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 1.3 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 sized by sieve combinations 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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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 distribution of sand sizes 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 ratio of the largest sand diameter to the smallest sand diameter in the bed. According to Đuriš, et al. (2013), good mixing in a bed can be achieved by using 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, meaning that the composition of the sand at any part of the bed is about the same.

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	$\frac{1}{\sqrt{\overline{U_{mf}}}} = \sum_{i=1}^{n} \frac{X_i}{U_{mf\,i}}$	$\overline{U_{mf}} = \sum_{i=1}^{n} X_i\, U_{mf\,i}$
	Segregated	$\frac{1}{\overline{U_{mf}}} = \sum_{i=1}^{n} \left[\frac{X_i}{U_{mf\,i}}\right]$	$\overline{U_{mf}} = \sum_{i=1}^{n} X_i\, U_{mf\,i}$
Turbulent flow	Mixed	$\frac{1}{\overline{U_{mf}}^{2}} = \sum_{i=1}^{n} \frac{X_i}{U_{mf\,i}^{2}}$	$\overline{U_{mf}}^{2} = \sum_{i=1}^{n} U_{mf\,i}^{2}\, X_i$
	Segregated	$\frac{1}{\overline{U_{mf}}^{2}} = \sum_{i=1}^{n} \frac{X_i}{U_{mf\,i}^{2}}$	$\overline{U_{mf}}^{2} = \sum_{i=1}^{n} U_{mf\,i}^{2}\, X_i$

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 the 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 $\overline{U_{mf}}$ 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 $\overline{U_{mf}}$ 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 $\overline{U_{mf}}$ (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 graphical method, which is theoretically derived in the paper, simply requires measurement of the pressure drop across the bed and of superficial velocity (can be calculated from 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 technique of separating particles 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.

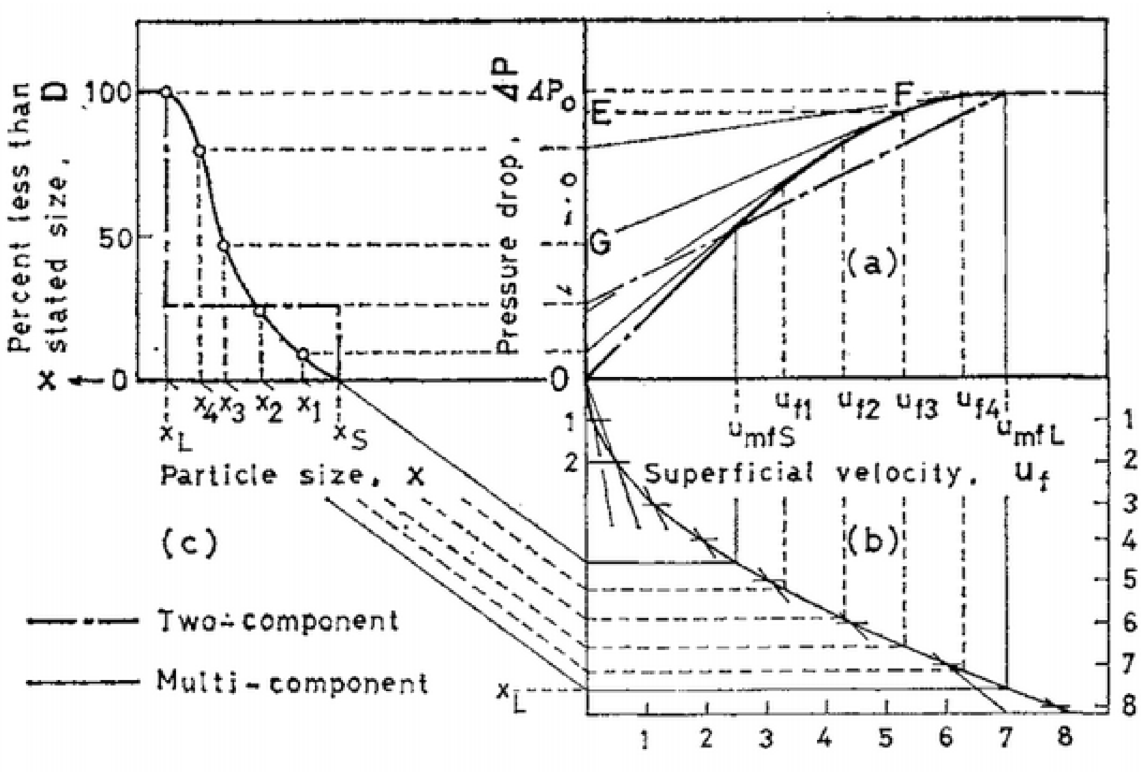


Figure 1: Construction to determine particle size distributions by plot of ΔP vs.u_f

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 accomplished by increasing collision of particles. One way to improve the effectiveness of backwashing is to use air scour. The effectiveness of this technique is 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 when using air scour (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:

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

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 was the theoretical maximum value upon which sand sizes were 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 was 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 were sieved. The team built a test filter in order to make sure that when the sand is fluidized, there is no segregation. Whichever sand size had the least segregation and best water filtration properties would 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 9.5 mm (⅜”) diameter tubing, with the flow controlled by a 9.5 mm (⅜”) ball valve. A flow expansion push-to-connect adapter is used to increase the 9.5 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 larger sized mesh is below the smaller sized mesh to provide more support and to ensure that the smaller mesh stays in place. 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 with a threaded cap. This removable cap allows sand to be added or taken out of the pipe in between experiments. A 9.5 mm (⅜”) tube leads from the top of the filter to the sink drain. Figure 2, below, depicts the experimental apparatus.

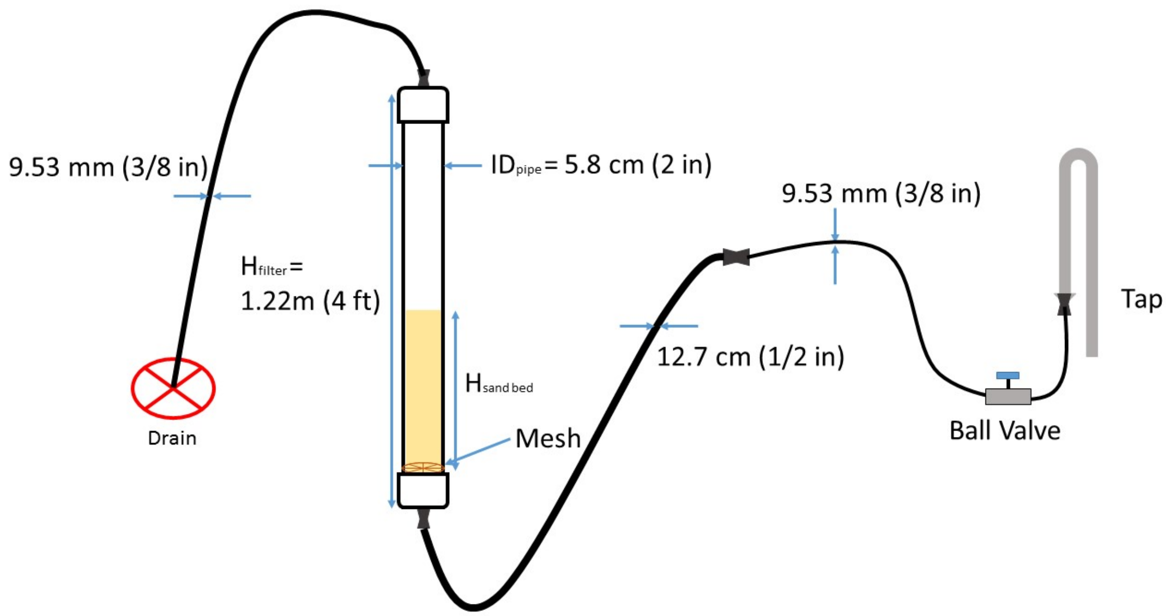


Figure 2: Experimental apparatus diagram

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 from 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: one a natural brown color, and the other dyed pink. The two different colors of sands are easy to distinguish 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.

The experimental procedure was the following:

1) Ran the filter through backwash at a high velocity for a few minutes to allow for bubbles to escape and to adjust the column for vertical alignment.
2) Turned off the flow to allow the sand to settle.

3) Ran the backwash at a high velocity for a few seconds to achieve good mixing (quantified visually).
4) Allowed the mixed sand to settle.
5) Ran the backwash at the desired backwash velocity.
6) Allowed the sand to fluidize to a constant height.
7) Took flow and bed height measurements.
8) Allotted a maximum of a minute of backwash after a stable fluidized bed height to quantitatively test for segregation.
9) Repeated steps 2-7 for different backwash velocities.

Segregation was tested through visual observations; if the two colored sands stratified, the majority of the pink sand was on top because of its smaller size, and the natural sand settled to the bottom. Segregation was defined as occurring if it was detectable by the human eye qualitatively and if segregation was noticeable before five minutes had passed.

Video links to watch a trial 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.

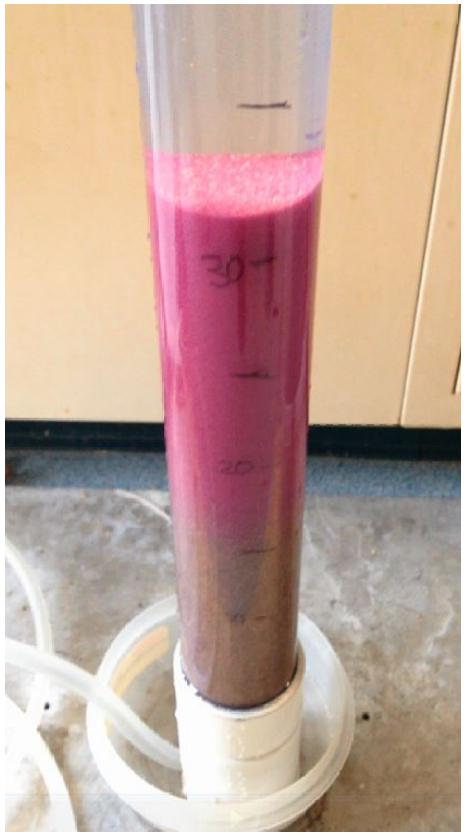


Figure 4: Sand segregation based on sand color distribution

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 test was performed on 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.

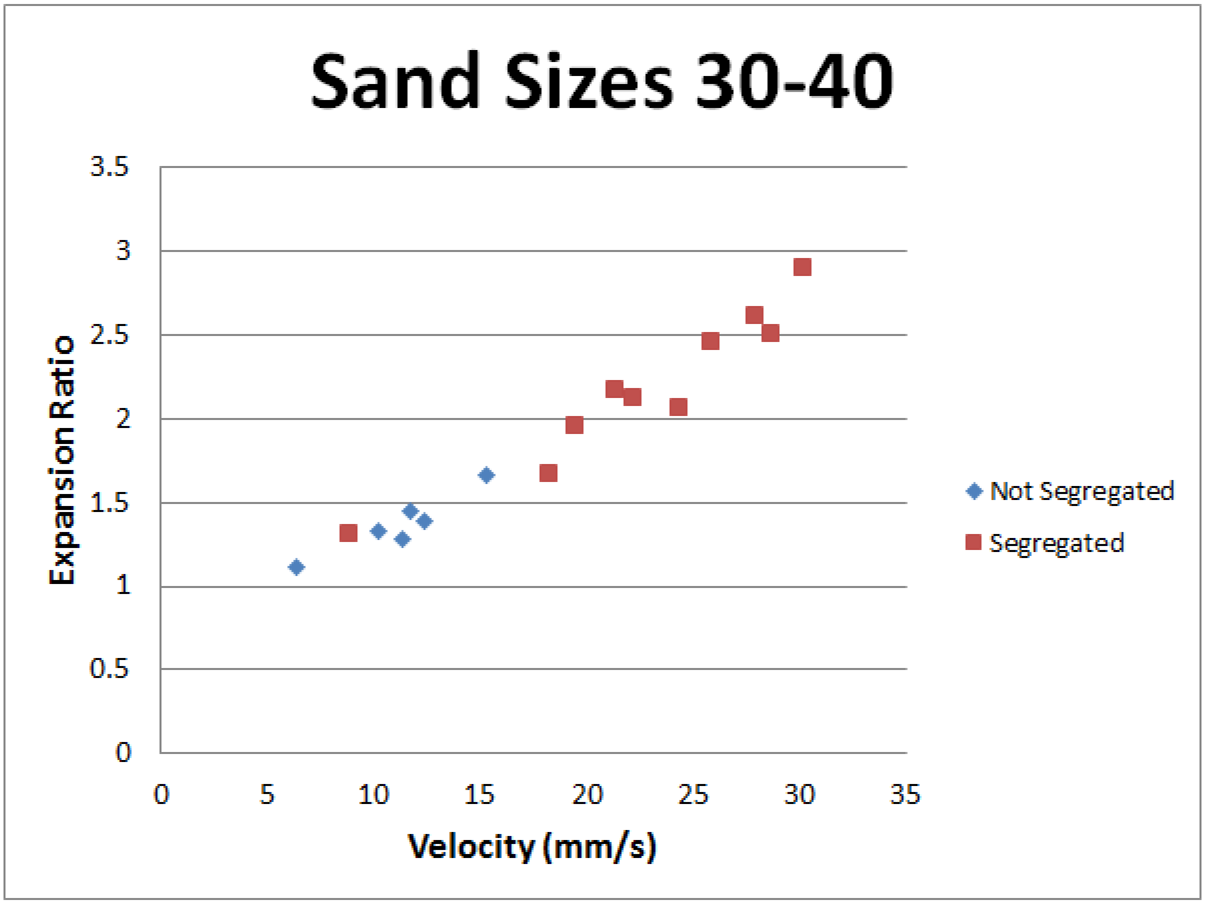
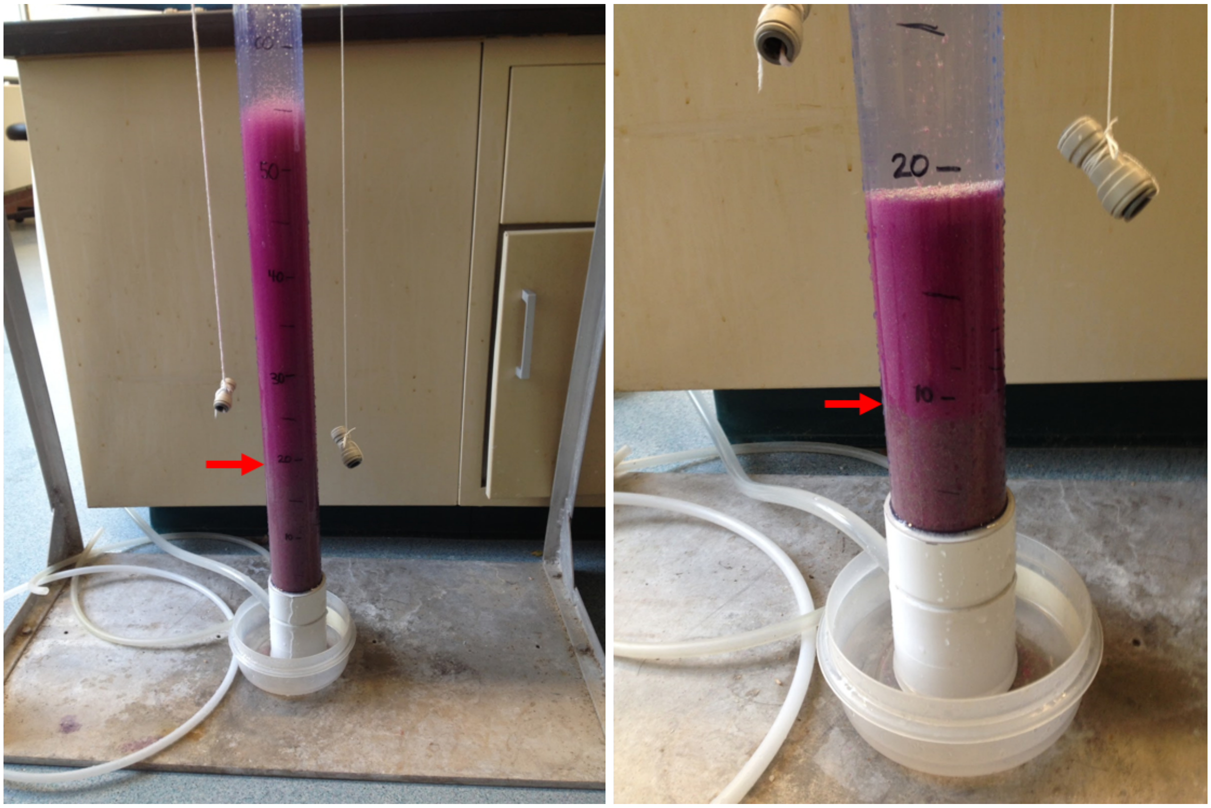


Figure 6: Plot of sand segregation test results for sand sizes 30-40

According to the graph, the expansion ratio increases as velocity increases. When the backwash velocity is below 15 mm/s, no segregation was observed (represented with blue diamonds), except for one trial. Velocities above this threshold value resulted in sand segregation (represented with red squares). 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.

We used the following equipment: 50 mL Beaker, 100 g electronic balance, 25 mL measuring cylinder, 2 kinds of sands.

We used the following method to calculate the densities:

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 weighed them (measured as 17.86 g).
3. Poured all the pink sand into a cylinder with 15 mL water and shook it fully to remove air bubbles. Measured the change in volume 22.5 mL for pink sand.
4. Put some normal sand into the beaker, measured at 17.86 g in order to compare with the pink sand.
5. Measured the volume of the normal sands like in Step 3, and found it to be 22.5 mL, as well.
6. Thus, the team determined that the two 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, and was often leaky at high backwash velocities. Despite using Teflon tape and using a wrench to screw on the cap as tightly as possible, leaking still occurred. Although the leaking was not extreme, it could cause air to enter the cap at the top. This problem could also affect the velocity readings taken, because the team calculated the flow rate by timing how fast the effluent water filled up a 500 mL container. If water is leaking from the cap, 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. Gas is more soluble at the colder temperatures found at the source, and is less soluble at the warmer temperatures in the lab, causing gas to exit solution as bubbles (Görgényi, et al., 2002). 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 an aeration system comprised of porous rock bubblers connected to pressurized air submerged in the water to strip the dissolved air.

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 assess the feasibility of adding baffles to the apparatus. 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, which will be dosed with coagulant prior to treatment. Turbidimeters should be used to quantify the turbidity of the influent water and the effluent water to see how much clay was removed by the filter. After forward filtration, different backwash velocities should be tested to see which velocity is the most effective in cleaning the filter during backwash.

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