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Hydraulic behaviors of an iron-rich heavy metal sorbent in a packed bed column

Thomas M. Connors
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TITLE: Hydraulic Behaviors of an Iron-Rich Heavy Metal Sorbent in a Packed Bed Column

DATE: May 29, 1994
HYDRAULIC BEHAVIORS OF AN
IRON-RICH HEAVY METAL SORBENT
IN A PACKED BED COLUMN

by

THOMAS M. CONNORS

A Thesis
Presented to the Graduate and Research Committee
at Lehigh University
in Candidacy for the degree of
Master of Science
in
Civil Engineering

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5/16/99
Date

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Abstract

ECOTITE is the trade name given to the granular iron rich material which is produced during the process of recovering metals from Electric Arc Furnace (EAF) dust. Previous studies show that ECOTITE has the ability to sequester heavy metal from aqueous solutions. Ecotite may be an inexpensive way to remove heavy metals from waste water compared to the more expensive traditional removal processes. A packed bed column is the most viable equipment configuration for utilizing ECOTITE as a heavy metal sorbent. The hydraulic behavior of ECOTITE has been found to be strongly dependent on the chemical composition of the influent waste water. The primary objectives of this study were to identify the effects of influent metal concentration, turbidity, attrition, and intermittent backwashing, on the performance of an ECOTITE column.

Suspended solids are filtered by the packed bed which causes an increase in the pressure drop across the bed. Very turbid waste waters may require frequent backwashing of the bed or filtration prior to treatment with the bed. Running the column in an upflow mode alleviated the negative effects of filtration.

At low heavy metal concentrations, the ECOTITE bed acts very similar to an ion exchange column. ECOTITE releases hydroxyl ions into solution resulting in an increased pH. At a high pH and high heavy metal concentrations metal precipitates
are formed which clog the bed and increase the pressure drop. The breakthrough of metals through the column was accompanied by a sharp drop in pH. This drop in pH could be used as an indicator of bed exhaustion.

Backwashing was an effective way of reversing the effects of filtration and heavy metal precipitation. The bed particle size and void fraction have a strong influence on the pressure drop across the bed. As the particle size decreases the pressure drop across the bed increases. The effects of bed particle shrinkage were negligible compared to the effects of filtration and metal precipitation.

The head across the bed can be calculated with reasonable accuracy using the Carman-Kozeny equation. Bed expansion calculations could be improved by preforming a sieve analysis on the ECOTITE bed.
Chapter 1

INTRODUCTION

1.1 ENVIRONMENTAL IMPACT OF HEAVY METALS

In recent years the presence of trace metals in surface and ground water has received considerable attention. Of special interest are the trace metals known as heavy metals which are harmful to humans and other organisms in small quantities. The toxicity and economic value of heavy metals has resulted in a demand to develop better removal processes of these metals.

Heavy metals are in an elemental group referred to by chemists as the transition elements. As a rough generalization, the "heavy metals" may be said to include all metals of the Periodic Table between Groups IVA and VII, such as lead, copper, chromium, manganese, cadmium, zinc, nickel, mercury and many others[1].

For some heavy metals including cadmium, mercury, and zinc, maximum permissible or recommended limits have been set on drinking water standards. In addition, a toxicity limit called the "threshold toxicity" has been established for many metals and is defined as the concentration above which a metal begins to have a deleterious effect. Cumulative metals such as cadmium, lead, and mercury, which
are susceptible to bioaccumulation, are particularly hazardous. Bioaccumulation is the process of toxic substances concentrating in organisms, as they move along the food chain, posing the greatest danger to organisms near the top of the chain [2]. Subsequently, regulatory agencies have established strict limits on the discharge of these metals into the environment and are moving toward a zero pollutant discharge level. Although the technology exists to meet the 'zero pollutant discharge rule', the economic cost of these technologies prevents the rule's implementation [3].

Heavy metal contamination can usually be traced to mining, industrial, and agricultural sources [4]. Industrial sources include metal plating factories, photographic laboratories, and printing plants. These industries could reduce the cost of their production processes by recovering and recycling the heavy metals present in their waste streams.

1.2 HEAVY METAL REMOVAL PROCESSES

There are several conventional methods for removing heavy metals from waste water. These methods include ion exchange, chemical precipitation, reverse osmosis, electrodialysis, distillation, and chemical oxidation/reduction. Heavy metal removal using these processes are very efficient, however, there a many drawbacks which diminish their overall cost benefit.

One drawback of reverse osmosis and electrodialysis besides the high capital cost, is that they are used to remove dissolved solids from brackish water and would
be very inefficient for waste streams containing low concentrations of dissolved metals. Coagulation and precipitation produce a hazardous sludge which must be disposed of, adding to the overall cost of the treatment process. In addition precipitation of heavy metals is difficult at low concentrations in the range of 1 to 100 mg/l. Ion exchange processes require a high capital cost and are uneconomical for treating waste waters with high concentrations of heavy metals.

Due to the shortcomings of the existing treatment processes, there has been a demand for new technology to treat heavy metal contaminated waste water. One new processes which has been studied involves using iron oxides as heavy metal adsorbents [5]. The main shortcoming of iron oxides is that they lose their ability to adsorb heavy metals at a pH below 6.5 (Fig. 1-1). Most heavy metal laden waste waters have a low pH since at higher pH, dissolved metals precipitate out of solution.

Previous work has been conducted on an inexpensive heavy metal adsorbent produced during the process of metal recovery from Electric Arc Furnace (EAF) dust [6]. This iron-rich material has been given the trade name of ECOTITE and will be referred to by this name throughout this report. A description of the adsorbent, the process by which it is produced, and the results of previous work on the adsorbent, are outlined in the next chapter.
1.3 PREMISE OF THE STUDY

Releases of heavy metals into the environment are strictly regulated due to their toxic effects. A packed bed column is the most viable equipment configuration to utilize ECOTITE for the removal of heavy metals from waste water. This study addresses the hydraulic concerns with using ECOTITE in a packed bed column including the build up of excessive pressure drops, channeling, bed clogging, particle attrition, and effects of filtration.

Previous experiments using ECOTITE were preformed in a small 10 mm diameter column. This setup needed to be scaled up in order to accurately measure the hydraulic behaviors of an ECOTITE column. The scaled up column is described in chapter 3.

ECOTITE is a conglomeration of smaller particles bound together by weak chemical or physicochemical bonding [7]. When ECOTITE is exposed to an acidic solution the ECOTITE particles gradual breakdown into smaller and smaller particles. As the particle size decreases (and the void fraction) the pressure drop across the column increases. The pressure drop can be calculated by the Carman-Kozeny equation under laminar flow conditions and is listed in appendix A. The amount and rate of pressure drop induced by particle size reduction must be evaluated before ECOTITE may be used for commercial use.

ECOTITE releases hydroxyl ions into solution resulting in an increased pH. As the pH is increased heavy metals in solution will precipitate out as metal hydroxides. The pressure drop across the column may increase dramatically if
heavy metal precipitates build up and clog the bed.

An ECOTITE packed bed will act as a filter removing suspended solids from the influent waste stream. The effects of waste water turbidity on the column performance needs to be evaluated to determine if pretreatment is required for wastes with high turbidity.

1.4 OBJECTIVES OF THE STUDY

The primary objective of this study was to evaluate the hydraulic behaviors of ECOTITE in a packed bed column. The chemical composition of the feed water including pH, heavy metal concentration, and turbidity, have a strong influence on the hydraulic characteristics of an ECOTITE column.

The study had the following objectives:

1. Determine the effects of various heavy metal concentrations on the pressure drop across the column.

2. Study the effects of filtration by the packed bed with various feed water turbidities.

3. Checking the increase in head loss across the column due to bed particle size shrinkage.

4. Study the influence of intermittent backwashing on the hydraulic properties of the column.

5. Determine if the Carman-Kozeny equation can be used to predict the
pressure drop across an ECOTITE packed bed.

6. Investigate the bed expansion at various backwashing flow rates.
Figure 1-1: Adsorption of Cd on Amorphous Iron Oxyhydroxide

Source: [5]
Chapter 2

ECOTITE

2.1 BACKGROUND

The Electric Arc Furnace (EAF) is widely used in the production of steel from recycled ferrous scrap. During the operation of the EAF a dust containing zinc, lead, and cadmium, is produced. The U.S. Environmental Protection agency (USEPA) has listed EAF dust as a hazardous waste under the Resource Conservation and Recovery Act (RCRA) due to the leachability of heavy metal oxides from the dust. Under RCRA the EAF dust must be treated by the best demonstrated technology (BDT). The USEPA has recognized the Waelz Kiln, a high temperature thermal process, as the BDT (Fig. 2-1). The Waelzing process allows most of the heavy metals present in the EAF dust to be reclaimed.

A by-product of the Waelzing process is a granular iron-rich material (IRM) which lacks the hazardous characteristics found in EAF dust. Horsehead Resource Development, Inc. (HRD), a subsidiary of Zinc Corporation of America, has been studying the possibility of using this IRM as a heavy metal sorbent [6]. ECOTITE is the trade name given to this IRM and will be referred to by this name throughout this report.
ECOTITE consists of a porous matrix of lime, silica, carbon, and iron and manganese oxides. ECOTITE’s physical characteristics and chemical composition are given in Table 2-1 and 2-2 respectively.

2.2 PREVIOUS WORK

Horsehead Resource Development, Inc., conducted preliminary tests on the IRM produced from the Waelzing process and discovered that the IRM possessed the ability to remove heavy metals from solution. Further research was performed by Anand Ramesh, a graduate student at Lehigh University, whose conclusions are summarized as follows:

- ECOTITE is capable of removing heavy metals from aqueous solutions via a cation exchange process.
- Metal uptake by ECOTITE is a very rapid process.
- ECOTITE’s metal uptake capacity (0.7 meq/gram of sorbent) compares well with that of commercially available chelating ion exchangers (0.8 meq/gram of dry resin).
- ECOTITE exhibits high selectivity towards bivalent transition metal cations.
- ECOTITE granules in the size range of 20-50 ASTM mesh permits its use in a fixed bed process.
- ECOTITE has an immense acid neutralizing capacity which is on the
order of 1.4 meq H⁺ per gram of ECOTITE.

- Leaching of Zn and Pb from ECOTITE, albeit at low concentrations, may effect ECOTITE's marketability.
Figure 2-1: Waelzing Process

Source: Horsehead Resource Development, Inc., information brochure
### Table 2-1: Physical Properties of ECOTITE

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Area</td>
<td>9.7 m$^2$/g</td>
</tr>
<tr>
<td>Pore Volume</td>
<td>25 %</td>
</tr>
<tr>
<td>Median Pore Distribution</td>
<td>4 μ</td>
</tr>
<tr>
<td>Void Volume</td>
<td>41.2 %</td>
</tr>
<tr>
<td>Bulk Density</td>
<td>1.49 g/cm$^3$</td>
</tr>
</tbody>
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### Table 2-2: Chemical Composition of ECOTITE

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
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</tr>
<tr>
<td>Ca</td>
<td>10.7</td>
</tr>
<tr>
<td>Si</td>
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<tr>
<td>Zn</td>
<td>4.2</td>
</tr>
<tr>
<td>Mn</td>
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</tr>
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<td>Mg</td>
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</tr>
<tr>
<td>Cu</td>
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</tr>
<tr>
<td>Na</td>
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</tr>
<tr>
<td>Cr</td>
<td>0.31</td>
</tr>
<tr>
<td>K</td>
<td>0.31</td>
</tr>
<tr>
<td>Pb</td>
<td>0.18</td>
</tr>
<tr>
<td>Ti</td>
<td>0.17</td>
</tr>
<tr>
<td>Ni</td>
<td>0.12</td>
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</table>
Chapter 3

EXPERIMENTAL PROCEDURE

3.1 MATERIALS

A description of ECOTITE and the process by which it is produced are described in the previous chapter. The ECOTITE used in all of the experiments was provided by HRD and was sieved using #16 and #48 (1.18 mm and 0.32 mm openings respectively) ASTM-11 specification sieves. The ECOTITE was rinsed using tap water prior to placement into the column.

Tap water from the City of Bethlehem, was used in all experiments. The pH of the tap water was adjusted to 4.5 with H₂SO₄ for all column runs. All heavy metal solutions used in the experiments were synthesized using analytical grade chemicals obtained from Fisher Chemical Co. Nitrate salts of the respective metal ions were used to prepare the feed solutions to minimize the effects of complexation (nitrate is an extremely poor ligand). Turbidity was simulated using kaolinite clay from Fisher Chemical Co.
3.2 EQUIPMENT SETUP

A twelve inch deep ECOTITE bed was used in all the column runs. The packed bed was supported by three, three inch layers of inert rocks increasing in diameter from top to bottom (Fig. 3-1). The rock base was in turn supported by stainless steel wire cloth.

The column used for all experiments was three inches in diameter and approximately four feet long (Fig. 3-2). Six taps and one control tap were positioned along the side of the column and connected to a manometer which measured the head loss at various bed depths. A velocity of 2 m/hr was used in all the column runs except where noted.

A schematic of the experimental setup is shown in figure 3-3. Feed solutions were synthesized in two 220 liter plastic barrels. The feed solution was pumped through the column in a downflow direction using a positive displacement pump. The liquid contained in the manometer had a specific gravity of 1.75. An automatic sampler (ISCO model 2700) periodically sampled the effluent from the column before being discharged to the sump. The effluent pH was also recorded.

The column was reconfigured to allow flow in an upward direction and then backwashed with tap water after each test run to flush out suspended solids filtered or heavy metal precipitates trapped by the bed.
3.3 ANALYTICAL METHODS

Zinc, Copper, and Calcium concentrations were analyzed using an atomic adsorption spectrophotometer (Perkins Elmer model 2380) in either a flame or graphite mode. All pH measurements were taken using a standard polymer-body liquid filled combination electrode using a Fisher Accumet model 930 pH meter.
12" of #16-#48 ASTM Mesh Ecotite

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3&quot;</td>
<td>of 1/8 - 1/16&quot; diameter Rock Base</td>
</tr>
<tr>
<td>3&quot;</td>
<td>of 1/4 - 1/8&quot; diameter Rock Base</td>
</tr>
<tr>
<td>3&quot;</td>
<td>of 1/2 - 1/4&quot; diameter Rock Base</td>
</tr>
<tr>
<td>10 x 10</td>
<td>Stainless steel Wire Cloth</td>
</tr>
<tr>
<td>6 x 6</td>
<td>Stainless steel Wire Cloth</td>
</tr>
<tr>
<td>2 x 2</td>
<td>Stainless steel Wire Cloth</td>
</tr>
</tbody>
</table>

Figure 3-1: Construction of ECOTITE Packed Bed
Figure 3-2: Dimensions of ECOTTTE Packed Bed Column
Column using ECOTITE

Figure 3-3: General Schematic of the Packed Bed
Chapter 4

RESULTS AND DISCUSSION

4.1 TAP WATER CONTROL RUN

Tap water was used as the influent feed to generate pressure drop data. The influent water was free of dissolved heavy metals and the pH was adjusted to 4.5. The tap water run results were used as a basis to compare with the results of other experiments which studied the effects of dissolved heavy metals, turbidity, and attrition, on the hydraulic behaviors of ECOTITE.

Figure 4-1 through 4-3 show the results of the tap water column run. The head loss across the column increases with increasing bed volumes. Figure 4-2 shows that a vast majority of the head loss was located in the top one inch of the ECOTITE bed. This indicates that filtration of suspended solids out of the influent water was the primary cause of the increasing head loss.

Effluent pH remained about 10.4 after passing close to 300 bed volumes of pH 4.5 feed solution. This verifies that ECOTITE has enormous acid neutralizing capacity and sustains this capacity via the slow release of hydroxyl ions. The zinc concentration in the column effluent remained below 0.5 ppm (Fig. 4-3).
4.2 COLUMN RUNS WITH VARIOUS ZINC CONCENTRATIONS

Several experiments were run with 0, 5, 50, and 100 ppm of zinc in the feed solution to determine the effect of metal concentration on the performance of the ECOTITE column. The results from these runs are shown in figures 4-4 through 4-20 located at the end of the chapter.

The results of the 5 ppm zinc run are shown in figures 4-4 through 4-6. The head loss across the bed from the 5 ppm zinc run was very similar to the control tap water run indicating that no heavy metal precipitation had occurred. The highest percentage of head loss was observed in the top inch of the bed which was the result of filtration. There was no difference in head loss inside the bed between the 5 ppm zinc run and the tap water control run indicating that heavy metal precipitates were not being formed in the bed. There was no significant change in pH which remained between 9 and 10 throughout the experiment. The zinc did not breakthrough the column as the effluent concentration of zinc was below 0.5 ppm for the entire column run. The lack of zinc breakthrough demonstrates the ability of ECOTITE to remove heavy metals via an ion exchange process. An ECOTITE packed bed column appears to be a viable removal process for waste containing less than 5 ppm total metal concentration.

The head loss encountered during the 50 ppm zinc run was substantially higher than the tap water and 5 ppm zinc runs (Fig. 4-7). Breakthrough of zinc occurred around 175 bed volumes and was accompanied by a sharp drop in pH (Fig.
4-9). The effluent zinc concentration after breakthrough leveled off at 27 ppm, therefore a substantial amount of zinc was being trapped in the column. Once the ion exchange capacity of the ECOTITE bed is exhausted, the aqueous zinc concentration in the bed begins to rise. The hydroxyl ions which are continually released by the bed keep the pH high enough to precipitate out the zinc trapping it in the bed. The formation of zinc hydroxides accounts for the sharp drop in pH observed. The zinc hydroxides which precipitate out of solution clog the bed and increase the pressure drop. This theory is confirmed by figure 4-8 which shows the head loss increasing across the entire bed (indicating metal precipitates clogging the bed) and not just in the top inch (indicating filtration) as previously observed in the tap water and 5 ppm zinc runs. The clogging of the bed by metal precipitates corresponds to the sharp drop in pH which in turn indicates heavy metal breakthrough. The fact that metal precipitates formed after the ion exchange capacity of the bed was exhausted indicates that metals are removed from solution by ion exchange before chemical precipitation.

Tap water was run after the 50 ppm test run for approximately 1000 bed volumes (Fig. 4-10 to 4-12). The zinc effluent concentration averaged about 1.5 ppm which resulted from zinc leaching off of the ECOTITE. A toxicity characteristic leaching procedure (TCLP) test should be preformed on exhausted ECOTITE to determine if spent ECOTITE qualifies as a hazardous waste. There would be a substantial increase in the cost of using ECOTITE as a heavy metal sorbent if the spent ECOTITE has to be disposed of as a hazardous waste.
Figure 4-13 shows the head loss generated in the 4 to 7 inch bed depth range for the 50 ppm zinc run and the subsequent tap water run after backwashing. The head loss for the 50 ppm zinc run started at 0.25 inches of water and ended near four inches of water where as the head loss during the tap water run remained below 0.5 inches of water. The head loss build up during the 50 ppm zinc run was due to the formation of heavy metal precipitates in the bed and was not due to the effects of filtration since filtration only effects the top inch of the bed. The return of the head loss from 4 inches of water at the end of the 50 ppm zinc run to 0.5 inches of water at the beginning of the tap water run shows the effectiveness of the backwashing process at flushing out heavy metal precipitates formed in the bed.

The head loss incurred in the 100 ppm zinc run was comparable to the 50 ppm zinc run (Fig. 4-14). Build up of pressure drops occurred in the top inch, indicating filtration, and in the bed itself indicating the formation of heavy metal precipitates in the bed (Fig. 4-15). The breakthrough of zinc occurred around 30 bed volumes and was accompanied by a sharp drop in pH (Fig. 4-16).

Figure 4-17 is a summary of the head loss histories across ten inches of the bed for the various zinc concentration runs. The 5 ppm zinc and tap water runs exhibited similar head loss patterns which were less than the head loss seen during the 50 and 100 ppm zinc runs. The head loss incurred in the 5 ppm zinc and tap water runs were due to filtration while the head loss seen in the 50 and 100 ppm zinc runs was attributable to zinc hydroxides precipitating in the bed as well as filtration. The difference in the amounts of head loss between the low or no zinc concentration
runs and the high zinc concentration runs was a direct result of metal precipitates forming in the bed.

Feed solutions containing 0, 5, and 50 ppm zinc concentrations were progressively run through the ECOTITE bed without backwashing between the different concentrations. The head loss increased noticeably when the 50 ppm zinc concentration was fed to the column (Fig. 4-18 and 4-19). The breakthrough of zinc through the column occurred shortly after the 50 ppm zinc solution was introduced into the column (Fig. 4-20). The zinc breakthrough was accompanied by a sharp drop in the effluent pH.

4.3 COLUMN RUNS VARYING THE FEED SOLUTION TURBIDITY

The amount of turbidity in the waste water has a dramatic effect on the head loss build up across the column. Several test runs were performed with various levels of turbidity in the feed solutions to evaluate the effects of filtration on the column performance. Kaolin clay was used in 20, 100, and 340 ppm concentrations to provide turbidity for the experiments.

The 20 ppm kaolin run developed less than half the head loss (1.5 inches of water) that the 100 and 340 ppm kaolin runs developed (4 inches of water) as shown in figures 4-21 through 4-26. The greatest amount of head loss for all three runs occurred in the top three inches of the bed indicating that filtration of the kaolin was taking place. The head loss after a turbidity run were returned to pre-run levels by
backwashing the column. This indicates that backwashing was effective in flushing out the kaolin particles filtered out of the feed solution by the column. Waste water with a high turbidity will require backwashing the bed frequently or filtration prior to treatment with the bed. This will add to the cost and complexity of using ECOTITE in a packed bed column.

Another possibility to lessen the impact of head loss build up due to filtration of turbid waste water, is to run the column in an upflow mode. Running the column in an upflow direction at a flow rate high enough to partially expand the bed will allow suspended particles to pass through the bed instead of being filtered out.

The previous turbidity runs were re-run with the column reconfigured for upward flow. The flow rate was increased to 1200 ml/min (15.8 m/hr) which expanded the bed by approximately five percent. This bed expansion allowed the kaolin particles to pass through the bed rather then be filtered out by the bed alleviating the effects of filtration. Figures 4-27 through 4-32 chronicle the results of the upflow turbidity runs. The head loss across the bed remained about 13 inches of water for all three levels of turbidity, indicating that running the column in an upflow manner is an effective way to treat turbid waters.

4.4 COLUMN RUNS WITH VARIOUS COPPER CONCENTRATIONS

Copper has a higher selectivity or binding strength than that of zinc onto ECOTITE [6]. If ion exchange processes are occurring copper, when introduced into
a column which has been previously exhausted with zinc, will replace the zinc on the ECOTITE and release zinc into solution. If precipitation is the primary heavy metal removal mechanism, copper, when introduced into a ECOTITE column previously exhausted with zinc, will precipitate out of solution and no zinc will be present in the column effluent.

A feed solution containing 10 ppm copper was introduced to a column previously exhausted with zinc to further clarify the dominant metal removal process employed by an ECOTITE bed. Figure 4-35 shows the effluent metal concentrations for the 10 ppm copper run. There was no breakthrough of copper, however, there was a marked increase in zinc concentration and a sharp drop in pH around 120 bed volumes. It is clear from the effluent histories that copper ions are exchanging with zinc ions on the ECOTITE bed. In a theoretical ion exchange process, the amount of copper taken out of solution would be replaced by the same amount of zinc being released into solution. The effluent zinc concentration was well below the 10 ppm level of copper that was feed into the column. Therefore ion exchange was not the only removal process occurring in the column, although, it may be the dominant one.

Backwashing of the column may expose unused exchange sites on ECOTITE particles which in effect allows an additional metal removal capacity. This may explain why zinc did not show up in the column’s effluent until after 120 bed volumes. The rate of head loss increases at about 120 bed volumes, the same point that zinc breaks through the column and the pH drops, indicating that metal precipitation has begun to occur (Fig. 4-34). There are no filtration effects inside
the bed, therefore, the increase of head loss in the one to four inch bed depth range must be due to the precipitation of zinc hydroxides (Fig. 4-34). Heavy metal precipitation may account for the effluent zinc concentration peaking at 5 ppm and not at the influent copper concentration of 10 ppm.

Figure 4-36 shows the copper ions progression into the ECOTITE bed and the subsequent replacement of the zinc ions. At the onset of the column run some copper was being absorbed by fresh ion exchange sites while the rest was replacing zinc due to copper’s greater affinity towards the ECOTITE. Initially the replaced zinc was being re-absorbed deeper into the column by other unused ion exchange sites exposed after backwashing. When all the ion exchange sites were used up the replaced zinc ions begin to react with the abundant hydroxyl ions to form metal precipitates. This caused a sharp drop in pH. After the bed was exhausted the copper ions should theoretically release 10 ppm zinc into the water. Only 3 ppm of zinc passed through the column, therefore the remaining 7 ppm of zinc was tied up in the column as metal precipitates.

An experiment was performed with 10 ppm of zinc and 10 ppm of copper present in the feed solution the results of which are presented in figures 4-37 to 4-39. A vast majority of the head loss occurred in the top three inches and was caused by a combination of filtration and heavy metal precipitation effects (Fig. 4-38). The zinc concentration in the top inch and a half, increased steadily until plateauing at 8 ppm around 125 bed volumes (Fig. 4-39). Copper concentrations in the top inch and a half of the bed rose slowly and steadily throughout the column run. It was
unclear weather metal precipitation, ion exchange or both, contributed to the removal of the copper. The pH in the top inch and a half dropped sharply in the first 100 bed volumes suggesting that hydroxyl ions were being taken out of solution by the formation of metal hydroxides.

The pH at the 4.5 inch bed depth began to drop around 140 bed volumes which corresponded to a rise in zinc concentration at the same bed depth. The fact that the pH dropped at the same time that zinc appeared in the 4.5 inch bed depth indicates that zinc hydroxides were being formed. The increase in head loss in the 3 to 6 inch bed depth verifies that metal precipitates are being formed. The copper concentration remained close to zero throughout the experiment at the 4.5 inch bed depth.

4.5 EFFECTS OF ATTRITION ON ECOTITE PARTICLES

The particle size and void fraction of a packed bed has a strong influence on the pressure drop across the bed. Considering laminar flow, the pressure drop per unit length of a packed bed may be calculated by the Carman-Kozeny equation listed in appendix A. Acidic waste water may accelerate the disintegration of ECOTITE particles dramatically increasing the pressure drop across the bed. Tap water was run through the column, and backwashed intermittently, to evaluate the effects of particle dissolution on the build up of head losses.

There were no noticeably effects of particle size reduction after passing 750
bed volumes of pH 4.5 tap water through the column (Figs. 4-40 and 4-41). Heavy metal precipitation and filtration effects are much greater than the effects of attrition. Backwashing may help remove very small particles from the column which would contribute to the head loss across the bed.

4.6 HYDRAULIC ANALYSIS OF THE PACKED BED

Several tap water runs were performed at various flow rates to evaluate the ability of the Carman-Kozeny equation to predict the head loss across an ECOTITE packed bed. The Carman-Kozeny and Reynolds number equations are listed in appendix A. The head loss of the ECOTITE packed bed increased with increasing flow rates as shown in figures 4-42 through 4-45. Table 4-1 lists the pertinent ECOTITE characteristics needed to calculate the Reynolds number and pressure drop for various flow rates. Table 4-2 summarizes the pressure drop and head loss per length of bed for the different flow rates used in the experiments. The Reynolds number for all of the flow rates performed were well below 10 indicating laminar flow. Table 4-3 shows the Carman-Kozeny predictions of head loss at different bed depths for various flow rates. The theoretical head loss predicted by the Carman-Kozeny equation matched very closely to the experimental head loss produced from the control tap water run as shown in figure 4-46. A log-log plot of head loss verses flow rate yields a straight line verifying that the head loss has a linear relationship to the velocity of the water passing through the column as indicated by the Carman-
4.7 BACKWASHING AND BED EXPANSION

Previous experiments revealed the effectiveness of backwashing in reversing the deleterious effects of filtration and heavy metal precipitation. Further experiments were run to measure the pertinent parameters needed to develop a backwashing process for packed bed columns using ECOTITE. Appendix B lists the equations used to calculate the settling velocities and expanded bed heights at different flow rates.

The ECOTITE particle diameter and density used were 0.05 cm and 2534 kg/m³, respectively. A shape factor of 0.85 was assumed for the ECOTITE which yielded a reynolds number of 40. After several iterations the settling velocity was determined to be 0.0844 m/s (304 m/hr) and the drag coefficient \( (C_d) \) was 1.41. The head required to begin fluidizing the bed was calculated to be 11.73 in. This corresponded well with the 12 to 14 in of head observed during the upflow experiments (Fig. 4-26 through 4-31).

The theoretically predicted bed depth for various backwashing velocities roughly corresponded to the bed depths observed during the backwash experiments. However, the experimental bed depths were consistently lower than the theoretical predicted depths. Some error was introduced into the theoretical predictions from
the assumption that all of the ECOTITE particles are the same size and therefore have the same settling velocities. A more accurate prediction can be performed using equations for beds consisting of nonuniform media. However, these equations require a sieve analysis of the bed media which was not available. In addition, the equations used to predict the settling velocity assume a spherical particle which is not the case for ECOTITE.
Figure 4-1: Head Loss During the Tap Water Control Run. E.B.C.T. = Empty Bed Contact Time

Head Loss (in of water)

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Figure 4-3: Effluent Zinc Concentration and pH for the Tap Water Control Run
Figure 4.4: Head Loss During the 5 ppm Zinc Column Run

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

Head Loss (in of water) vs. Bed Volumes

- Exit pH
- 1" Bed Depth
- 4" Bed Depth
- 7" Bed Depth
- 10" Bed Depth
- 12" Bed Depth

5 ppm Zinc
Figure 4.5: Head Loss per Length of Bed for the 5 ppm Zinc Column Run

- Flow Rate = 150 ml/min
- Velocity = 2 m/hr
- E.B.C.T. = 9.87 min
- One Bed Volume = 1.48 liters

5 ppm Zinc

pH

Bed Volumes

\[ \text{dH/dL (in/in)} \]

0-1" Bed Depth
1-4" Bed Depth
4-7" Bed Depth
7-10" Bed Depth
10-12" Bed Depth
Exit pH
Figure 4-6: Effluent Zinc Concentration and pH for the 5 ppm Zinc Column Run
50ppm Zinc

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

Figure 4.8: Head Loss per Length of Bed for the 50 ppm Zinc Column Run
Figure 4-9: Effluent Zinc Concentration and pH for the 50 ppm Zinc Column
Figure 4.10: Head Loss During the Tap Water Run after the 50 ppm Zinc Run

Tap Water
After 50ppm Zinc Test Run

Flow Rate = 150 ml/min
Flow Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

Head Loss (in of water) vs. Bed Volumes

Exit pH
1" Bed Depth
4" Bed Depth
7" Bed Depth
10" Bed Depth
12" Bed Depth
Figure 4-11: Head Loss per Length of Bed for the Tap Water Run after the 50 ppm Zinc Run

\[ \frac{dH}{dL} \text{ (in/in)} \]

- **Flow Rate** = 150 ml/min
- **Velocity** = 2 m/hr
- **E.B.C.T.** = 9.37 min
- **One Bed Volume** = 148 liters

Legend:
- □ 0.1-10" Bed Depth
- — 1.4" Bed Depth
- × 10-12" Bed Depth
- ▲ Exit pH

**Tap Water**

- **Bed Volumes**
  - 0
  - 100
  - 200
  - 300
  - 400
  - 500
  - 600
  - 700
  - 800
  - 900
  - 1000
  - 1100
  - 1200

- **pH**
  - 7
  - 8
  - 9
  - 10
  - 11
  - 12
Tap Water
After 50ppm Zinc Test Run

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

Figure 4-12: Effluent Zinc Concentration and pH for the Tap Water Run after the 50 ppm Zinc Run
Figure 4-13: Comparison of Head Loss in the 4-7 inch Bed Depth Range for the 50 ppm Zinc Run and the subsequent Tap Water Run

- Flow Rate = 150 ml/min
- Velocity = 2 m/hr
- E.B.C.T. = 9.87 min
- One Bed Volume = 1.48 liters

50 ppm Zinc and Tap Water
4-7" Bed Depth

<table>
<thead>
<tr>
<th>Head Loss (in of water)</th>
<th>Bed Volumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 ppm Zn</td>
<td>Tap Water</td>
</tr>
</tbody>
</table>

- 50 ppm Zn
- Tap Water

45
Figure 4.14: Head Loss During the 100 ppm Zinc Column Run

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

100 ppm Zinc

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

Figure 4.15: Head Loss per Length of Bed for the 100 ppm Zinc Column Run
Figure 4-16: Effluent Zinc Concentration and pH for the 100 ppm Zinc Run

- Flow Rate = 150 ml/min
- Velocity = 2 m/hr
- One Bed Volume = 1.481 liters
- E.B.C.T. = 9.87 min

100 ppm Zinc

- ■ Exit Concentration
- ▲ Exit pH
Head Loss Across 10" Bed Depth

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

Figure 4-17: Head Loss for Various Zinc Concentrations at the Ten inch Bed Depth

- ■ Tap Water
- ▲ 50 ppm Zn
- ★★ 5 ppm Zn
- ○○ 2nd Tap Water
- —— 100 ppm Zn
0, 5, & 50 ppm Zinc

Figure 4.18: Head Loss During the 0, 5, & 50 ppm Zinc Column Runs

Head Loss (in of water)

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T = 9.87 min
One Bed Volume = 1.48 liters

- Exit pH
- 1" Bed Depth
- 4" Bed Depth
- 7" Bed Depth
- 10" Bed Depth
- 12" Bed Depth
0, 5, & 50 ppm Zinc

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T = 9.87 min
One Bed Volume = 1.48 liters

Figure 4-19: Head Loss per Length of Bed for the 0, 5, & 50 ppm Zinc Column
0, 5, & 50 ppm Zinc Effluent Concentrations

Flow Rate = 150 ml/min
Velocity = 2 m/hr
One Bed Volume = 1.481 liters
E.B.C.T. = 9.87 min

- Zn Concentration  ▲ Exit pH
20 ppm Kaolin

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.67 min
One Bed Volume = 1.48 liters

Figure 4.2.1: Head Loss During the 20 ppm Kaolin Column Run

Head Loss (in. of Water)

Bed Volumes

Exit pH
3" Bed Depth
6" Bed Depth
9" Bed Depth
12" Bed Depth
20 ppm Kaolin

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

- Exit pH
- 0-3" Bed Depth
- 3-6" Bed Depth
- 6-9" Bed Depth
- 9-12" Bed Depth
Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Figure 4.24: Head Loss per Length of Bed for the 100 ppm Kaolin Column Run

100 ppm Kaolin

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

pH

Bed Volumes

Exit pH
0-3" Bed Depth
3-6" Bed Depth
6-9" Bed Depth
9-12" Bed Depth
Figure 4.25: Head Loss During the 340 ppm Kaolin Column Run

- Exit pH
- 3" Bed Depth
- 6" Bed Depth
- 9" Bed Depth
- 12" Bed Depth

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Flow Rate = 150 ml/min

Velocity = 2 m/hr

E.B.C.T. = 9.87 min

One Bed Volume = 1.48 liters

Bed Volumes

- Exit pH
- 6.9" Bed Depth
- 0.3" Bed Depth
- 9 - 12" Bed Depth
- 3.6" Bed Depth
Flow Rate = 1200 ml/min
Velocity = 15.8 m/hr
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters
Figure 4.28: Head Loss per Length of Bed for the 20 ppm Kaolin Column Run in the Upflow Mode

- Flow Rate = 1200 ml/min
- Velocity = 2 m/hr
- E.B.C.T. = 1.01 min
- One Bed Volume = 1.48 liters

Bed Volumes vs. pH

- Exit pH
- 0-3" Bed Depth
- 3-6" Bed Depth
- 6-9" Bed Depth
- 9-12" Bed Depth
Figure 4-29: Head Loss During the 100 ppm Kaolin Column Run in the Upflow Mode

Head Loss (in of water)

- Exit pH
- 9" Bed Depth
- 3" Bed Depth
- 12" Bed Depth
- 6" Bed Depth

Flow Rate = 1200 ml/min
Velocity = 15.8 m/hr
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters

Bed Volumes

100 ppm Kaolin Upflow Mode
Figure 4-30: Head Loss per Length of Bed for the 100 ppm Kaolin Column Run in the Upflow Mode

100 ppm Kaolin
Upflow Mode

Flow Rate = 1200 ml/min
Velocity = 15.8 min
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters

Bed Volumes

Flow Rate = 1200 ml/min
Velocity = 15.8 min
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters

Bed Volumes

Flow Rate = 1200 ml/min
Velocity = 15.8 min
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters

Bed Volumes

Flow Rate = 1200 ml/min
Velocity = 15.8 min
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters

Bed Volumes

Flow Rate = 1200 ml/min
Velocity = 15.8 min
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters

Bed Volumes

Flow Rate = 1200 ml/min
Velocity = 15.8 min
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters

Bed Volumes
Figure 4-31: Head Loss During the 340 ppm Kaolin Column Run in the Upflow Mode

Flow Rate = 1200 ml/min
Velocity = 15.8 m/hr
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters
340 ppm Kaolin
Upflow Mode

Flow Rate = 1200 ml/min
Velocity = 15.8 m/hr
E.B.C.T. = 1.01 min
One Bed Volume = 1.48 liters
10 ppm Copper

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

Figure 4.33: Head Loss During the 10 ppm Copper Column Run

Head Loss (in of water)

Bed Volumes

Exit pH
1" Bed Depth
4" Bed Depth
7" Bed Depth
10" Bed Depth
12" Bed Depth

pH
Figure 4-34: Head Loss per Length of Bed for the 10 ppm Copper Column Run

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

10 ppm Copper
Figure 4.35: Effluent pH and Zinc and Copper Concentrations for the 10 ppm Copper Column Run

Flow Rate = 150 ml/min
Velocity = 2 m/hr
One Bed Volume = 1.481 liters
E.B.C.T. = 9.87 min

10 ppm Copper
Effluent Metal Concentrations

- [Graph showing effluent metal concentrations over bed volumes]

- Zn Concentration
- Cu Concentration
- Exit pH
Figure 4-36: Zinc and Copper Concentrations versus Bed Depth at Various Bed Volumes
10 ppm Copper and 10 ppm Zinc

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.46 liters
10 ppm Copper and 10 ppm Zinc

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Figure 4-39: pH, Zinc, and Copper Concentrations for the 10 ppm Zinc and Copper Column Run at 1.5 and 4.5 inch Bed Depths

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Figure 4-40: Head Loss for the Tap Water with Intermittent Backwashing

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters
Figure 4.4i: Head Loss per Length of Bed for the Tap Water with Intermittent Backwashing

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min
One Bed Volume = 1.48 liters

- Exit pH
- 0-1" Bed Depth
- 1-4" Bed Depth
- 4-7" Bed Depth
- 7-10" Bed Depth
- 10-12" Bed Depth
Figure 4.42: Head Loss for Tap Water Varying the Flow Rate; Run #1

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min

Flow Rate = 225 ml/min
Velocity = 3 m/hr
E.B.C.T. = 6.58 min

Q = 300 ml/min
V = 4 m/hr
C.T. = 4.94 min

Head Loss (in. of water)

Bed Volumes

- Exit pH
- 1" Bed Depth
- 4" Bed Depth
- 7" Bed Depth
- 10" Bed Depth
- 12" Bed Depth

Bed Depth

- 4"
- 8"
- 12"
Figure 4.13: Head Loss per Length of Bed for Tap Water Varying Flow Rate

Run #1

- Exit pH
- 0-1" Bed Depth
- 1-4" Bed Depth
- 4-7" Bed Depth
- 7-10" Bed Depth
- 10-12" Bed Depth

Flow Rate = 150 ml/min
Velocity = 2 m/hr
E.B.C.T. = 9.87 min

Flow Rate = 225 ml/min
Velocity = 3 m/hr
E.B.C.T. = 6.58 min

Q = 300 ml/min
V = 4 m/hr
C.T. = 4.94 min

Bed Volumes

pH

0.45
0.4
0.35
0.4
0.3
0.25
0.2
0.15
0.1
0.05
0

0 10 20 30 40 50 60 70 80
Figure 4.44: Head Loss for Tap Water Varying the Flow Rate; Run #2

- Exit pH
- 1" Bed Depth
- 4" Bed Depth
- 7" Bed Depth
- 10" Bed Depth
- 12" Bed Depth

Tap Water Varying Flow Rate
Run #2

Q = 300 ml/min
V = 4 m/hr
C.T. = 4.94 min
Flow Rate = 450 ml/min
Velocity = 6 m/hr
E.B.C.T. = 3.29 min

Q = 150 ml/min
V = 2 m/hr
C.T. = 9.67 min

Flow Rate = 600 ml/min
Velocity = 8 m/hr
E.B.C.T. = 2.47 min
Figure 4.45: Head Loss per Length of Bed for Tap Water Varying the Flow Rate

Tap Water Varying Flow Rate
Run #2

Flow Rate = 300 ml/min
V = 4 m/hr
C.T. = 4.94 min

Flow Rate = 450 ml/min
Velocity = 6 m/hr
E.B.C.T. = 3.29 min

Flow Rate = 600 ml/min
Velocity = 8 m/hr
E.B.C.T. = 2.47 min

-■- Exit pH
- ■- 0-1" Bed Depth
- x- 1-4" Bed Depth
- ▲- 4-7" Bed Depth
- △- 7-10" Bed Depth
- ▲- 10-12" Bed Depth

Bed Volumes

P H
Table 4-1: Pertinent ECOTITE Characteristics needed to calculate hydraulic properties

<table>
<thead>
<tr>
<th>Avg. Dm (cm)</th>
<th>Density (g/cm^3)</th>
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<td>REYNOLDS NUMBER</td>
<td>PRESSURE DROP (N/m^2 per m)</td>
<td>HEAD LOSS (m/m)</td>
</tr>
<tr>
<td>-------------------</td>
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Table 4-2: Reynolds Number, Pressure Drop, and Head Loss for Various Flow Rates
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<th>Flow Rate (ml/min)</th>
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<th>225</th>
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Table 4-3: Carman-Kozeny Head Loss at Different Bed Depths for Various Flow Rates
Figure 4-46: Comparison of Experimental Head Loss verses the Carman-Kozeny Equation's Prediction
Figure 4-47: Log-Log Plot of Head Loss Versus Flow Rate for Various Bed Depths
Figure 4-48: Backwash Flow Rates verses Bed Expansion for Tap Water Run #1, Run #2, and the Theoretical Predictions
Chapter 5

CONCLUSIONS AND COMMENTS

5.1 REVIEW OF THE PREFORMED STUDY

ECOTITE is the trade name given to the iron rich material produced from the process of metal recovery from EAF dust. Previous work has determined ECOTITE’s ability to absorb heavy metals out of aqueous solutions. Packed bed columns are the most viable equipment configuration to utilize ECOTITE as a heavy metal sorbent. This study focused on developing a correlation between the feed water compositions and the pressure drop across the ECOTITE column. Packed bed columns using ECOTITE could replace more expensive conventional metal removal processes if a workable procedure for designing the columns is identified.

Experiments were conducted varying the chemical composition of the influent waste water to determine the effects on the performance of the ECOTITE bed. Excessive pressure build up across the bed from variables such as influent metal concentrations, waste water pH, attrition, and turbidity, were of major concern.
5.2 CONCLUSIONS

• Suspended solids are filtered by the fixed bed which caused an increase in the pressure drop across the bed. Running the column in an upflow mode alleviated the deleterious effects of filtration.

• At low heavy metal concentrations, ion exchange was the primary removal process.

• Removal of heavy metals via ECOTITE, occurs by ion exchange before metal precipitation.

• At high heavy metal concentrations, metal precipitates are formed which clog the bed and increase the pressure drop.

• Backwashing was an effective way of reversing the effects of filtration and heavy metal precipitation.

• Bed particle shrinkage due to attrition was negligible compared with filtration and metal precipitation.

• Breakthrough of heavy metals through the bed was accompanied by a sharp drop in effluent pH. The pH drop could be used as an indicator for bed exhaustion.

• Leaching of metals off of the column may affect ECOTITE’s marketability.
5.3 FUTURE WORK

Additional work should be preformed on ECOTITE if it is to be marketed as a heavy metal sorbent.

- Studies should be preformed to readdress the problem of leaching of heavy metal off of exhausted ECOTITE.
- Regeneration studies should be preformed to determine if ECOTITE is reusable.
- Experiments with the column running in an upflow direction should be preformed on high influent concentration of metals to determine if bed clogging by metal precipitates is avoided. Collection of the heavy metal precipitates must be addressed.
- A sieve analysis should be performed on an ECOTITE bed to improve the accuracy of the calculations used to predict bed expansion due to backwashing.
REFERENCES


A.1 CARMAN-KOZENY EQUATION

In a study by Darcy (1856) the hydraulic gradient was determined under laminar flow conditions in a porous media to be a function of the depth of the porous media, the hydraulic permeability of the porous media, and the viscosity of the liquid flowing through the porous media [8]. Subsequently, Carman (1937) developed a theoretical expression for the hydraulic gradient by postulating a physical model of the porous media. The Carman-Kozeny equation to calculate the pressure drop per unit length of the bed is given as

\[ \frac{\Delta P}{L} = \frac{k \mu S^2 V_0}{\epsilon_0^3} \]

where \( V_0 \) = superficial liquid-phase velocity, m/hr

\( \mu = \) viscosity of water or liquid, kg/m·s

\( \epsilon_0 = \) void fraction, dimensionless

\( k = \) Kozeny-Carman constant

\( S = \) specific surface area, m²/gm
\( L = \text{length of bed, m} \)

The Kozeny-Carman constant has been experimentally shown to be approximately 5 [8]. For spherical particles, \( S \) is given by

\[
S = \frac{6 \ (1 - \epsilon_0)}{d_p}
\]

where \( d_p = \text{mean particle diameter, cm} \)

The relationship between head loss and pressure drop is given by

\[
\Delta P = \Delta H \rho_L g
\]

where \( \rho_L = \text{density of water or liquid, kg/m}^3 \)

\( g = \text{gravity, m/s}^2 \)

The Carman-Kozeny equation to calculate the head loss per unit length of a packed bed is given by

\[
\frac{\Delta H}{L} = \frac{180 \ (1-\epsilon_0)^2 \ \mu \ V_0}{\epsilon_0^3 \ d_p^2 \ \rho_L \ g}
\]

The pressure drop across a packed bed is strongly influenced by the particle diameters and the void fractions.
A.2 REYNOLDS NUMBER

Flow through a porous media may be laminar or turbulent depending on the properties of the porous media and the liquid which flows through the media. Laminar flow is observed when the Reynolds number is less than 10 [8]. The Reynolds number in a porous media is defined as

\[ Re = \frac{d_p \cdot V_0 \cdot \rho_L}{\mu \cdot (1 - \varepsilon_0)} \]

where \( V_0 \) = superficial liquid-phase velocity, m/hr

\( \mu \) = viscosity of water or liquid, kg/m s

\( \varepsilon_0 \) = void fraction, dimensionless

\( d_p \) = mean particle diameter, cm

\( \rho_L \) = density of water or liquid, kg/m^3
APPENDIX B

B.1 SETTLING VELOCITY

The settling of particles in a fluid can be analyzed by Newton's law of sedimentation. Newton's law yields the terminal velocity of a particle, by equating the gravitational force on the particle with the frictional resistance or drag force [9]. Newton's law for spherical particles is given by

\[ V_t^2 = \frac{4}{3} g \left( \frac{\rho_p - \rho_w}{C_D \rho_w} \right) \frac{d_p}{\rho_p} \]

where \( v_t \) = terminal settling velocity, m/s

\( g \) = gravity, m/s²

\( \rho_p \) = density of ECOTITE particle, kg/m³

\( \rho_w \) = density of water or liquid, kg/m³

\( d_p \) = mean particle diameter, m

\( C_D \) = coefficient of drag (see b.2), dimensionless

The settling velocity is dependent on the drag coefficient which in turn is dependent on the reynolds number [12]. An initial settling velocity is estimated from
which the drag coefficient and reynolds number are calculated and used to readjust the initial estimate of the settling velocity. Several iterations may be needed to calculate an accurate settling velocity.

B.2 DRAG COEFFICIENT

The equations to calculate the drag coefficient \( (C_D) \) vary with the different flow regimes [10]. For laminar, transitional, and turbulent flow, the values of \( C_D \) are given by

\[
C_D = \frac{24}{Re} \quad \text{(laminar)}
\]

\[
C_D = \frac{24}{Re} + \frac{3}{Re^{0.5}} + 0.34 \quad \text{(transitional)}
\]

\[
C_D = 0.4 \quad \text{(turbulent)}
\]

where \( Re = \) Reynolds number, dimensionless

All of the backwashing experiments were conducted in the transitional flow
range.

### B.3 REYNOLDS NUMBER

Reynolds numbers less than 1.0 indicate laminar flow, values above $10^4$ indicate turbulent flow, and intermediate values indicate transitional flow [10]. The Reynolds number for a settling particle is defined as

$$Re = \frac{\Phi \, v_t \, \rho_w \, d_p}{\mu}$$

where $v_t =$ settling velocity, m/s

$\rho_w =$ density of water or liquid, kg/m$^3$

$d_p =$ mean particle diameter, m

$\mu =$ viscosity of water or liquid, kg/m·s

$\Phi =$ shape factor, dimensionless

The shape factor ($\Phi$) is added to account for a lack of particle sphericity. For perfect spheres, the value of $\Phi$ is 1.0, for most filter media $\Phi$ ranges from 0.75 to 0.85 [10].

### B.4 BED EXPANSION EQUATIONS
To hydraulically expand a porous bed, the head loss must equal the buoyant mass of the particles in the fluid. The head loss through an expanded bed remains essentially unchanged since the total buoyant mass of the bed is constant. The head loss required to initiate the expansion of a porous bed is given by

\[ h_{rb} = L \left(1 - \varepsilon\right) \frac{\rho_p - \rho_w}{\rho_w} \]

where \( L \) = bed depth, m

\( \rho_p \) = density of ECOTITE particle, kg/m\(^3\)

\( \rho_w \) = density of water or liquid, kg/m\(^3\)

\( \varepsilon \) = void fraction, dimensionless

The expanded bed depth is a function of the terminal settling velocity, which remains constant, and the backwash velocity [11]. An increase in the backwash velocity will result in a greater expansion of the bed. The expression relating the backwash velocity to the expanded bed depth is given as follows

\[ L_{rb} = \frac{L \left(1 - \varepsilon\right)}{1 - \left(\frac{V_B}{V_T}\right)^{0.22}} \]

where \( L \) = bed depth, m

\( \varepsilon \) = void fraction, dimensionless
\( v_t = \) settling velocity, m/s

\( v_B = \) backwash velocity, m/s
Thomas Michael Connors was born on April 17, 1969 in New Rochelle, New York, to John and Sally Connors. He received his bachelor of science degree in Civil Engineering from Lehigh University, Bethlehem, PA, in 1992. He continued at Lehigh University to pursue a Masters of Science in Environmental Engineering.
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OF
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