.65 feet

Q = 28.23 gpm/sq ft at 20°C

W_1 = 5 grams

$$\text{Then, } 4.65(\text{ft}) = K_3 \frac{(Q\ \text{gpm/ft}^2)\ (5\ \text{grams})}{(454\ \text{gram/lb})\ (.0402\ \text{ft}^2)}$$

$$K_3 = \frac{4.65 \times 454 \times 0.0402}{QX5}$$

$$K_3 = \frac{17}{Q},\ \frac{\text{ft}^5 \cdot \text{min}}{\text{lb} \cdot \text{gal}}$$

At a temperature of 20°C, K_3 becomes

$$K_3 = \frac{17}{28.23} = \underline{0.60}\ \frac{\text{ft}^5 \cdot \text{min}}{\text{lb} \cdot \text{gal}} \quad \text{(Table 9 of this thesis)}$$

5. Calculation of a salt solution concentration:

Take, for example, Na_2SO_4: M.W. = 142.06

Volume of the distilled water in the CHP filter was

$$v = 56.775 \text{ liters } (H_2O)$$

1 ppm = .05677 gm in 56.775 liters, or

$$100 \text{ ppm} = \frac{5.677}{v} \text{ gm}$$

Therefore, if we take 5.677 gm of Na_2SO_4, this is equivalent to 100 ppm of Na_2SO_4 in the total volume of water in the filter system

$$m = \frac{\text{ppm}}{1000 \times \text{M.W.}} \quad \text{(molality)}$$

$$m = \frac{100}{1000 \times 142.06} = \underline{0.703 \times 10^{-3}}$$

Concentration, in terms of ions:

If we assume that Na_2SO_4 dissociates into $2\left[Na^+\right]$ and $\left[SO_4^{--}\right]$, three ions are formed from each molecule. Therefore, 5.677 grams of Na_2SO_4 is equivalent to

$$\frac{(5.677 \text{ gms}) \quad (6.02 \times 10^{23} \text{ mol}^{-1} \times \text{molecules})}{(142.06 \text{ gm/mole})} = 0.242 \times 10^{23} \text{ molecules}$$

$$0.242 \times 10^{23} \times 3 = \underline{0.726 \times 10^{23}} \text{ ions}$$

$(6.02 \times 10^{23} \frac{\text{molecules}}{\text{mole}}$ is Avogadro's number)

<u>Summary</u>: 100 ppm of Na_2SO_4 provides

molality = 0.703×10^{-3}

ions = 0.726×10^{23} ions in the system.

B. K_3 Filter

$$h_1 = K_3QW_1$$

In the K_3 filter,

Filter area, A = .0218 sq ft.

W_1 was measured in grams instead of (lb/sq ft)

Q was measured in ml/sec instead of (gpm/sq ft)

H was measured in inches of manometer liquid instead of ft of water

Conversion of these units and simplification was accomplished as follows:

$$h_1 = \frac{h(2.94-1)}{12} = \frac{1.94}{12}\ h, \text{ ft of water}$$

Where: 2.94 is the specific gravity of the manometer liquid

h = manometer reading in inches of manometer liquid

$$Q = q\left(\frac{0.0002642 \text{ gal}}{\text{ml}}\right)\left(\frac{60 \text{ sec.}}{\text{min.}}\right)\left(\frac{1}{.0218 \text{ sq ft}}\right) = 0.728q$$

Where, q = discharge in ml/sec.

$$W_1 = w\left(\frac{1}{454}\frac{\text{lb}}{\text{gms}}\right)\left(\frac{1}{.0218 \text{ sq ft}}\right) = 0.1010w, \frac{\text{lb}}{\text{sq ft}}$$

where, w = weight of precoat in grams

Upon substitution of these values in the K_3 equation, we obtain

$$K_3 = \frac{1.94}{12 \times 0.728 \times 0.1010}\ \frac{h}{q \times w}\ \frac{\text{ft}^5 \cdot \text{min}}{\text{lb} \cdot \text{gal}}$$

$$K_3 = 2.22\ \frac{h}{q \times w} \quad (\text{at } 20^\circ\text{C}), \qquad \frac{\text{ft}^5 \cdot \text{min}}{\text{lb} \cdot \text{gal}}$$

When: q = discharge in ml/sec.

h = manometer reading in inches of manometer liquid.

w = weight of diatomite precoat in grams.

XVII. APPENDIX D: ABBREVIATIONS AND SYMBOLS

Abbreviation	Meaning
A	Filter or septum area
^{o}C	degrees Centigrade
C_D	concentration of diatomite (body feed rate), mg/l
C_i	ionic concentration
CHP	constant head permeameter
cm	centimeter
η	viscosity
ft	feet
gal	gallons
gm	grams
gpm/sq ft	gallons per minute per square foot of filter area
h	head loss
ID	inside diameter
in.	inches
K_3	coefficient of permeability
Kg/cm^2	kilogram per square centimeter
lb	pound
lb/ft^3	pounds per cubic foot
m	molality, number of moles of solute present with each kilogram of solvent

mg	milligram
min	minutes
ml	milliliters
ml/sec	milliliters per second
mm	millimeters
M.W.	molecular weight
μ	ionic strength
mv	millivolts
N	normality, number of equivalents of solute per liter of solution
OD	outside diameter
ppm	parts per million
Q	rate of filtration, volume per unit of area per unit of time
rps	revolutions per second
S	slope ratio
sec	second
t	minute
v	volume
V	velocity
VHP	variable head permeameter
wt	weight
ζ	zeta potential
Z_i	the number of electronic charges on the ion