StaRS Backwash, Fall 2014

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Abstract

The goal of StaRS Backwash is to determine the sand grain sizes and distribution for the most efficient and effective backwash in the stacked rapid sand filters. The proper fluidization velocity for efficient backwash must first be determined. An expansion ratio of 1.5 is the current standard for the sand bed during fluidization. A sand size ratio below 1.5 is suggested for minimal segregation during backwash. The team ran experiments with sands sizes of 20-40 and 30-40 at different backwash velocities to test for segregation. Through the experiments, the team found that the 20-40 sized grains always segregated at all backwash velocities, but the 30-40 sand, which is under the 1.5 sand size ratio, did not segregate below backwash velocities of 15 mm/s. Current AguaClara plants use a backwash velocity of 11 mm/s, so using 30-40 sand would be a good option because it should not segregate according to the data collected.

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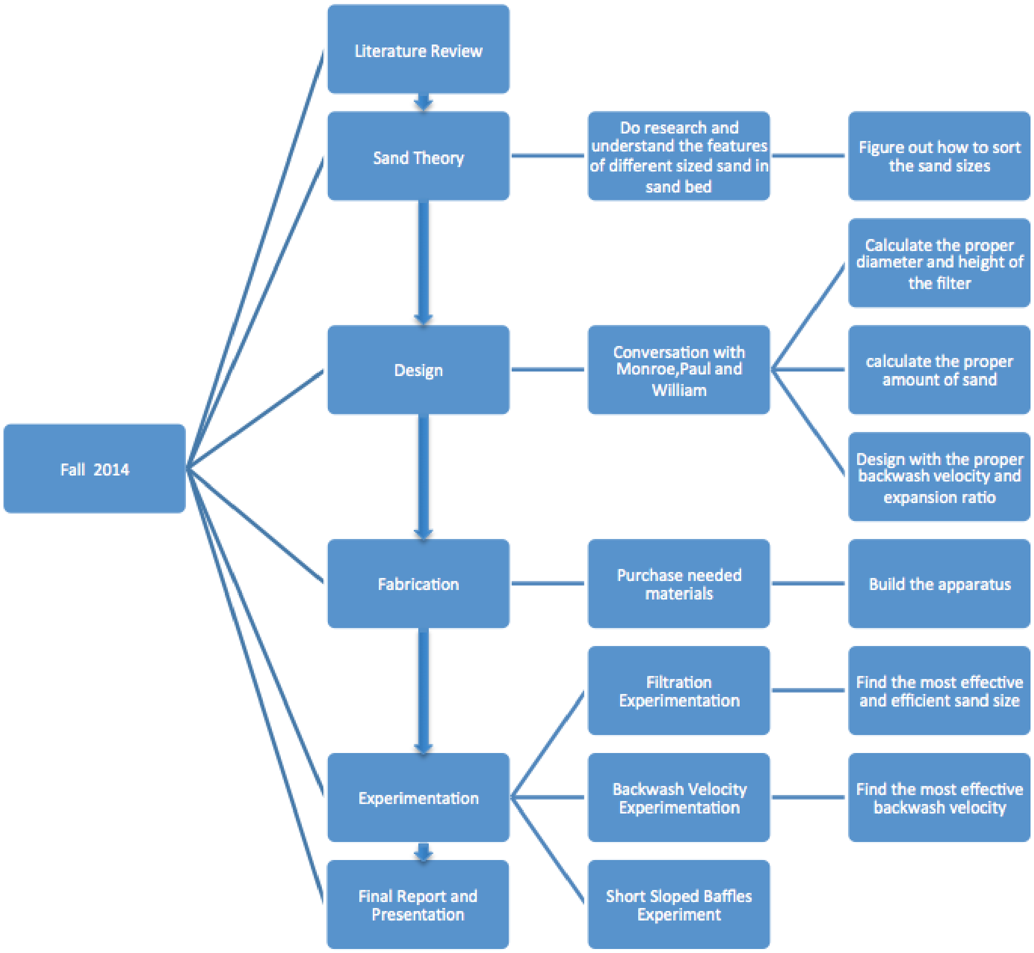
Task List

Task Map



Task Details

1. Literature Review (by Friday 10/10, completed) - entire team
    a. Read and understand the three articles linked under the challenges
    b. Get a good grasp on the basics of filtration and backwash with stacked rapid sand filters
    c. Find and read another article relating to filtration/backwash
2. Sand Theory (by Wednesday 9/24, completed) - Nick Farino
    a. Finding particle sizes and uniformity coefficients that will in theory not be segregated after backwash and have an expansion ratio of approximately 1.4-1.8
    b. Do extensive research on sand sizes and gradations to understand the feasibility and effectiveness of different sizes in the sand bed
    c. Get samples of sand and figure out how to sort the sand sizes

3. Design (by Friday 10/10, completed) - Vicki Chou
    a. Design an experimental apparatus that emulates a filter bed of the stacked rapid sand filter
    b. Calculate the proper diameter and height of the filter
    c. Calculate the proper amount of each sizing of sand and the total amount of sand
    d. Design with the parameters of a backwash velocity of 11 mm/s and an expansion ratio of 1.4-1.8
    e. Talk with Monroe/Will to finalize design plans
4. Fabrication (by Wednesday 11/5, completed) - Chenhao Qi
    a. Use the design for the experimental apparatus to locate what materials need to be purchased
    b. Purchase needed materials
    c. Build the apparatus
    d. Build the base and support system using the iron shelf.
    e. Buy colored sand for observing segregation easily.
5. Filtration Troubleshooting (by Wednesday 11/19, completed) - Vicki Chou
    a. Begin testing the experimental apparatus
    b. Test to see if the colored sand could be observed after backwash and if the color is waterproof
    c. Test to see if the expansion ratio is within the design range and if the sand is fluidizing properly
    d. Test to see if the sand is not segregating after backwash using colored sand
    e. Fix any issues that come up and repeat process until the experimental apparatus is performing properly
6. Filtration Experimentation (by Wednesday 11/26, completed) - Rui Zhang
    a. Begin running experiments with different grain sizes and ratios
    b. Test different sand types for effectiveness in filtration and backwash
    c. Find the degree of segregation by observing the distribution of colored sand.
    d. Draw conclusions on what size sand grains are the most effective and efficient during backwash
7. Short Sloped Baffles Design (if time permits) - Nick Farino
    a. Research baffle design
    b. Plan out baffle design and feasibility
8. Short Sloped Baffles Experimentation (if time permits) - Chenhao Qi
    a. Add short sloped baffles to the experimental apparatus between the sand bed and the backwash effluent waste pipe
    b. Test backwashing for the effectiveness of the baffles
9. Backwash Velocity Experimentation (if time permits) - Nick Farino
    a. Test different backwash velocities for effectiveness(Current backwash velocity of 11 mm/s may not be the best velocity so other velocities should be explored and tested)
10. Final Report and Presentation (by end of semester) - entire team

a. Prepare a presentation that concisely and effectively communicates the work accomplished this semester, highlighting important findings and design updates
b. Submit a final report that thoroughly explains all progress made throughout the semester and easily communicates data and conclusions drawn from the experiments

Team Roles

Team Coordinator - Nick Farino
    - keeps schedule
    - keeps track of what was accomplished at each meeting
    - leads team meetings with advisors
Materials Coordinator - Chenhao Qi
    - identifies materials that need to be purchased
    - finds and purchases materials (through Casey)
    - keeps track of all purchases and future purchases
Design/Fabrication Coordinator - Vicki Chou
    - leads design of experimental apparatus
    - leads construction and fabrication of the apparatus
Data Coordinator - Rui Zhang
    - organizes data
    - does preliminary analysis of data
    - leads data discussion

Introduction

An effective backwash is essential for a sand filter to function properly, but the design parameters that facilitate an effective backwash are not well understood. Fluidization of the sand bed is essential in removing particles during backwash, and it is governed by the sand size and the backwash velocity. Finding the right sand sizes and size distribution is needed to prevent segregation of the sand bed after backwash. A better backwash would impact the efficiency of the stacked rapid sand filters by more thoroughly cleaning the bed allowing the sand grains to collect more colloids during each filtration run. An improved understanding of fluidization can also potentially save water by decreasing backwash time while still achieving a sufficient backwash quality.

Literature Review

Sand Size Ratio

In a fluidized bed consisting of differing sand sizes, segregation occurs where larger particles settle to the bottom and smaller particles migrate to the top. A sand bed of differing sand densities also segregates where higher density particles end up on the bottom and lower density particles end up on the top of the bed. The degree of segregation is dependent on the size ratio, d_R, which is the largest sand diameter compared to the smallest sand diameter in the bed. According to Đuriš, et al. (2013), good mixing in a bed can be achieved through a d_R less than 1.5. At a size ratio of less than 2, the maximum mixing intensity is at a porosity (ε) of about 0.7.

Minimum Fluidization Velocities of Multi-component Solid Mixtures

Expressions for predicting minimum fluidization velocities of multi-component solid mixtures in terms of mono-component values for the velocity and the bed voidage at incipient fluidization are discussed. The expressions are listed below in Table 1.

$\overline{U_{mf}}$: The average of minimum fluidization velocities.

U_{mfi} *: The minimum fluidization velocities of species i.*

X_i : The volume fraction of the *i*th solid species

Table 1. Expressions for the prediction of minimum fluidization velocities of multi-component mixtures

Regime	Mixing state	Size-different mixture	Density-different mixture
Laminar flow	Mixed	$\frac{1}{\sqrt{\overline{U_{mf}}}} = \sum_{i=1}^{n} \frac{X_i}{U_{mfi}}$	$\overline{U_{mf}} = \sum_{i=1}^{n} X_i U_{mfi}$
	Segregated	$\frac{1}{\overline{U_{mf}}} = \sum_{i=1}^{n} \left[\frac{X_i}{U_{mfi}}\right]$	$\overline{U_{mf}} = \sum_{i=1}^{n} X_i U_{mfi}$
Turbulent flow	Mixed	$\frac{1}{\overline{U_{mf}}^2} = \sum_{i=1}^{n} \frac{X_i}{U_{mfi}^2}$	$\overline{U_{mf}}^2 = \sum_{i=1}^{n} U_{mfi}^2 X_i$
	Segregated	$\frac{1}{\overline{U_{mf}}^2} = \sum_{i=1}^{n} \frac{X_i}{U_{mfi}^2}$	$\overline{U_{mf}}^2 = \sum_{i=1}^{n} U_{mfi}^2 X_i$

In laminar flow, the averaging procedure for the mean fluidization velocity in the case of density-different solid mixtures is different from the case of mixtures differing in their sizes both for mixed and segregated bed conditions. For density-different solid mixtures, the mean fluidization velocities for a mixed bed and a segregated bed are the same in laminar flow. But, for size-different solid mixtures, the mean fluidization velocities for a mixed bed and a segregated bed are different.

Unlike laminar flow, averaging procedures of size-different mixtures for both segregated beds as well as completely mixed beds are same in turbulent flow. Density-different mixtures are also handled the same, regardless of whether they are mixed or segregated, in turbulent conditions .

The level of mixing significantly affects the prediction of $\overline{\mathrm{U}_{\mathrm{mf}}}$; different values of $\overline{\mathrm{U}_{\mathrm{mf}}}$ will be obtained for segregated and mixed beds in laminar conditions. If the sizes of the constituent species are not significantly different so that the volume contraction is rather insignificant,

$$\frac{1}{\sqrt{\overline{U_{mf}}}} = \sum_{i=1}^{n} \frac{x_i}{U_{mfi}}$$

will be applicable. In this case, a mixed bed will possess a higher $\overline{\mathrm{U}_{\mathrm{mf}}}$ as compared to a segregated bed. On the other hand, if the size difference is large, the concomitant volume change of mixing will be significant. The $\overline{\mathrm{U}_{\mathrm{mf}}}$ of a mixed bed in this case could be smaller than that of a segregated bed. The reason for this is the fact that the lower porosity will cause a higher pressure drop in the mixed bed, which is ultimately reflected by the lower values of $\overline{\mathrm{U}_{\mathrm{mf}}}$(Asif, 2013).

Measurement of size and size distribution of particles by fluidization

In this paper, a method of particle size distribution measurement which depends upon the use of fluidization was developed. This method simply requires measurement of the pressure drop across the bed and of flow rate, which is the independent variable in the experiments this method uses. In this paper, the method was verified by measurements made using screening, the practice of separating granulated ore into multiple grades by particle size. As a result of comparing the size distributions found with their method and with screening, the researchers confirmed the validity of the method. They found that the size distributions observed for binary and the tertiary mixtures were in good agreement with those obtained by microscopic measurement. However, they noted that the characteristics of multi-component particles need to be investigated further. As shown in Figure 1, the researchers graphed pressure drop against superficial velocity to calculate particle size distribution.

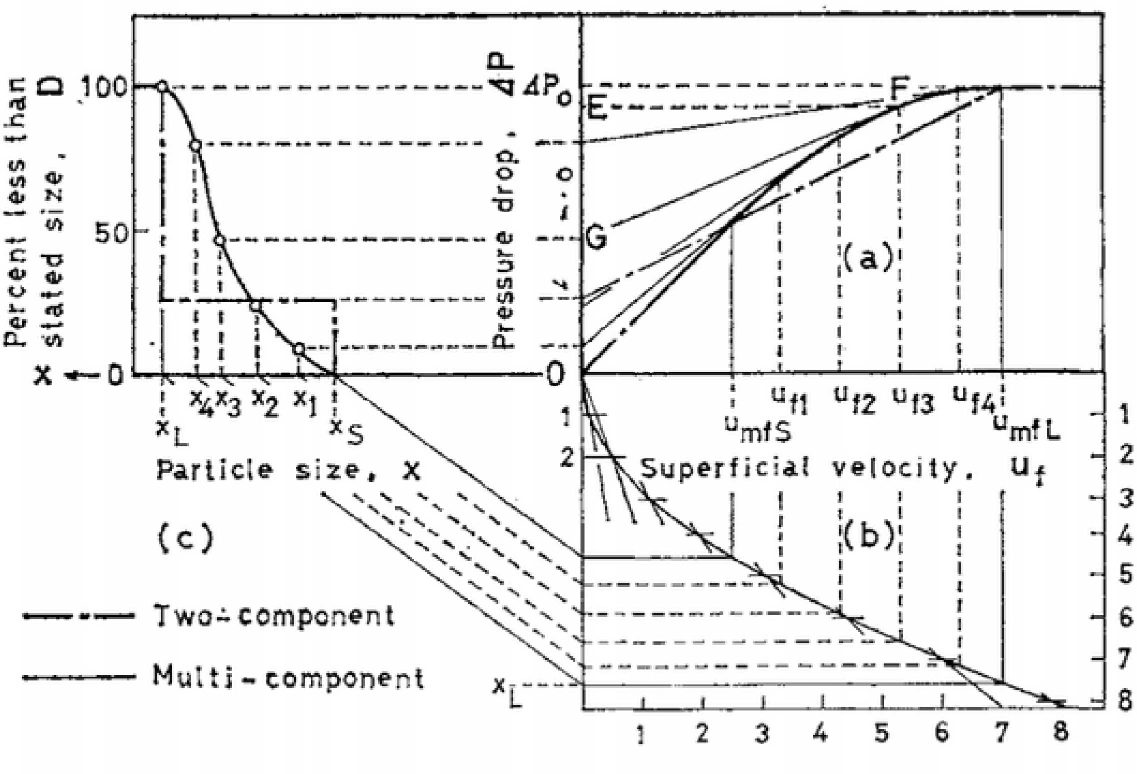


Fig.1 Construction to determine particle size distributions by plot of ΔP vs.u_f

The equations the author derived in this paper are listed below.

For two-component particles, the velocity is

$$u_s = \frac{u_{mfS}}{\left(1-\frac{u_{mfS}}{u_{mfL}}\right)\left(\frac{W_S}{W_O}\right)+\left(\frac{u_{mfS}}{u_{mfL}}\right)} = \left(\frac{W_S}{W_O}u_{mfS}+\frac{W_L}{W_O}u_{mfL}\right)^{-1}$$

u_S—The apparent minimum fluidizing velocity

u_{mfS}—Velocity of beginning of fluidization

u_{mfL}—Velocity of complete fluidization

W_S—The weights of the fine (small) particles

W_L —The weights of the coarse (large) particles

W_O —The weights of overall particles

For multi-component particles, the velocity is

$$u_s = (\Sigma W_i / W_O u_{mfi})^{-1}$$

u_{mfi} —The harmonic mean of the minimum fluidizing velocity

W_i —The weights of components i.

Air Dynamics Through Filter Media During Air Scour

Using water fluidization alone to backwash filters can be limited by low grain contact and abrasion. A more thorough cleaning is done through the collision of particles. One way to increase the effectiveness of backwashing is to use air scour. The effectiveness of this technique related to the abrasion between sand grains. The intensity of abrasion is related to (1) the effective stresses between the grains and (2) the magnitude of their relative movement. These two effects are contradictory - the higher effective stress at low water flow rates (less fluidized bed), and greater movement at increasing water flow rates (more fluidized bed). These effects predict the existence of an optimum air-water flow rate combination for cleaning effectiveness (Hewitt and Amirtharajah, 1984).

There are four distinct patterns of air moving through the sand bed depending on water flow:

(a) At no water flow there is little bed movement. The only possibility for this method to detach particles attached to the grains lies in the upper 6 in. of the media where some movement occurred.
(b) At the condition that air scour plus subfluidization water flows, that is, at about 5% of minimum fluidization water flow rate, the air moves through the media in distinct channels which form and collapse.
(c) At the condition that air scour plus subfluidization water flows for collapse-pulsing, that is, at about 20% and 45% of minimum fluidization, the air moved through the bed in a pulsing action in which the media moved in a general downward and inward direction towards the air pockets which formed and collapsed.
(d) At the condition that air scour plus water flows close to fluidization, that is, at about 80% of minimum fluidization, the air moved through the media in the form of bubbles, and the characteristics of motion are similar to two phase or fluidized bed systems.

(Hewitt and Amirtharajah, 1984)

Methods

From the literature summarized above and specific parameters of the actual AguaClara sand filter, the team came up with three initial specifications that the sand bed had to meet in order to successfully fluidize. These specifications are listed below:

1 – **Largest sieve size to smallest sieve size ratio should be less than or equal to approximately 1.5**

From Đuriš, et al. (2013), it was found that an aggregate size with a largest sieve to smallest sieve ratio of over 1.5 will segregate when fluidized

2 – **No particle can be smaller than 0.2 mm**

Filtered water goes through a 0.2 mm sieve leaving the AguaClara plant sand filter (according to Monroe), particles smaller than 0.2 mm will pass through this sieve along with the water.

3 – **The bed must fluidize with a nominal velocity of 0.011 m/s, but no individual particle should have a settling velocity less than that, or the particle will leave the filter with the backwash water.**

To begin, the team had to find a particle size that would fit the criteria above.

Thus, to start, the team used the minimum fluidization velocity equation:

$$V_{min} = \frac{[\varepsilon_{FlSand} * g * D^2]}{[36 * k * \nu * (1 - \varepsilon_{FlSand})]} * [\frac{\rho_{sand}}{\rho_{water}} - 1]$$

assuming:

- a Kozeny constant (k) of 5,
- a kinematic viscosity of 1.004E-6 m^2/s (20° degrees C)
- $\varepsilon_{FlSand} = 0.4$
- Density of Sand = 2650 kg/m^3 and Water = 998.2 kg/m^3 (20° C),

the team calculated a diameter value of **0.76 mm**, which will be the theoretical maximum value upon which sand sizes will be based.

Next, the team went to the Mogami Lab (in Hollister) to see what sieve sizes were available in the range 0.2 mm – 1 mm.

It was found that there were the following sieve sizes:

- **No. 20 Sieve (0.841 mm)**

- **No. 30 Sieve (0.595 mm)**
- **No. 40 Sieve (0.420 mm)**
- **No. 50 Sieve (0.297 mm)**
- **No. 70 Sieve (0.210 mm)**

To satisfy the requirement that the ratio of the largest to smallest sieve be less than 1.5, the team found the following possible gradation ranges:

- **The No. 20 Sieve and No. 30 Sieve: Ratio = 1.41**
- **The No. 30 Sieve and No. 40 Sieve: Ratio = 1.42**
- **The No. 40 Sieve and No. 50 Sieve: Ratio = 1.41**
- **The No. 50 Sieve and No. 70 Sieve: Ratio = 1.41** *(Fortunately, this was still under 1.5, so the missing No. 60 is not problematic)*

Based on these findings, the team analyzed each option:

The team decided to not test the first option (No. 20 to No. 30), because the average particle size could possibly be larger than 0.76 mm (calculated earlier). Monroe also informed the team that this size was tried in the past, and resulted in fluidization problems.

The team also decided to not test the fourth option (No. 50 to No. 70), because the Number 70 sieve is very close in size to the 0.2 mm screen passed by the filtered water in the filter. This could potentially lead to particle washout.

Therefore, there remained two options:

- **The No. 30 Sieve and No. 40 Sieve: Ratio = 1.42**
- **The No. 40 Sieve and No. 50 Sieve: Ratio = 1.41**

Both of these sand sizes have been sieved. The team has built a test filter in order to make sure that when the sand is fluidized, there is no segregation. Whichever has the least segregation and best water filtration properties will be chosen for use.

Experimental Apparatus

The flow path through the experimental apparatus starts from the tap. The flow from the tap is delivered through 9.53 mm (⅜") diameter tubing, with the flow controlled by a 9.53 mm (⅜") ball valve. A flow expansion fit-to-connect adapter is used to increase the 9.53 mm (⅜") tubing to a 12.7 mm (½") tube, which connects to the bottom of the sand filter column. The sand filter pipe is a 1.22 m (4 ft) long clear 50.8 mm (2") diameter PVC pipe, capped on either end with a PVC cap. The bottom cap has two copper wire meshes, sizes 8 and 80, glued using PVC cement to the opening in order to contain the sand within the filter pipe and out of the tubing. The length of the pipe should be long enough to exceed the height any sand will reach while fluidized, so no wire mesh was attached to the top of the filter. The sand bed height varies by experiment, so the top cap of the filter is designed to be removable by being threaded. This removable cap allows sand to be added or taken out of the pipe in between experiments. A

9.52 mm (⅜”) tube leads from the top of the filter to the sink drain. Figure 2, below, depicts the experimental apparatus.

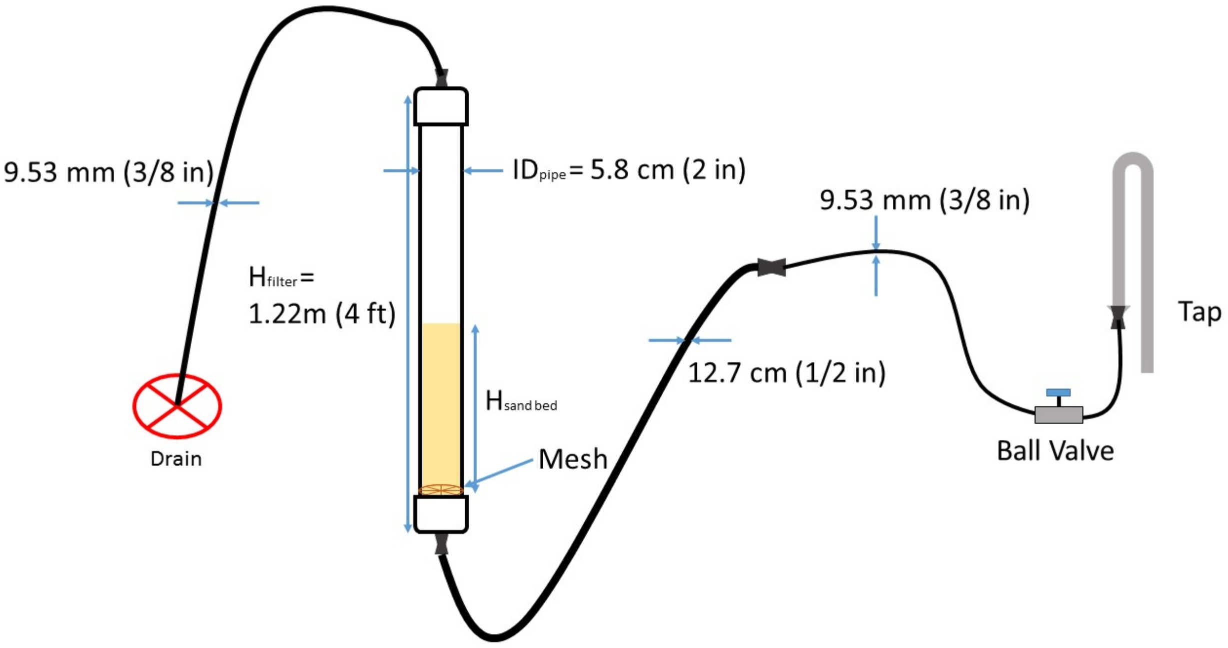


Figure 2: Experimental apparatus diagram

In order to stabilize the sand filter, a base assists in keeping the filter upright and sturdy. The base consists of an aluminum A-frame with a flat base. The filter column rests on a 5.8 cm (2”) diameter PVC pipe. A 12.7 mm (½”) hole was drilled in the base PVC pipe stub to allow the tubing through the bottom of the filter to connect to the source. The top of the filter is fixed to the aluminum frame using zip ties. Figure 3 shows the experimental apparatus setup.

Figure 3: Experimental apparatus setup

Testing for Sand Segregation

To test for sand segregation, the team used two different colored sands: natural brown colored and dyed pink. The two different colors of sands are easy to distinguish apart from each other even after being mixed. The pink sand was sieved to three different sizings of No. 30-40, 40-50, and greater than 50. The first test done was combining natural brown sand of sizes 20-30 with pink sand of sizes 30-40. The mixture contained 300 mL each of the natural and pink sand. Different velocities of backwash were tested for segregation and for the expanded bed ratio.

The second test done was with natural brown sand of sizes 30-35 and pink sand of sizes 35-40. This test was performed to test for segregation with a sand size ratio of less than 1.5. The mixture of natural and pink sand was 1:1, with 180 mL of each type of sand. Once again, different velocities of backwash were used to experiment for the effect of velocity on the segregation of the sand particles.

Segregation was tested through visual observations; if the two colored sands are stratifying, the majority of the pink sand is on top because of its smaller size, and the natural sand settles to the bottom. It was determined that segregation occurs if it is detectable by the human eye qualitatively and if segregation is noticeable before five minutes have passed.

Video links to watch trials for each test:
(20-30) http://youtu.be/0B55IEIg4zE
(30-40) http://youtu.be/ZZxW6k7gcPQ

Results and Discussion

Sand Segregation

Test 1

After testing sand segregation using a 1:1 ratio (300 mL : 300 mL) of natural sand sizing 20-30 and pink sand sizing 30-40, it was evident that segregation occurs for this sand size distribution. At all velocities tested, the sand bed stratified with the smaller pink sands on top and the larger natural sands on the bottom. Figure 4 shows the clear color distribution after fluidizing and settling of the sand bed.

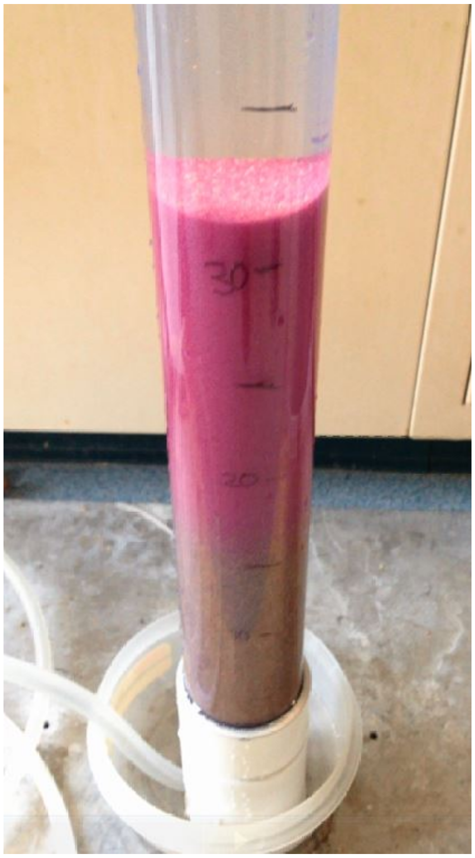


Figure 4: Sand segregation based on sand color distribution

While testing, it was important to ensure that the column was perfectly vertical. Any sloping of the filter caused the filter to act as a tube settler, which effectively negates the purpose of the filter. When the filter was slightly tilted, more mixing occurred, which diminished the effects of segregation and provided false evidence that stratifying does not occur. In order to prevent tilting of the filter, the team tied two weighted strings as plumbs parallel to the filter to help with vertical alignment, shown in Figure 5.

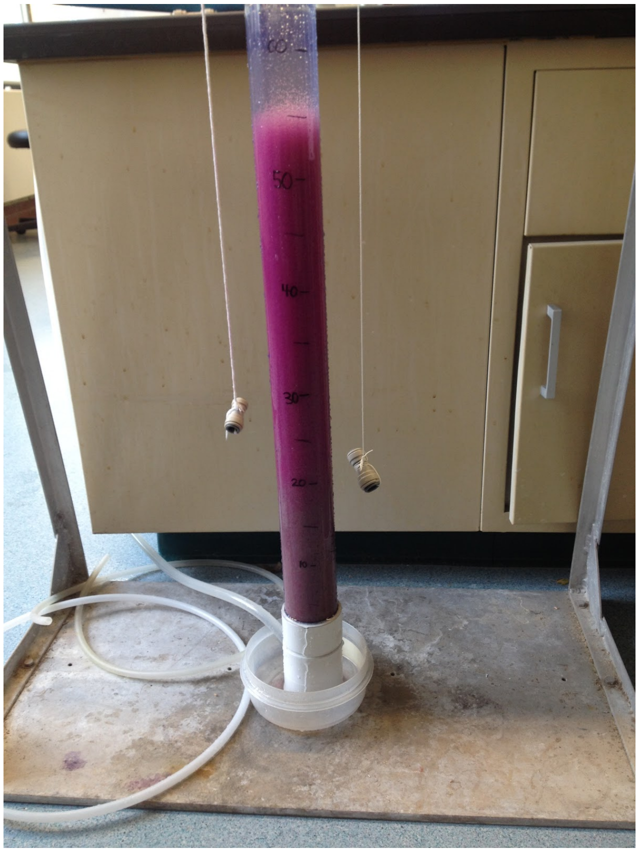


Figure 5: Filter column with two parallel hanging plumbs

At all velocities, the team discovered that the sand always segregated. The sand size ratio for this experiment was above the 1.5 ratio, which Đuriš, et al. (2013) suggested to be the maximum ratio in order to not have sand segregation. Therefore, the results from this experiment support Đuriš, et al.'s (2013) conclusions. It is important to note that in this set of tests, it appeared that sand segregation was not related to expansion ratio. No matter how high the upward velocity and expansion ratio was, the sand still segregated. Although the team previously predicted that sand segregation would be a function of expansion ratio, the results of these tests seemed to disagree.

Test 2

The next segregation testing was performed on using 180 mL of yellow sand (sieve size 30-35) and 180 mL of pink sand (sieve size 35-40). Since this sand size ratio was below 1.5, it was expected that the sand would not segregate. Although the Đuriš, et al. (2013) research paper suggested that a sand mixture with a sand size ratio under 1.5 would not segregate, the team discovered that at many expansion ratios the sand still did segregate. At lower velocities, however, the sand did not segregate, suggesting that there is a threshold velocity where any backwash velocities above this value will cause the sand to segregate. Figure 6 shows the results of this test based on different backwash velocities.

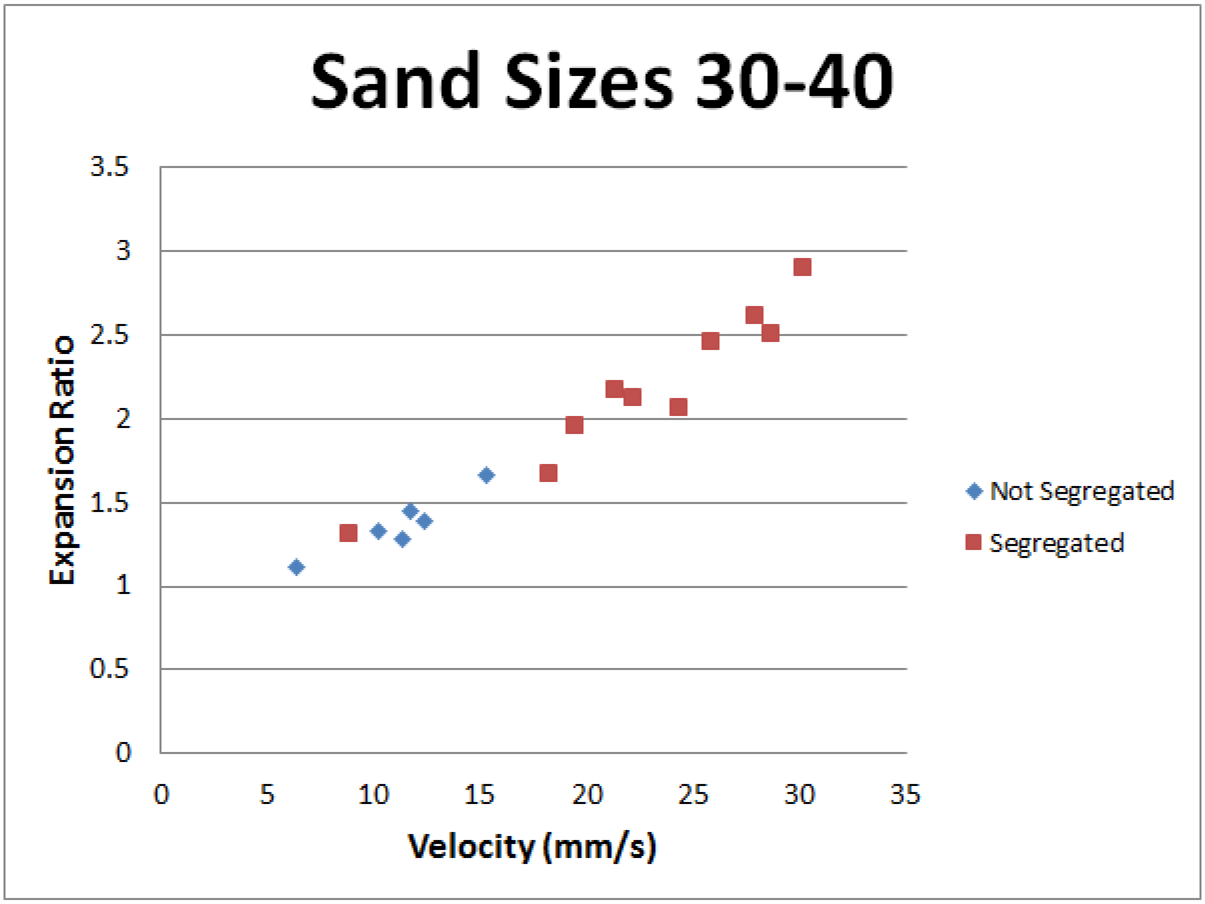
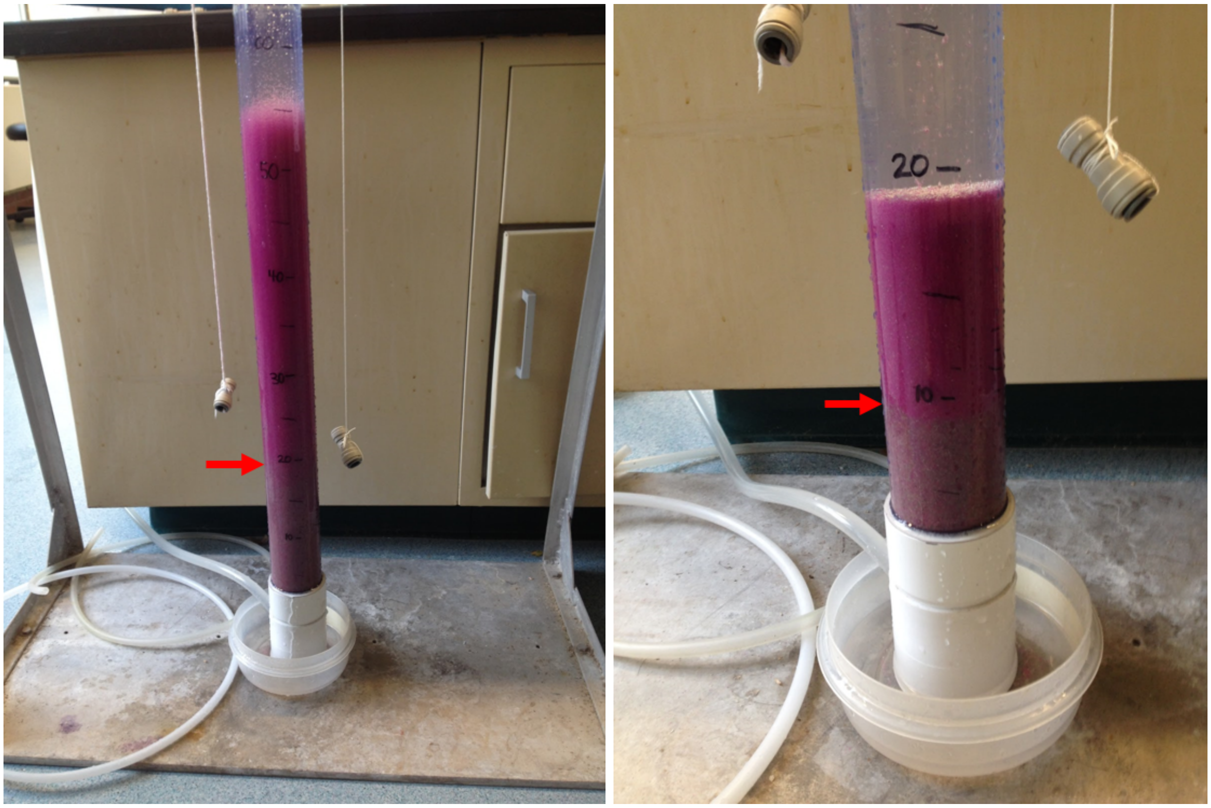


Figure 6: Plot of sand segregation test results for sand sizes 30-40

According to the graph, the expansion ratio increases as velocity increases, and these two variables have a good linear relationship.

As the graph shows, when the backwash velocity is below 15 mm/s, no segregation was observed, except for one trial. Velocities above this threshold value resulted in sand segregation. The standard AguaClara backwash velocity is 11 mm/s, so it is below the threshold value, suggesting that the sand grains of sizes 30-40 should not segregate at this velocity.

An observation made during testing is that the sand bed mixes well if the backwash is run for five seconds at a higher velocity, above 20 mm/s. A possible way to mix a segregated bed after backwash is to use a quick spurt of flow for a few seconds, although this may not be possible in AguaClara filters without the implementation of several filters run in parallel.



(a) (b)

Figure 6. a: Sand segregation for sand sizes 30-40 at backwash velocity 30.2 mm/s, b: Settled sand bed after testing; The red arrow indicates the distinct segregation between the larger natural sand grains and the smaller pink sand grains

Density Test

In order to figure out if the segregation is caused by the different sizes and not by different densities, the team calculated the densities of the sand particles without porosity.

Equipment: 50mL Beaker, 100g electronic balance, 25mL measuring cylinder, 2 kinds of sands.

Method:

1. Put the beaker on the balance and press “CAL” to set this as 0 scale.
2. Put some pink sand into the beaker (around 10 mL) and weigh them, which is 17.86 g.
3. Pour all the pink sand into a cylinder with 15 mL water and shake it fully. Write down the volume as 22.5 mL.

4. Put some normal sands into the beaker, which should be 17.86g.
5. Measure the volume of the normal sands as Step 3, which is 22.5 mL as well.
6. Thus, the team could tell the 2 kinds of sands have the same density, which is 2.38 g/mL.

Problems Faced

A few problems arose during experimentation. As mentioned previously, inaccurate tests with false results can happen if the filter column is not vertically aligned. This problem was mitigated by placing two hanging plumbs next to the column, and the column was adjusted accordingly to be parallel to these plumbs. The column was also manually adjusted by visually observing if the sand grains were “settling” onto the slanted side of the column. Another issue is that the top cap of the filter is a threaded PVC cap, so is often leaky at high backwash velocities. Despite using Teflon tape and using a wrench to screw on the cap as tight as possible, leaking still occurred. Although the leaking is not extreme, it could cause air to enter the cap at the top. This could be a problem in affecting the velocity readings taken because the team calculates the flow rate by timing how fast the effluent water fills up 500 mL. If water is leaking from the cap and bubbles enter through the leaks and leave with the effluent water, the flow rate exiting will not be the same as the flow rate entering the column. A new fitting for a removable cap should be researched and implemented to make the cap leak-free and easier to remove and put on.

Another problem was the presence of bubbles in the water. This problem is caused by the pressure and temperature difference between the water source and the tap water. These bubbles in the column pose a large problem because the smaller sand grains attach to the bubbles and float at the top of the fluidized sand bed, or even to the top of the filter and out the column. These suspended sand grains can distort the top height of the sand bed, making it difficult to discern what height the sand bed has fluidized to, as shown in Figure 7. This problem can be resolved by adding a source tank with a constant volume of water and porous rock bubblers submerged in the water.

Figure 7. Air bubbles suspending small sand grains

Future Work

1. Short Sloped Baffles Design

For next semester, the team could do research on baffle design and plan out baffle feasibility. Short sloped baffles could be attached to the experimental apparatus in the filter column between the sand bed and the backwash effluent waste pipe. The effectiveness of the baffles to help with mixing should be tested with different sand sizes, expansion ratios, and backwash velocities.

2. Backwash Velocity Experimentation

Different backwash velocities should be tested for effectiveness (the current backwash velocity of 11 mm/s may not be the best velocity, so other velocities should be explored and tested). Effectiveness of the backwash velocity could be tested through running the filter in the forward direction. A stock tank of raw water with clay added to it would be needed to act as the influent water and turbidimeters should be used to quantify the turbidity of the influent water and the effluent water to see how much clay was removed through the filter. Different backwash velocities should be tested to see which velocity is the most effective in cleaning the filter during backwash.

References

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