EVALUATION OF SILVER TREATED SHALE AS PACKED BED WATER FILTERS

by

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TABLE OF CONTENTS

List of Tables

List of Figures

Abstract

Accessing clean water is a problem that faces many countries worldwide. Several filtration techniques exist, but they are typically too complicated or too expensive to use in third world countries. Therefore, the objective of this research is to evaluate a proposed method which could potentially be used to address this problem. It is known that silver works as an antibacterial agent, but the question of how it can be used to provide drinking water still remains. This research studies flow through packed beds of silver treated shale and evaluates how effective it is at removing bacteria.

1. Introduction

Despite many advances in water filtration technologies, affordable and effective filtration for many third world countries is still an issue. Bacteria existing in rivers and streams from many sources including human and animal waste makes the water unsafe to consume without effective treatment. Several designs for slow sand filters, activated carbon filters and cartridge filters exist, but none of them are affordable enough to provide large scale quantities of water for abundant and safe daily consumption over a long term time period. Although the exact mechanism is still debatable, metals have been known to be toxic to bacteria. Silver has a particularly strong effect on microorganisms which makes it appealing to those who are interested in studying water filtration. The objective of this research is to study water flow through packed beds of varying size compositions and relate it to the bacteria remediation from silver treated expanded shale.

2. Background

Many metals show what is referred to as an oligodynamic action which is the attack of the ions on the bacteria. The exact mechanism is still unknown although many ideas exist. This concept is rumored to have been known since about 450 BC which was noticed by Herodotus, an ancient Greek historian. A more modern attempt at understanding it was made by Karl Wilhelm von Nägeli, a Swiss botanist. Nägeli studied silver and other metals and developed the term oligodynamic ("small power" from latin origin). In particular, silver seems to have a high toxicity to microorganism and therefore, very little is needed for dramatic results. [1] This is one reason silver is of interest for this research. Silver nitrate decomposes at 440°C which is a reasonable temperature to reach and would only need to be reached once for a fairly short period of time.[2] The decomposition reaction can form NO_x and Ag_2O. [3] The decomposition

temperature of Silver (I) Oxide (Ag_2O), which is the most thermodynamically favorable Silver Oxide compound, is 200°C. Since the decomposition temperature for silver nitrate is higher than that of silver oxide, silver nitrate will decompose into $Ag_{(s)}$, $O_{2\,(g)}$ and $NO_{2\,(g)}$. [2]

Expanded shale is typically used as filler material in building products, treatment for wastewaters and as enhancement of soils. It is formed by firing shale in a rotary kiln. It is brought to 800°F to evaporate water rapidly. Then, it is heated to temperatures in excess of 2000°F to expand entrapped gases and burn off organic material.[4]

Expanded shale was chosen as the material to use for biological remediation since it offers a relatively porous structure. A high surface area material would have more room for silver treatment and more contact with bacteria. The shale for this research was supplied by Norlite Corporation, who uses the Normanskill Shale bed in Cohoes, NY. Each size was tested using the BET method to verify its surface area. The coarse, medium and fine particles yielded surface areas of 0.42, 0.40 and 1.65 m^2/g respectively. These are relatively low compared to other materials but expanded shale is an abundant, cheap material. Although higher surface areas would be desirable, surface area is not the focus of this research so experimentation was carried out with the shale.

Similar techniques for bacteria remediation have been implemented in the past. Reid Harvey's patent uses colloidal silver as a mechanism to deactivate bacteria. His filter design is quite different primarily due to the fact that the application of silver is different as well as the use of a prefired clay body rather than a loose packed particle bed. Reid uses a clay with a particle size of 10 to 30 mesh fired with a combustible material to create pores. Some of the combustible materials include rice flour, milled corn cobs, grain flour and other organics. The size of these organics is recommended to be approximately 350 mesh according to this design.

The clay and combustibles are mixed with water and dried for two days. The firing schedule for this filter includes temperatures of 500°C and higher depending on the clay material and kiln, for a dwell time of 3 to 6 hours. This porous material or grog is then ground up and combined with more clay (of the same or different composition as the grog), water and combustible material. This mixture is pressed as a damp mixture (water from clay and additional water) into a shape similar to dry pressing. The pressed shape is dried for up to four days and then fired again to temperatures above 500°C but most preferably up to 1100°C. The fired body can then be treated with colloidal silver by some unspecified method.[5] The process of producing these filters takes multiple days. Ideally, the filters would have much simpler processing steps and not include multiple firing steps. The proposed design in this research only requires a temperature no more than 500°C and for a much shorter dwell time.

R.K. McGeary has published a well-known article on particle packing. One significant finding from this article is that packing density is affected by the container size. His data indicates that the container should be at least ten times larger than the particle to eliminate boundary hindrance on packing.[6] This has been taken into consideration in this experimentation. The coarse particles used were about 3 mm in diameter. The diameter of the graduated cylinder used for the packing data was about 6 cm and the glass tubing used for the biological testing was about 56 mm. The schedule 80 PVC pipe for flow studies was 8 cm. All of which satisfy McGeary's recommendation for container size.

There are several types of bacteria that could potentially grow in water. Escherichia coli is naturally living inside animal intestines. Although it is not the most dangerous of microorganisms, it can still cause short-term illness for anyone and more serious health risks in young children and the elderly. Typically, e. coli is used as an indicator bacteria. The presence of

e. coli generally means that the water is contaminated with human or animal waste and could potentially contain more threatening pathogens, viruses and worms. For these reasons and its ability to rapidly reproduce, e.coli was chosen as the bacteria used in this research.[7]

3. Experimental Procedures

a. Packing Efficiency Data

Preliminary packing studies were done with 10 different ternary compositions of tabular alumina with varying only the percentage of coarse (+8 mesh), medium (-16-+35 mesh) and fine (-70 mesh) particles on a weight basis. The sizes were obtained by sieving. T-64 Tabular Alumina from Almatis and Expanded Shale from Norlite Aggregate were used. The alumina was used for obtaining packing and flow data only to establish a mathematical model which predicts packing and flow rates for any composition of coarse, medium and fine within the endpoints. The same data was then collected for the endpoints of shale particles which was used to adjust the model for the shale sizes.

For each composition, the quantities of coarse, medium and fine particles were weighed out separately. The particles were mixed by hand and placed into a graduated cylinder. The cylinder was then placed on a vibrating table with a constant frequency until the bed settled to a minimum volume. The volume was recorded. The packing density was obtained by dividing the known total mass of the mixture by the recorded volume for each composition. The packing efficiency was then calculated by dividing the packing density by the calculated theoretical density of the material determined by the Rule of Mixtures.

To supplement the packing efficiency data, material densities were necessary. To obtain this data, He Pycnometry was used.

b. Flow Data

The parameters considered to describe the water flow through the packed beds were composition, hydrostatic pressure, dry packing efficiency, packing homogeneity and residence time or flow rate.

An apparatus was constructed out of schedule 80 PVC pipe, plastic tubing, 100 mesh screen and hose barb fittings in order to keep the head pressure constant during each run, to be able to adjust the pressure between runs, to hold a packed bed of material and to be able to easily collect water that flowed through the bed. Figure 1 shows the setup.

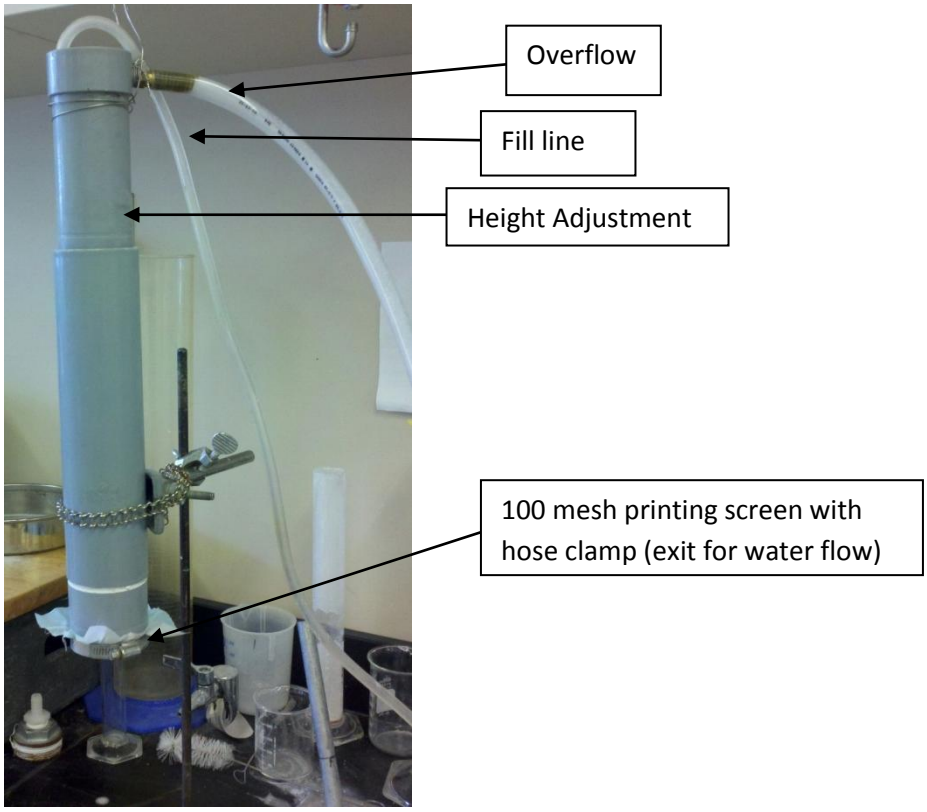

Figure 1. A photograph of the set up used for obtaining flow data

The beds were prepared by hand mixing the powders obtained on a weight basis according to which filter composition was being tested. The total weight of the bed was 250g. The screen was attached to the bottom of the filter using a steel hose clamp. The clamp was tightened leaving a small lip below the screen. The purpose of the lip was to prevent damage of the screen from residual material on tables. The mixed powder was then poured into the pipe. The distance between the top of the bed and the middle of the overflow tube was adjusted to 13.5”. This was determined based on the limits of the apparatus and to keep a comparable head pressure. The pipe (table to hose clamp contact) was placed on a vibrating table for approximately 30 seconds to help settle the particles. Then, with the pipe secured to the base, water was flowed through the bed for a minimum of 5 minutes to further settle the particles. If this was not done, the residence time significantly increased with time. Typically, data was collected by placing a graduated cylinder below the apparatus and timing the collection of 2000 ml. Some filters had very slow flow rates so instead of timing it based on volume, it was based on weight. The volume of water collected after some time was converted to volume using water’s density at room temperature. The volume was then divided by its corresponding time of collection to determine the flow rate (ml/sec).

c. Application of Silver

In order to kill bacteria, silver was to be added to the shale particles. Essentially, the silver was first placed on the shale surface by placing them into a silver nitrate solution. The solution was prepared at a concentration of 5g of silver nitrate per liter of water. Then, the shale was removed from the solution, dried and heated to above the decomposition temperature (440°C) of silver nitrate. [2] The heating schedule was simply a heating ramp (not critical to the

objective) to 550°C, held for an hour and then cooled at an uncontrolled rate. The remaining silver should be left behind somewhere on the shale. In an attempt to verify that the silver was successfully applied, thermogravimetric analysis (TGA), Electron Dispersive Spectroscopy (EDS) and Scanning Electron Microscope (SEM) analyses have been used. EDS and SEM was done with the FEI Quanta 200 F.

d. Bacterial Remediation

The bacteria used for the bacterial remediation testing with the silver treated shale were Escherichia coli (e. coli). It was prepared using LB Broth. Agar was used for growing bacteria colonies before and after treatment. Table I shows the composition of the broth and agar.

Table I. A table which includes the batches for the broth and agar used for obtaining bacteria data

	Broth	Agar
Tryptone	2.5 g	2.5 g
Yeast Extract	1 g	1 g
NaCl	2.5 g	2.5 g
Agar	-	7.5 g
Distilled Water	500 ml	500 ml

After mixing the ingredients, the broth and agar were placed in Harvey Sterile Max autoclave for a 15 minute 121°C cycle which is recommended for liquids. The broth and agar were stored in a refrigerator when not being used for testing. To make bacteria infested broth, pre-grown e.coli was placed into the broth which was incubated at 37° C for approximately 24 hours.

Obtaining data for bacteria remediation followed a commonly used spread plate colony counting technique as described in literature with only some slight deviations.[8] Glass testing tubes were constructed by using epoxy to fasten 100 mesh steel screen patches to the bottom. These tube assemblies were autoclaved. The silver treated shale for 6 different size compositions were placed inside the tubes. The tubes were moved into a laminar flow hood where the rest of the work was done. The prepared inoculated LB broth was then diluted 1:1 with sterile water to increase the volume of fluid to be flowed through the filter beds. It was assumed that although the fluid was diluted the level of bacteria present would still be sufficient for the analysis. The fluid was then poured over the media in the tubes. The effluent fluid was collected. The set up is shown in Figure 2.

Figure 2. A photograph of the set up for flowing and collecting fluid for bacteria data

For some of the filters, it was apparent that filter media passed through the screen on the bottom of the tube. This only occurred for a short time. The particle inclusive fluid was not used for analysis. Fluid that appeared particle free was collected. The fluid was then distributed into a well plate. Each column contained 8 samples. A column for the sterile water/inoculated broth mixture and for the sterile water/non-inoculated broth mixture were prepared as well as one column for effluent fluid from each filter bed. Then, using UV-Vis spectroscopy, absorbance values for each well were obtained. The data was normalized so that it could be directly correlated to the amount of bacteria present. Samples of 980 µl of sterile water and 20 µl of effluent fluid (1:50 dilution) were prepared in alcohol sterilized plastic tubes. The tubes were mixed using a mini-vortex mixer. Then, using sterile cotton swabs, the dilutions for each filter were spread out on agar plated petri dishes and incubated at 37°C for well over 24 hours. Dishes for just sterile water were also prepared and incubated in the same way. The purpose of the spread plating was to provide a visual to support the spectroscopy data.

4. Results and Discussion

a) Packing Density

The packing efficiency data includes values calculated based on the skeletal density of the powders and the rule of mixtures as well as just using the theoretical density of alumina. The He Pycnometer (skeletal density) results are shown in Table II.

Table II. A table which includes the density for the materials determined by helium pycnometry

Material	Coarse Density (g/cm^3)	Medium Density (g/cm^3)	Fine Density (g/cm^3)
T-64 Tabular Alumina	3.73	3.74	3.87
Expanded Shale	2.25	2.25	2.63

The packing densities and efficiencies for tabular alumina are shown in Table III.

Table III. A table that includes packing density data from measurements as well as calculated efficiencies

Run #	Coarse	Medium	Fine	volume	Density	% Packing Efficiency from Theoretical Density of Alumina (100*ρ /3.96)	% Packing Efficiency from Rule of Mixtures Density
1	1.00	0.00	0.00	460	2.174	54.9%	58.3%
2	0.67	0.17	0.17	380	2.632	66.5%	70.0%
3	0.00	1.00	0.00	490	2.041	51.5%	54.5%
4	0.17	0.17	0.67	370	2.703	68.3%	70.6%
5	0.50	0.50	0.00	410	2.439	61.6%	65.2%
6	0.00	0.50	0.50	360	2.778	70.1%	72.9%
7	0.50	0.00	0.50	360	2.778	70.1%	73.1%
8	0.00	0.00	1.00	390	2.564	64.8%	66.2%
9	0.00	0.50	0.50	360	2.778	70.1%	72.9%
10	0.00	0.00	1.00	400	2.500	63.1%	64.6%
11	0.33	0.33	0.33	340	2.941	74.3%	77.7%
12	1.00	0.00	0.00	450	2.222	56.1%	59.5%
13	0.00	1.00	0.00	470	2.128	53.7%	56.8%
14	0.50	0.00	0.50	350	2.857	72.2%	75.1%
15	0.50	0.50	0.00	420	2.381	60.1%	63.7%
16	1.00	0.00	0.00	450	2.222	56.1%	59.5%
17	0.17	0.67	0.17	400	2.500	63.1%	66.4%

The Rule of Mixtures is as follows: Density = $(f_1)(\rho_1)+ (f_2)(\rho_2)+ (f_3)(\rho_3)$ where f_i = component fraction of total and ρ_i=density of component. This calculated value and the theoretical density of alumina were used to determine the packing efficiencies. This data was

modeled using Design-Expert software.[9] Figure 3 is the resulting ternary contour map displaying the packing density data for tabular alumina.

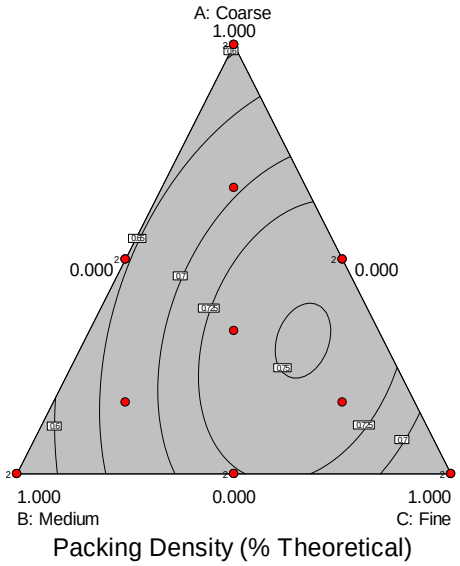

Figure 3. A contour map of the measured packing data formed using Design-Expert software.

From the sieving results, Figure 4 was developed showing that the sizes used for the modeling (T-64 Tabular Alumina) and the silver treatment (shale) are nearly 1:1.

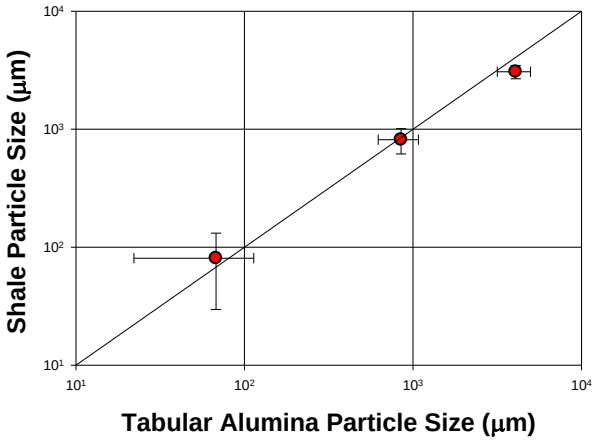

Figure 4. A plot of the calculated particle size distribution from the sieve analysis

The calculated size distributions are described in Table IV.

Table IV.A table of the particle size distribution data as calculated from the sieve analysis

	Shale			Tabular		
µm	Coarse	Medium	Fine	Coarse	Medium	Fine
D75	3489.0	1036.2	134.2	5077.8	1108.2	121.3
D50	3071.4	814.8	80.6	4071.2	849.9	67.8
D25	2703.7	640.7	48.5	3264.2	651.9	37.9

McGeary's article on particle packing reports that maximum density of a ternary component particle composition occurs at volume percentages of 66:25:9 for size ratios of 77:7:1 (coarse:medium:fine). The tabular alumina in this research has a size ratio of 60:12:1.[6] This ratio is different with volume percentages of 33:18:49. This result is very different from McGeary's findings. The difference may be related to the size distribution, average size difference and the slightly different size ratio. Also, McGeary used metal spheres which are much closer to being perfectly spherical.

b) Flow Data

The ternary component diagram as shown in Figure 5 shows a map of flow data obtained using the previously described procedure for T-64 Tabular Alumina.

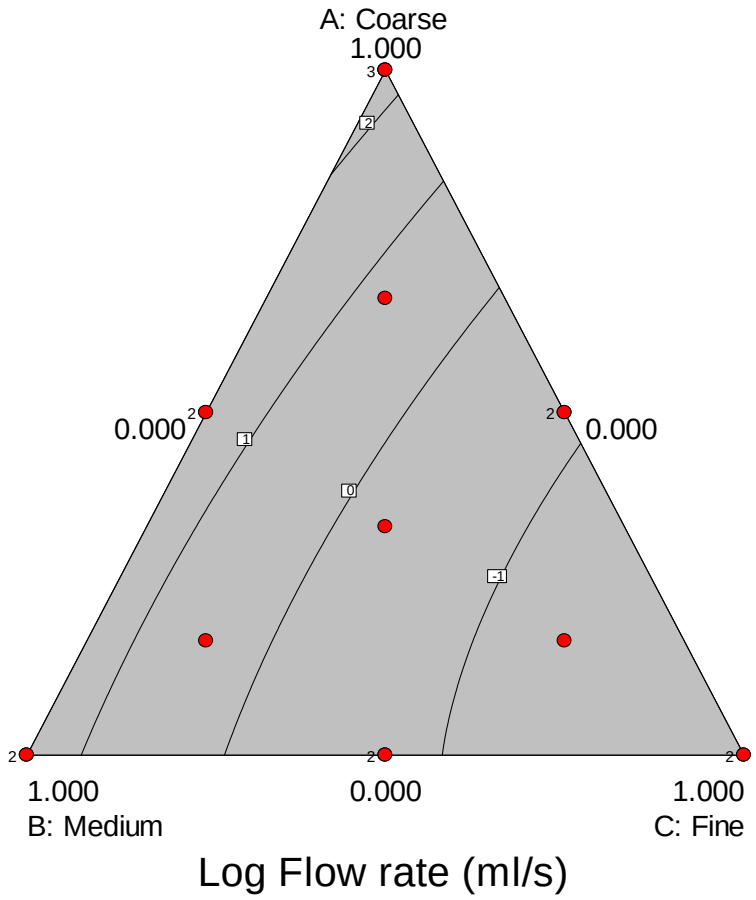

Figure 5. A contour map formed by Design-Expert of the measured flow data

The map uses the log scale because there is no obvious trend from the data on a linear scale. On a log scale however, the map shows that flow is strongly dictated by the fines. The coarse and medium do not restrict the flow very much without the fines. This does not correlate with the packing density data. If it did, then the map would show the lowest flow rate near the highest packing density as indicated by the center of the ring in the packing density map. This is useful information because it is now known that to restrict the flow to a minimum, the bed should be composed of all fines. Adding in any mediums to a binary coarse and fine mixture actually increases the flow rate despite the slight increase in packing density. This fact that it

does not decrease flow could potentially be a result of the particle size distribution. The fines alone however, did not result in the lowest flow rate. It required a mixture of coarse and fines to obtain a minimum. This model is expected to hold true for any particle sizes as long as it adjusted to those particular sizes.

Figure 6 shows a comparison of the flow rates for the tabular alumina to the shale.

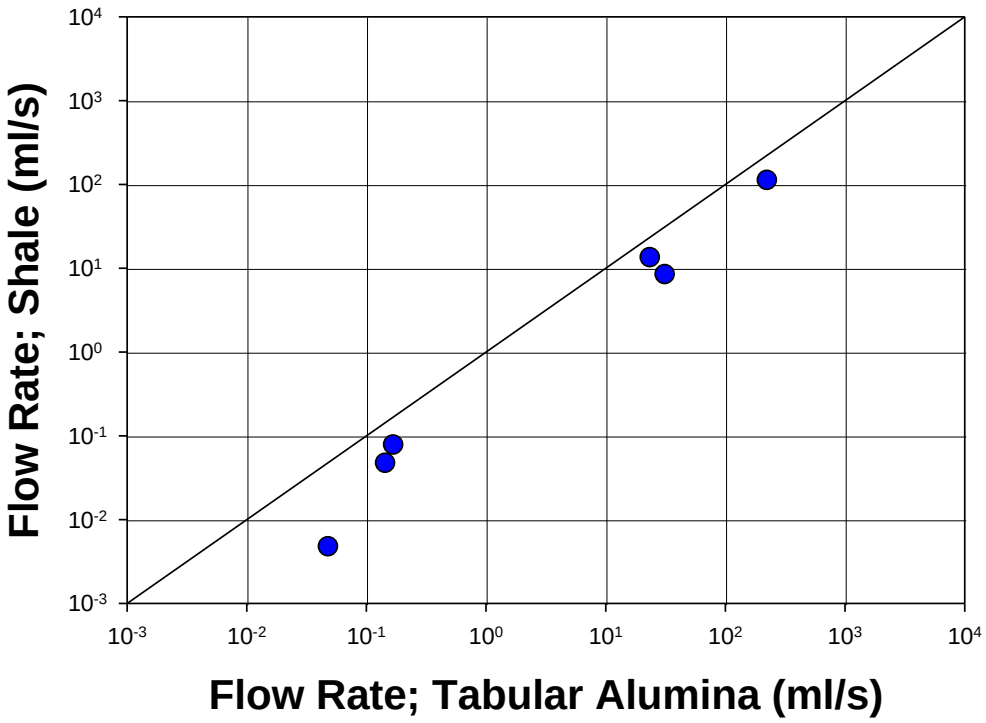

Figure 6. A plot of measured flow rate data which compares the model material (T-64) with silver treated material (shale)

It is not perfectly 1:1 but it is relatively close as shown by the y = x line in the plot.

One observation that is worth noting is the settling of fines through the coarser material. The bed almost became two separate beds, the top containing entirely coarse material and the bottom containing a mixture of fine and coarse material. More specifically, this would

happen when there was a concentration of fines such that the fines did not fill the void space entirely within the coarse material.

c) Application of Silver

As mentioned, EDS and SEM were used to verify that silver was successfully added. Figure 7 shows a micrograph of a bright spot found within the silver treated medium particles.

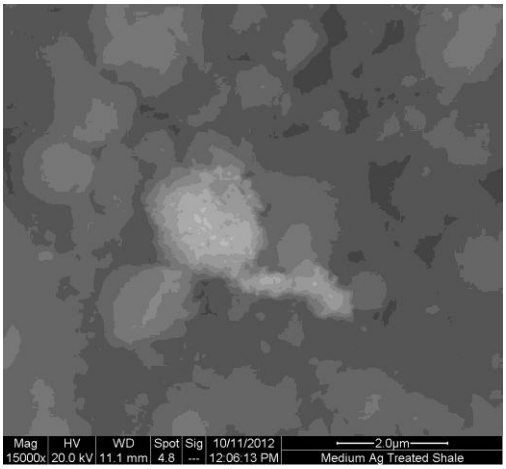

Figure 7. A micrograph of a clump of bright particles found on medium treated shale which are likely to be AgCl

Since silver is expected to show up bright, this spot was of particular interest. EDS analysis data of a spot similar to this is shown in Figure 8.

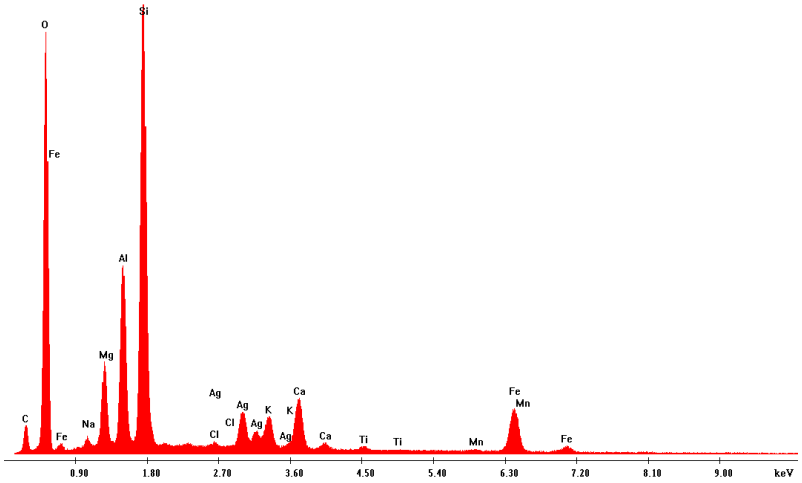

Figure 8. A plot of EDS data collected from a bright clump of particles found in SEM analysis

This plot suggests that silver is present as well as chlorine. The other elements shown are likely to exist within the shale substrate. The fact that silver and chlorine exist at this spot suggests that AgCl has formed and exists as the bright spot shown in the micrograph. Since this is not a desirable reaction for bacteria remediation, this should be eventually improved so that the reaction does not occur. This may be difficult since silver in the presence of chlorine will readily react. Metallic silver by itself was not found by itself anywhere else. One possible reason for not finding it is because the metallic silver may be too small in size and in quantity. Another reason may be because it has formed deep in pores. To test this, a fractured particle should be analyzed. This has not yet been done.

The next attempt to verify that the desired reaction of silver nitrate decomposition has occurred and that silver has been left behind on the shale was thermogravimetric analysis. Figures 9, 10 and 11 show the weight loss percentage with increasing temperature of silver treated coarse, medium and fine particles respectively.

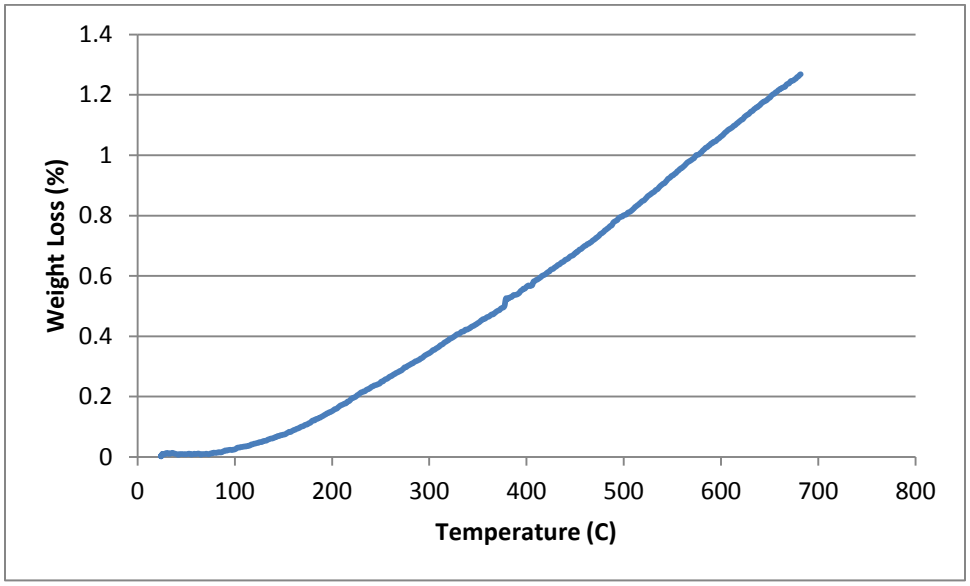

Figure 9. TGA data from coarse silver treated shale particles

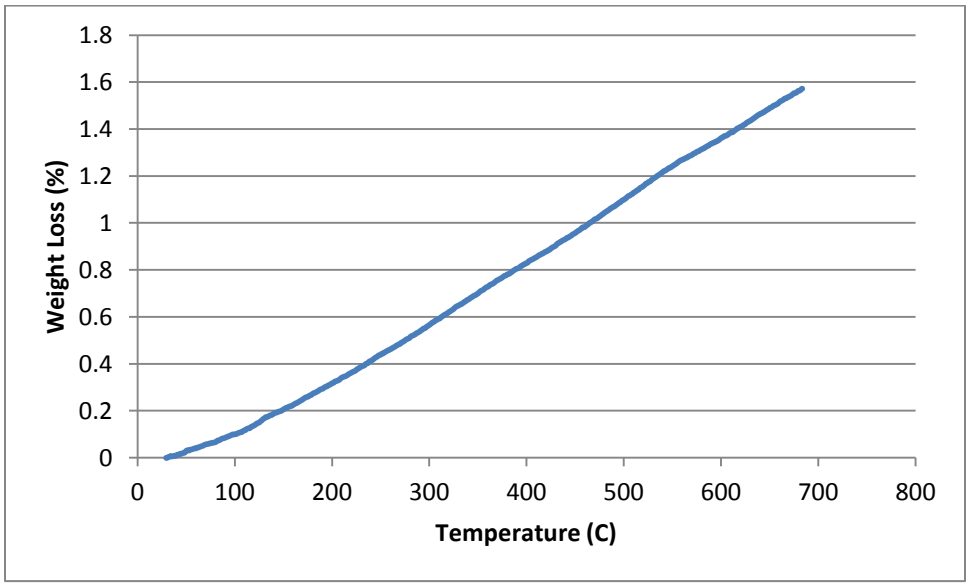

Figure 10. TGA data from medium silver treated shale particles

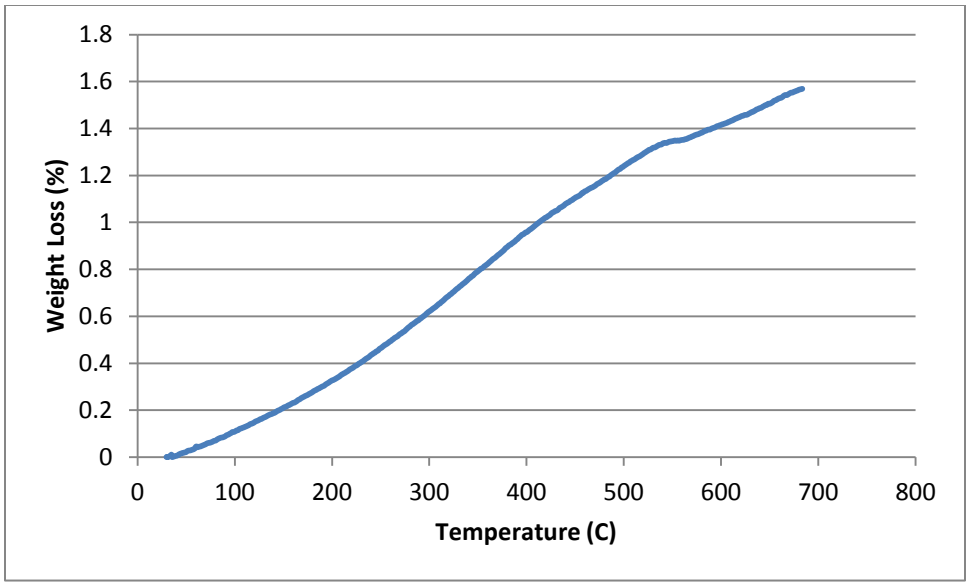

Figure 11. TGA data from medium silver treated shale particles

None of these plots have a clear indication of where this reaction occurs. As previously mentioned, it is expected to occur at 440°C. Since the weight loss appears gradual, a baseline for comparison was created by analyzing untreated fines as shown in Figure 12.

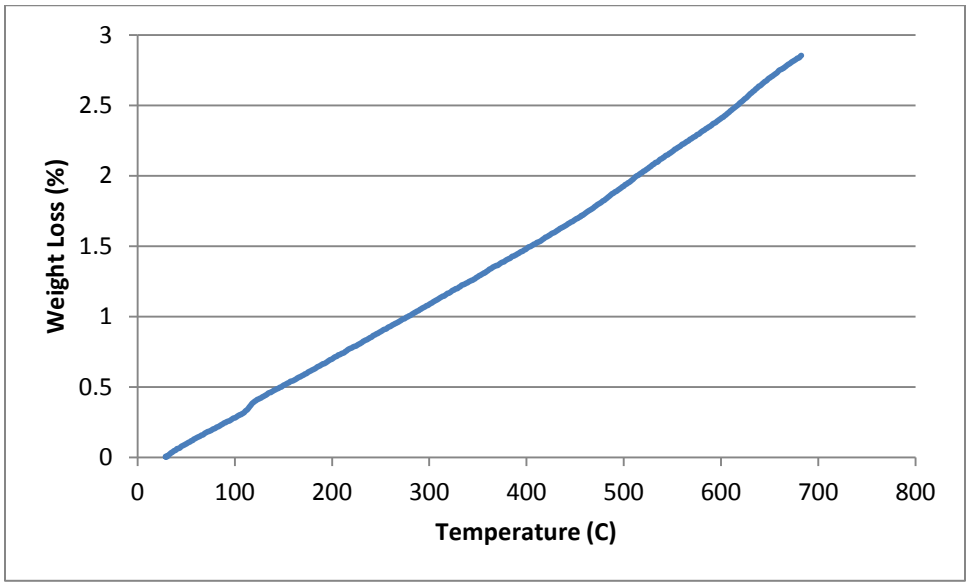

Figure 12. TGA data from fine untreated shale particles

The weight loss for the untreated fine also appears gradual, which suggests that it is an effect caused by the instrumentation. Another attempt at verifying the reaction of silver nitrate decomposition was to analyze silver nitrate treated A-10 alumina. Figure 13 shows the analysis of the treated alumina.

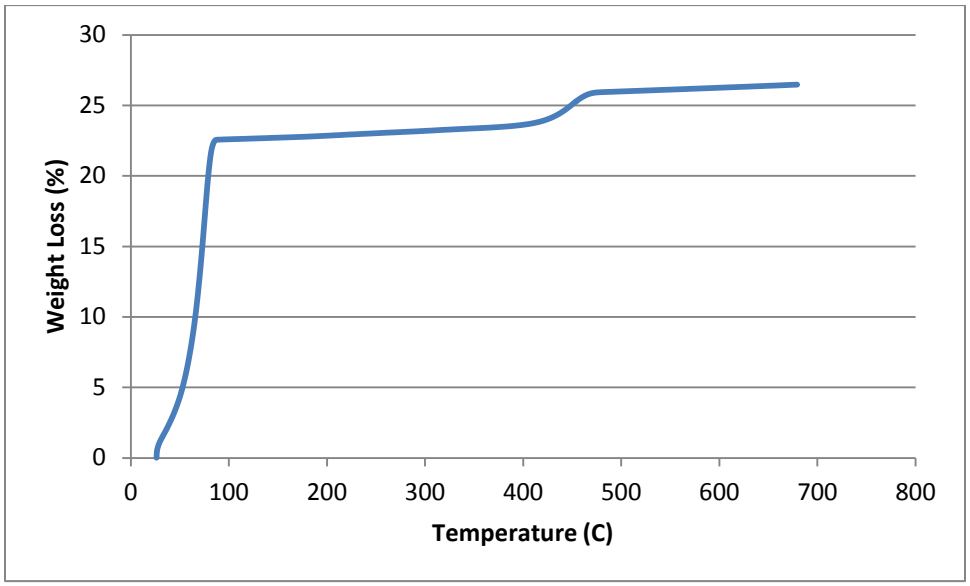

Figure 13. TGA data from silver treated A-10 alumina particles

The sample analyzed came from a batch consisting of 0.0358g silver nitrate, 0.0378g A-10 alumina and 0.2400g of distilled water. The first large drop in weight up to about 100°C is due to the water loss. This is not shown in the shale analyses because the samples were dry. The second drop in weight from about 420 to 470°C is expected to be from the silver nitrate decomposition. Figure 14 shows the analysis of untreated alumina.

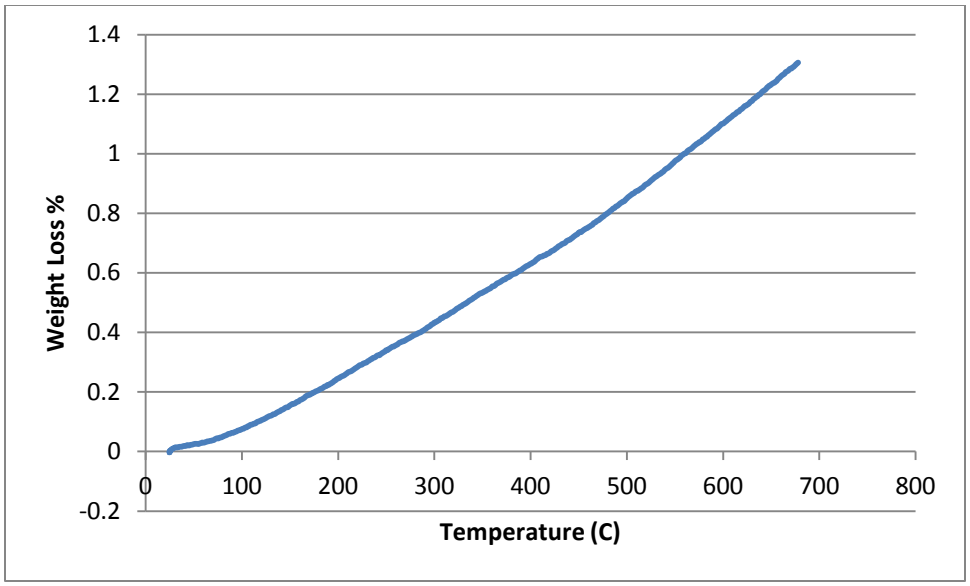

Figure 14. TGA data from medium silver treated shale particles

There is no drop due to water loss or nitrate decomposition in the untreated alumina, which is expected however, the gradual weight loss believed to be from the instrument still exists. Using these plots, the heating schedule for the shale was determined which included a dwell time of an hour at 550°C. The heating rate was determined by the maximum capability of the kiln and the cooling rate was uncontrolled. Both heating and cooling were not critical rates for the objective of decomposing silver nitrate.

Figure 15 shows a color change that occurred during the heat treatment

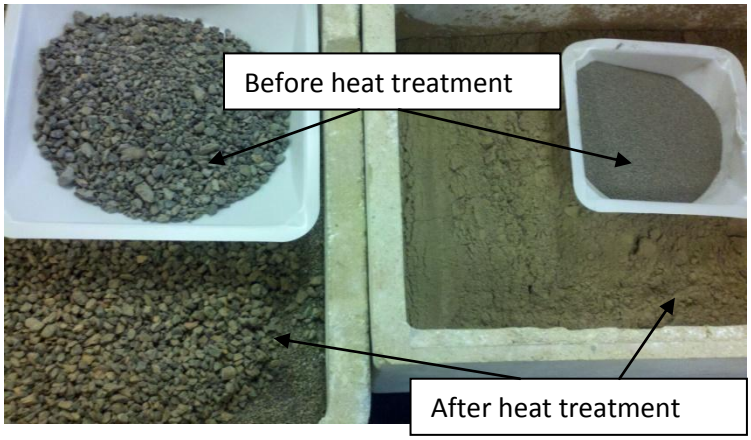

Figure 15. A photograph showing the color change of the shale before and after heat treatment

There is an obvious color change which may be an indicator that some reaction has occurred. The color change is not due to water loss because the shale was dry in both cases.

d) Bacteria Remediation

A quick preliminary test before the testing with the filters began was a check of the zone of inhibition. The zone of inhibition is a region around an antimicrobial agent that is clear due to the effective killing of bacteria. Sterile agar was heated in a microwave and poured into a sterile Petri dish. Before the agar solidified, silver treated shale of each of the three sizes was placed into dish. Once it solidified, sterile swabs were used to collect pre-grown e. coli and spread the bacteria over the surface of the agar. The dishes were allowed to incubate overnight. Figures 16, 17 and 18 show that the bacteria were unable to grow around each of the different sizes of shale.

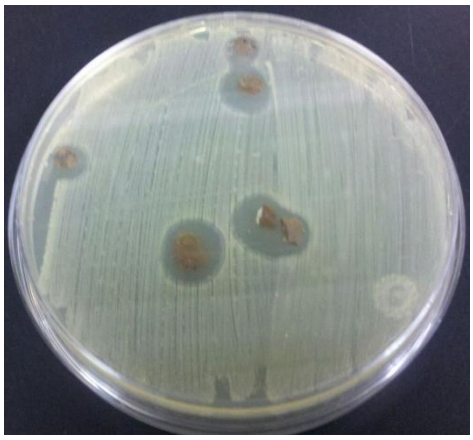

Figure 16. A photograph of silver treated coarse shale and the zone of inhibition (100mm diameter dish)

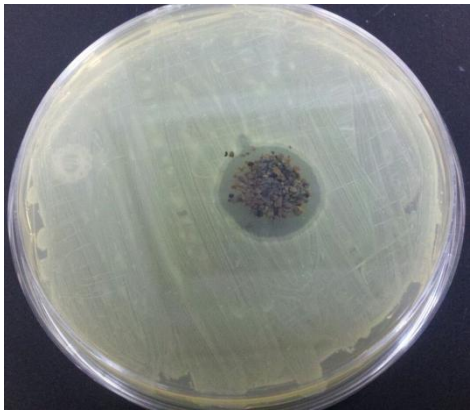

Figure 17. A photograph of silver treated medium shale and the zone of inhibition (100mm diameter dish)

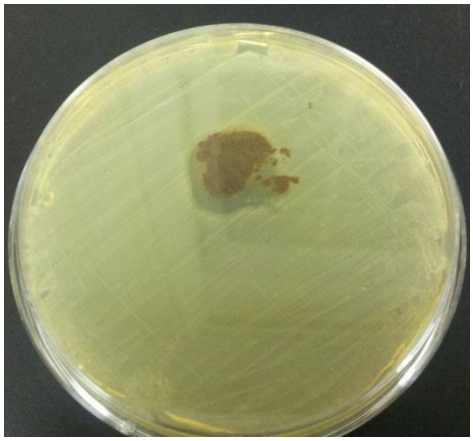

Figure 18. A photograph of silver treated coarse shale and the zone of inhibition (100mm diameter dish)

Although the zone of inhibition test was not used for quantitative purposes, it does show that all three treated shale sizes can kill bacteria after some critical exposure time.

Figure 19 summarizes the data obtained from the UV-Vis Spectroscopy analysis.

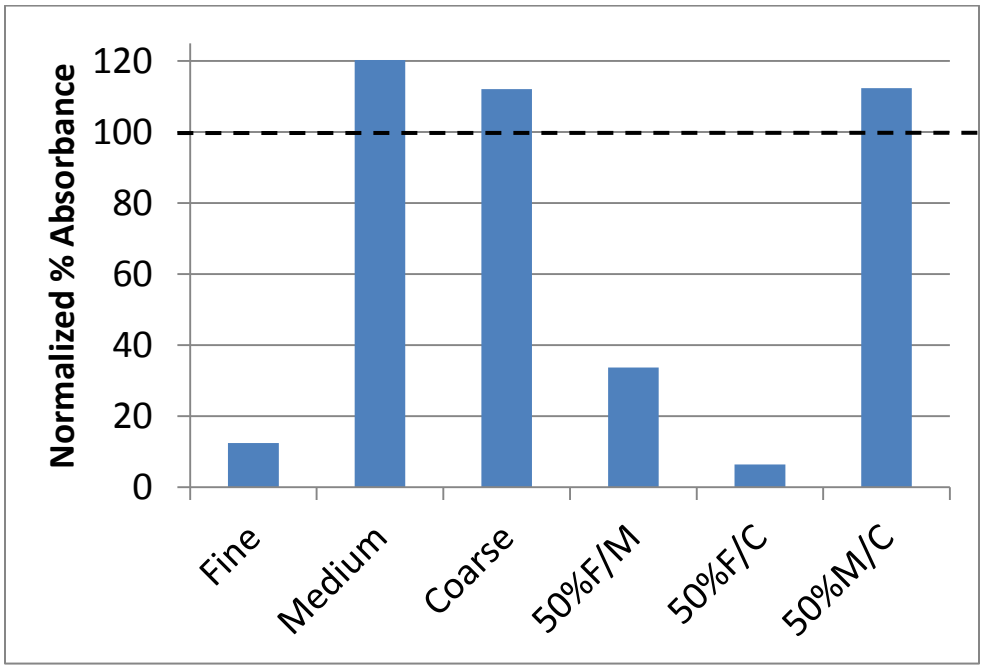

Figure 19. A plot of the normalized absorbance values obtained from UV-Vis spectroscopy for each filter

The data clearly suggests that filters with fines show significantly better bacteria remediation compared to those that do not. From the previous flow studies, it is understood that the concentration of fines dictates the flow rate. Therefore, the filters with fines provided a slow enough flow rate or a long enough residence time for some bacteria remediation. The others have a flow rate that is too fast and a residence time that is too short for bacteria remediation. Since the measurement of absorbance is affected by any turbidity in the fluid, a number of things including shale and dust particles that slipped passed the screen can have an effect on the absorbance reading. The values have been normalized but only by using broth and

water that have not come in contact with the filters which means that shale particles would not be in the fluid. This could account for why the values are above 100% for the coarse, medium and 50% medium/coarse filters. For the same reason, it is likely that the recorded values for the filters with fine particles are actually higher than they should be.

The well plate used for the UV-Vis Spectroscopy was saved and incubated to see if the bacteria growth in the wells supported the spectroscopy data. Figure 20 shows the well plate which is explained in Table V.

Figure 20. A photograph of the 96 well plate used for the absorbance measurement after it was incubated for over 24 hours at 37°C (Each row is a repetition of the same composition as the rest of the wells in that column)

Table V. A list to identify the columns shown in Figure 20

Column	Fluid Description
1	Broth and Sterile Water Only
2	Inoculated Broth and Sterile Water
3	Effluent from Fine Filter
4	Effluent from Medium Filter
5	Effluent from Coarse Filter
6	Effluent from 50% Medium/Fine Filter
7	Effluent from 50% Coarse/Fine Filter
8	Effluent from 50% Coarse/Medium Filter

Figure 20 does support the absorbance values. The effluent fluid from the fine filters show up clear whereas the coarse, medium and 50% coarse/medium filters are cloudy. Cloudiness indicates bacteria growth. The only unexpected part of this image is that the broth and supposedly sterile water had bacteria growth. This indicates that contamination is a possibility. During the tests, fine shale particles obviously leaked passed the screen on the bottom of the tube into the effluent fluid. The fluid used for the spectroscopy testing was collected only after it appeared that the fluid flowing from the filter was clear. If some shale particles were still in the fluid, an effect similar to the zone of inhibition test may have been happening. The silver on the particles would continue killing bacteria in the effluent fluid with time which would make the relationship between absorbance and the residence time invalid. Although the absorbance was measured within only a few hours of the test, it is still a significant amount of time. One point that suggests that the data collected is valid to at least some extent is that it is likely that some fine silver coated dust on the coarse and medium particles likely got into the effluent fluid for those filters. Bacteria growth still occurred in these samples meaning that it is likely that the samples collected were acceptable and fine particles in the fluid did not affect the data.

Figure 21 shows the spread plating results using the 1:50 dilution as described in the procedures.

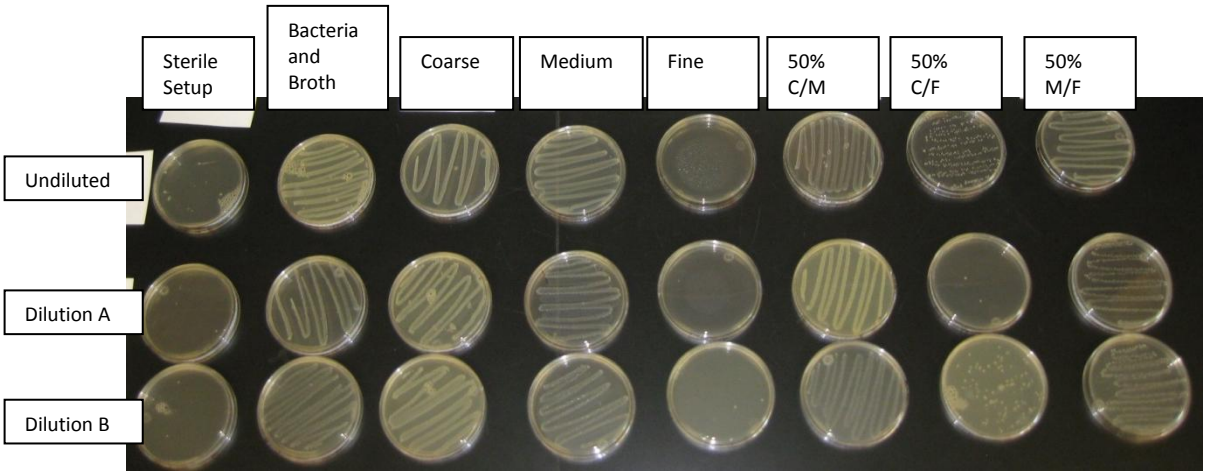

Figure 21. A photograph of the petri dishes used for spread plating after incubation

This technique is designed to observe bacteria growth so each dish was incubated for over 24 hours at 37°C. These results also match up to the spectroscopy data. However, there is evidence of some contamination. The dishes with sterile water and broth should not contain any colonies but they do have some. Additionally, the undiluted fine dish does not contain any colonies whereas there are some in diluted fine dish A. Although it is not perfect, overall it does support that the absorbance values are believable.

5. Conclusions

Figure 22 shows the absorbance values from the bacteria testing plotted against the flow rates for the corresponding filter beds.

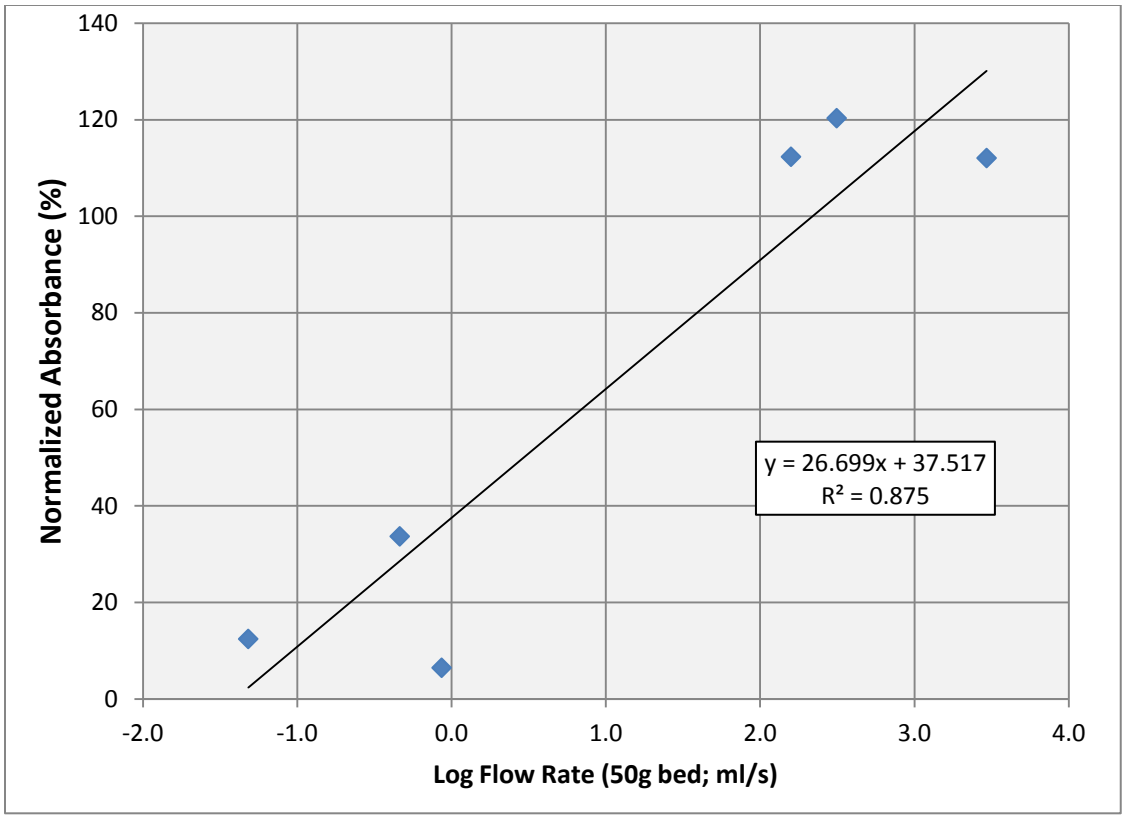

Figure 22. A plot of absorbance values versus the extrapolated flow rates.

The flow rates in the plot are calculated for 50g beds. This was done by using the packing density data, size of the container used for obtaining flow rates and the flow rates for 250g beds to get a correction factor in units of ml*cm/s. Essentially, this is the flow rate times bed height. The bed heights for 50 gram beds were calculated using the packing density and size of the container. Then, dividing the correction factor by the bed height of the 50g beds resulted in having a corresponding flow rate. This relationship should be confirmed with flow tests of different bed heights but for this modeling, it is assumed to be a reasonable estimate. Since it makes more sense to discuss the data in terms of residence time (s/ml), the flow rates can simply be inverted. The point where the absorbance is zero (ideal target of 100% bacteria killed) is calculated to occur where the residence time is 62 s/ml.

Figure 23 ties together the bacteria data and flow data.

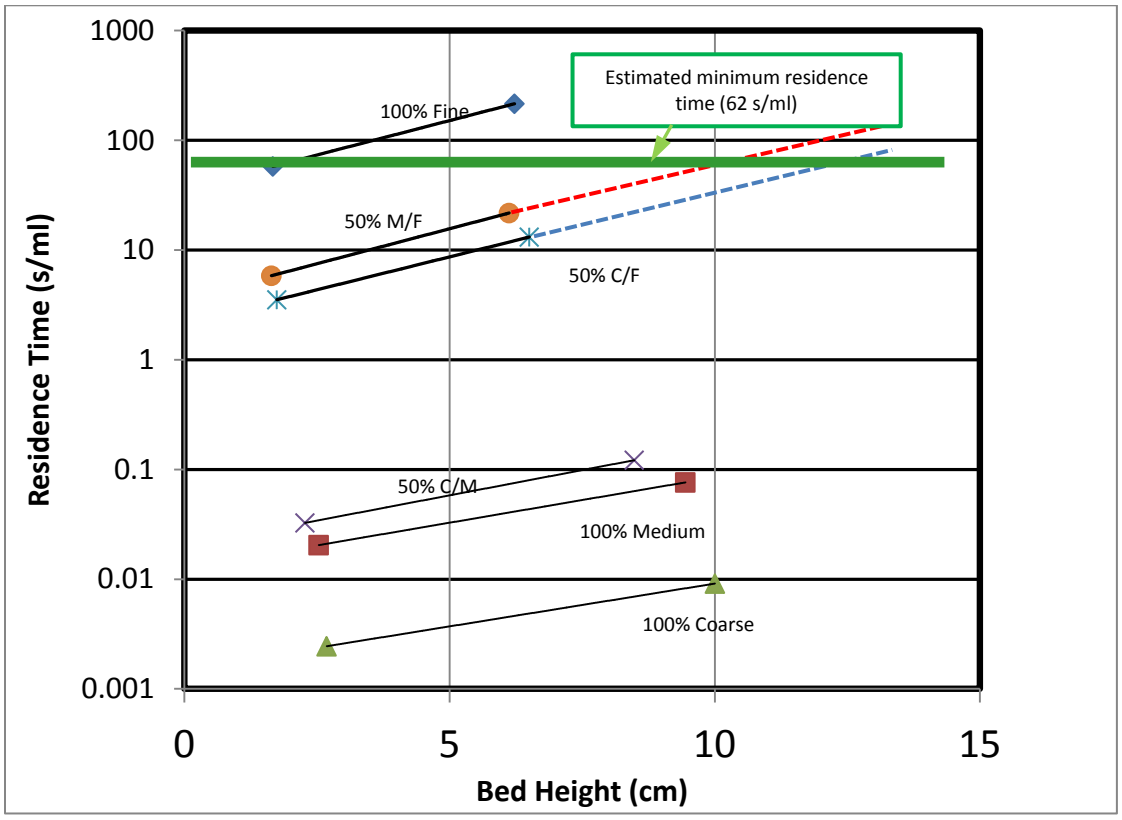

Figure 23. A plot of residence time for the bed compositions with bacteria data versus the corresponding bed heights.

The thick, green line indicates the calculated critical residence time from Figure 23. With the residence time for each of the filters now plotted in relation to the bed height, the minimum bed height to achieve the minimum residence time can be predicted by extrapolation of the lines. For example, a bed composed of 50% medium and 50% fine particles needs to be at least 10 cm for 62 s/ml and therefore, effectively kill the bacteria. Similarly, a coarse bed would require a very large bed height (some point off the chart area) in order to effectively kill the

bacteria. Currently, this model only works for the sizes and conditions used in this research but could be further developed into being useful for all material sizes.

6. Future Work

This research can be followed up with several additional studies. One very useful study would be to study pore size of the beds and create model relating bed height, residence time and pore size. This could be applied to any material of any size distribution as long as the average pore size was known. The model developed so far is only applicable to the sizes used in this research. Another study could be of the surface area effects on bacteria remediation. Using materials of different surface areas in these tests, a relationship could be developed. With more surface area, there will be more exposure of the bacteria to the silver so there should be an effect on residence time required for complete bacteria remediation. Only one silver concentration was used for this research but there is likely an optimum concentration for material treatment based bacteria remediation efficiency and cost. Head pressure affects flow rates so a relationship could also be developed between head pressure and flow rates. Since the long term goal of this research is to provide clean drinking water, a study on particulate filtration is also necessary. Bacteria remediation is only part of it. Drinking water obviously should also be free of particulates of dirt, grass, sticks, stones and any other source. Useful lifetimes of the filters should also be determined. The filters are not expected to be effective for forever so it is necessary to find out how long the filters will produce drinkable water. The tests in this research are not perfect and therefore there is room to improve them. Redesigning the testing apparatus is a possibility. For example, it would be desirable to reduce or eliminate the amount of material that leaks past the screen at the bottom of the tube.

7. Literature References

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