REMOVAL OF *CRYPTOSPORIDIUM*-SIZED MICROSPHERES USING GRANULAR MEDIA FILTRATION

by

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ABSTRACT

WESLEY GOSNELL. Removal of *Cryptosporidium* -sized microspheres using granular media filtration (Under the direction of DR. JAMES E. AMBURGEY)

Cryptosporidium is a 5-µm chlorine-resistant protozoan parasite that infects humans. *Cryptosporidium* in treated (chlorinated) recreational water has been the direct source of at least 208 outbreaks in the United States between 2015 and 2019. Sand filtration is the primary treatment method in the United States for treated recreational water and is generally ineffective at removing *Cryptosporidium*. In this study, a *Cryptosporidium*-sized surrogate (5-µm diameter polystyrene microspheres) was used to determine the removal of four different filters. The 12-inch sand filter had an initial removal of 22.6% with no coagulant added, but the addition of 0.05 mg/L as Al of PACl increased the removal to 99.8% at 2 turnovers and 99.9% at 48 turnovers. However, these experiments had no added total organic carbon (TOC) in the water. The addition of 2 ppm of TOC in the 12-inch sand filter at the same coagulant dose decreased removal to 74.9% after 2 turnovers. A 36-inch sand filter using coagulant produced average removals ranging from 86.5% to 90.6% at 1 turnover and seems well-suited for recreational water treatment. A Vortisand filter showed an initial microsphere removal of 62.6% without coagulant addition. A filter with 22-inches of ceramic media had an initial removal of 99.6% without any coagulant addition, but after 8 weeks of treating water with an organic bather load the average removal decreased to 49.8%. Regeneration of the ceramic media was performed at the lab-scale and showed potential benefits with a maximum of 93.2 removal, and future research on regeneration of ceramic media is recommended to minimize the effect of TOC on this media.

DEDICATION

This thesis is dedicated to all my friends and family who loved and supported me through this journey.

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LIST OF ABBREVIATIONS

Al	aluminum
ANSI	American National Standards Institute
APSP	Association of Pool and Spa Professional
CDC	Centers for Disease Control and Prevention
DI	deionized
GPM	gallons per minute
L	liter
lbs.	pounds (standard US)
m/h	meter per hour
mm	millimeter
mg	milligram
mg/L	milligram per liter
mj/cm^2	millijoule per centimeter squared
mL/Min	milliliter per minute
mv	millivolt
nm	nanometer
NaOH	sodium hydroxide

PACl	polyaluminum chloride
ppm	parts per million
TOC	total organic carbon
μm	micrometer
UV	ultraviolet

CHAPTER 1: LITERATURE REVIEW

1.1 *Cryptosporidium*

Cryptosporidium is a 4.5 µm – 5.5 µm chlorine-resistant protozoan parasite that infects humans. Cryptosporidiosis is a disease caused by ingesting *Cryptosporidium*, which can cause extreme diarrhea in humans and was the leading cause of waterborne disease outbreaks in the United States from 2001-2010 (CDC 2021, Painter et al. 2015). *Cryptosporidium* in treated recreational water has been the direct source of at least 208 outbreaks in the United States between 2015 and 2019 (CDC 2021). Cryptosporidiosis symptoms can include diarrhea, fever, nausea, vomiting, and cramping lasting up to 3 weeks (Gharpure 2019; Hoxie 1997). Diarrhea in young children (under 5 years of age) is the second leading cause of death in the United States (CDC 2021). *Cryptosporidium* is released through bowel movements and each bowel movement can have up to 100 million oocysts/fecal release. Research has shown that ingesting only 10 oocysts can cause infections in humans (Dufour et al., 2006, Teunis et al., 2002, Yoder and Beach, 2010, Suppes et al. 2016).

In the United States, 444 cryptosporidiosis outbreaks have been reported from 2009 to 2017. These were reported by 7,465 cases in 40 states and Puerto Rico. The number of outbreaks has increased by 13% per year, and the leading cause was swallowing contaminated water in swimming pools. Treated recreational water was associated with 156 (35.1%) of the outbreaks, resulting in 4,232 (56.7%) cases and 183 (63.8%) of the hospitalizations (Gharpure 2019, CDC 2019). It was estimated that 1 mL of feces can contain as many as 5×10^7 oocysts, and a small child's average loose bowel movement is 150 mL (for a total of up to 7.5×10^9 oocysts per fecal release). This amount of fecal matter released into a typical 450 m^3 (119,000 gal.) swimming pool would average

16,700 oocysts/L (Gregory 2002). An adult swimmer ingests on average 32 mL of water per hour of swimming while children swallow on average four times as much per hour (Dufour et al 2017). A swimmer ingesting only 10 mL of pool water would ingest an average of 167 oocysts assuming uniform mixing and no treatment, which is well above the dose capable of causing infection (Kebabijan 1995).

1.2 Current Methods of Treatment in Drinking Water Treatment

Current methods for removal or inactivation of *Cryptosporidium* in recreational water is to use sand filters to remove the oocysts or ultraviolet (UV) radiation to penetrate and deactivate the ability of the cell to reproduce (Adeyemo et al. 2019). UV disinfection has been shown to neutralize more than 99.9% of C*ryptosporidium* in recreational water at 2-3 mJ/cm^2 (K.G. Linden et al. 2001, Clancy et al. 2000).

Chlorine is commonly used in recreational water treatment typically between 1 and 4 mg/L of free chlorine at pH 7.0 to 7.8 to neutralize common disease-causing bacteria and viruses (CDC 2020). *Cryptosporidium* can survive more than 7 days at a typical dose of 1 mg/L free chlorine (CDC 2021, Korich et. al. 1990, Chauret et. al. 2001, Croll et al. 2007). Drinking water treatment plants use coagulation in conjunction with sand filtration to remove *Cryptosporidium* from their water. Coagulation using alum ($Al_2(SO_4)_3 \cdot 18H_2O$) showed greater than 3 log removal at a dose of 5 mg/L (Brown 2009).

Similarities exist between drinking water and recreational water, but the driving factor for recreational water is the cost and complexities associated with UV disinfection and coagulation for recreational water. Sand filtration methods in recreational water in conjunction with coagulation fall short of capabilities due to the surface loading rates of a water treatment facility being 4 to 5 times less than that of a pool filter (e.g., 5 to 10 m/h for drinking water versus 37 to 49 m/h in pools) (Amburgey et al 2012). Coagulation, much like UV disinfection, requires complicated processes that require constant testing and compliance with government organizations to ensure safety of the water. Pool owners are reluctant to train, equip, and maintain expensive chemical rooms and operators to comply with rigorous daily, monthly, and yearly government testing schedules.

1.3 Current Methods of Treatment in Recreational Water

Sand filtration has been shown to be ineffective in removing *Cryptosporidium* from recreational water with only 0.19 log (36%) or less removal from recreational water. This research was done using 5-µm diameter polystyrene microspheres as a surrogate (Amburgey et al. 2012). Sand filtration with coagulation using poly aluminum chloride (PACl) can significantly increase the removal of *Crypto*-sized particles. With coagulation, greater than 99% removals were achieved (Croll et al. 2007, Amburgey et al. 2012, Lu & Amburgey 2015). Filtration in a lab-scale experiment using 0.05 mg/L as Al yielded greater than 90% removal and at a dose of 0.3 mg/L as Al greater than 99% removal was achieved (Croll et al., 2007).

Regenerative media filtration (RMF) has been shown to be at least 90% effective in removing 4.5-micron sized particles from recreational water. One research study showed that RMF filtration can achieve removal of *Cryptosporidium* sized particles by up to 99.7% under normal operating conditions (Lamb, 2022).

1.4 Research Objective

The objective of this research is to determine the removal of Cryptosporidium using granular media filtration with the effect of total organic carbon (TOC) using sand filters with coagulation, an ion exchange ceramic media, and a Vortisand filter that is typically used in industrial cooling system filtration applications and not used in recreational water.

CHAPTER 2: EXPIRIMENTAL METHODS AND PROCEDURES

2.1 Seeding Suspension

YG-fluorescent carboxylate-modified polystyrene microspheres (Polysciences, Inc, Cat. #16592, 4.5 µm, Niles, Illinois) were used as a surrogate for *Cryptosporidium*. A 1 L seeding suspension was made using the microspheres and DI water. The seeding solution was continuously stirred in a 1 L beaker with a magnetic stir plate (IKA, Color Squid) and a Teflon-coated stir bar prior and during the experiment. The microspheres were pumped into the filter system before the filter pump using a peristaltic pump (Watson Marlow, Model 505Di). The peristaltic pump was primed with the solution prior to being connected to the filter system. The microspheres were pumped into the filter system prior to the pump to aid in mixing prior to reaching the influent sample port.

The volume of spheres added to the 1000 mL of DI water was calculated using formula 3.1 below.

$$C_1 \times Q_1 = C_2 \times Q_2 \tag{3.1}$$

Where:
C_1= Concentration of spheres in seeding solution.
Q_1= Flowrate of peristaltic pump.
C_2=Concentration of spheres in the influent of filter.
Q_2=Flowrate of the filter.

The influent concentration was calculated to feed 12 spheres per mL. The peristaltic pump was set to deliver 67 mL per minute. The volume of the sphere solution was made to be that the peristaltic pump could operate for the 11 minutes of each experiment with sufficient volume to prevent adding air to the feed line of the peristaltic pump. The flowrate of the peristaltic pump was calculated using formula 3.2 below.

$$\frac{V}{t} = Q \qquad (3.2)$$

Where: V =Volume of seeding suspension
t = Time of experiment
Q = Flowrate of peristaltic pump

The flowrate of the filter pump for experiments was 30 GPM or 48 GPM. With the parameters of equation 3.2 known, the concentration of the microsphere seeding suspension (C_1) was calculated. The microsphere manufacturer listed a concentration of 5.58 x 10^8 microspheres per mL. This concentration was used to calculate the volume of sphere concentrate to add to the seeding suspension in the experiment. Equation 3.3 was used and can be seen below.

$$\frac{C_1 \times V}{C_m} = V_s \qquad (3.3)$$

Where: C_1= Concentration of spheres in seeding solution used in experiment.
V= Volume of seeding suspension used in experiment.
C_m=Concentration of microspheres from manufacture solution.
V_s= Volume of manufacture sphere solution to be added to the seeding suspension used in experiment.

2.2 Filter Media

2.2.1 12-inch Filter

The 12-inch filter body was a Hayward Pro-Series High Rate Sand Filter (model # S210S) (Hayward Pool Products, INC., Elizabeth, New Jersey). Six inches of #36 garnet (effective size

0.5-.0.6 mm) was placed at the bottom of the filter and measured to be 3-inches above the laterals to prevent media escaping through the laterals. 12-inches of sand (effective size 0.45 mm) was placed above the #36 garnet.

2.2.2 36-inch Filter

The 36-inch filter body was manufactured by Waterco (model# WD 600) (Waterco, Augusta, Georgia). 6-inches of #36 garnet (effective size 0.5-.0.6 mm) was placed at the bottom of the filter and measured to be 3-inches above the laterals to prevent media escaping through the laterals. 36-inches of sand (effective size 0.45 mm) was placed above the #36 garnet.

2.2.3 Ceramic Media Filter

Three inches of #36 garnet (effective size 0.5 – 0.6 mm) was placed bottom of the Certikin filter (Model# SPFDB) (Certikin, Oxfordshire England). Twenty two inches of Ceraflow-70 (effective size 0.15 – 0.25 mm) (Wateropolis, Newbury, OH) was then placed on top of the garnet media which was measured to be 3 inches above the laterals to prevent media from escaping out of the filters through the laterals.

2.2.4 Vortisand filter

A Vortisand® filter with a 24-inch outside diameter and 49.5-inch length with a capacity of 83 US gallons was used and was mounted on a skid (Serial # 1424001) (Xylem Water Solutions USA, Inc, Charlotte, NC). This filter had automated control valves with a built in pump that runs the system as programmed by the manufacturer. The Vortisand filter used a 3-inch schedule 80 PVC pipe that was inserted to the swim spa as a supply line. The effluent was piped to the swim spa as a return line 4 feet away from the inlet pipe and pointed in the opposite direction to prevent short circuiting of the system. A picture of the complete system can be seen below in Figure 2.1.

Figure 2.1: Vortisand filter on skid

2.3 Swim Spa

The lab scale swim spa is a 1,500-gallon (5,500 liters) of water. The pool was continuously monitored with a water quality control system (Hayward, Poolcomm, CAT5000, Charlotte, North Carolina). The controller was connected to a pH probe (Hayward, CAT PRO-15, Charlotte, North Carolina) and an oxidation reduction potential (ORP) prove *Hayward, CAT PRO-25). The water temperature was also measured by the controller. A mixture of 1:10 muriatic acid (Jasco, Memphis, TN) dilution was used to reduce the pH of the pool when above 7.5 using a peristaltic pump (Pulsafeeder, Chemtech XPV, Punta Gorda, FL). When the ORP was measured to be below 770 mV a 1:10 dilution of bleach was added to the pool until a measured value of 770 mV was achieved.

To create pool water, chemicals were added to the water in the spa. The spa jets were turned on during the addition of chemicals to encourage mixing. A volume of 105 mL of muriatic acid was added to the spa to achieve a target pH of 7.5. Then 75 mL of bleach (The Clorox Company, Oakland California) was added to the pool to achieve a free chlorine concentration of 1 ppm. Hardness was increased using 2 pounds of calcium chloride (Poolife Calcium Plus) to achieve the target hardness of 180 mg/L as $CaCO_3$. Alkalinity was added to the spa as 2 lbs of baking soda (Arm & Hammer, Pure Baking Soda) (Church & Dwight, Ewing Township, New Jersey) to achieve the target alkalinity of 80 mg/L as $CaCO_3$. Temperature in the pool was regulated using the pool heater which was set to 86 degrees Fahrenheit.

2.4 Cleaning and Filling Spa Procedures

After each experiment was performed, the filter was turned into the closed position and the 1500-gallon pool was drained using the pool pump to the level of the intakes. The remaining water was drained using a ball valve and vacuumed out using a 2.5-gallon vacuum (Shopvac, Williamsport, Pennsylvania). The pool was then filled with tap water from Charlotte, North Carolina and after being filtered through two 20-inch sediment filters (Hydronix, Chino Hills, CA) in series.

2.5 Experiment Procedures

To start each experiment, five 3-minute backwash cycles were performed with 5 minutes of filtering between each backwash. The filter was backwashed prior to the filter operating in the filter position to allow for the microspheres in the filter to be removed from the filter. The backwash water was sent to an external drain to prevent contamination of the pool.

After the backwashing sequence, the pool pump was turned off and pool chemistry was verified using a Taylor K-2006C Complete (FAS-DPD Chlorine) test kit (Taylor Water Technologies LLC, Sparks Glencoe, Maryland). The pool pump and filter was turned on and samples were taken to measure any carryover. Fifteen minutes later 22.7 g of instant coffee (Kraft Heinz, Pittsburg, PA) was added to achieve 3 mg per L TOC. The pool filter operated for 60 minutes before the microsphere seeding began. Triplicate samples were taken at 3-time intervals using conical bottom centrifuge tubes (Corning, Centristar, Corning, New York). A one-minute offset between influent and effluent samples with the influent sample taken first to account for the detention time from the microsphere seeding location to the effluent sample location. Once the last sample was taken, the experiment was concluded. Sample times can be seen in Table 1 below.

Table 1: Sample collection times in minutes

Influent	Effluent
2	3
6	7
10	11

2.6 Hydraulic Residence Time

Hydraulic residence time (turnovers) were calculated based on the volume of the swim spa (1,500 gallons) divided by the flow rate of each of the filters as determined by the surface loading rate. Equation 3.4 was used to calculate turnovers can be seen below.

$$Turnover = \frac{V}{Q} \tag{3.4}$$

Where: V= Volume of swim spa (gallon)
Q= Pump flow rate (gpm)

2.7 Sample Processing

Samples were collected in 50 mL centrifuge tubes. Samples were shaken for 30 seconds by hand and mixed with the vortex mixer (Fisher Scientific, Hampton, New Hampshire) for an additional 30-seconds prior to analysis to resuspend the microspheres. The effluent samples were processed first to reduce possible contamination of the high concentrations of spheres in the influent samples.

The equipment used for processing samples were washed with DI water to include 3 sets of tweezers (Millipore), 2 glass 15 mL microanalysis filter funnels (EMD Millipore, Burlington, Massachusetts), and 3 funnel clamps (Millipore). The regulated 3-place vacuum manifold was rinsed with DI water prior to a 3-µm polycarbonate track etched (PCTE) filter (Isopore, 25 mm, Millipore Sigma, Burlington, Massachusetts) being placed on top of each of the manifolds. The PCTE filters were placed using 1 set of tweezers each. The tweezers were used only for that sample for placement and removal of the filter. Constant suction was on the manifold, and each filter placement location had an individual valve to control suction.

Sample processing involved opening the suction valve on the individual funnel and pouring the desired volume of sample into the funnel. The suction was turned off, and the clamp and funnel were removed. Tweezers were then used to remove the filter and transfer it to a sample slide (Corning 2948-75x25) by horizontally sliding the filter and placing the filter on the center of the sample slide. A drop of polyvinyl alcohol-DABCO (PVA-DABCO) (Freer 1984) was placed onto the center of the filter and a cover slip (Corning, 25mm square) was placed squarely over the center of the filter. The cover slip was allowed to settle by gravity (never pressed). The slide was placed in a horizontal sample box to dry. This process was repeated for the two other samples, and after the remaining two samples were processed the tweezers, funnels, and clamps were washed with DI water. All remaining samples were processed in the same way.

The first samples processed were the carryover samples. The effluent samples were then processed and followed by the influent samples. After the first 5 effluent samples were processed, a blank sample using 50 mL of DI water was processed to check for cross contamination. Additional blank samples were taken after all effluent slides were processed and again after the first 5 influent samples were processed.

The sample slides were analyzed under an epi-fluorescent microscope (Zeiss, Axioskop, Car-Zeiss-Stifung, Stuggart, Germany) at 100x total magnification. The fluorescent filter set had a 450-490 nm excitation wavelength range, a 510 nm dichroic filter, and a 520 nm emission filter. Samples were counted using a hand counter and recorded.

2.8 Total Organic Carbon Experiment

Total organic carbon (TOC) was added in the form of Maxwell House Instant Coffee (Kraft-Heinz, Chicago, IL), which was determined to have 51.2% TOC per gram. A coffee solution (10 grams of instant coffee in 100 mL of DI water) was then tested 3 times using a TOC analyzer. The source water was determined to have a concentration of 1 ppm of TOC and 2 ppm of TOC was added to the pool using the volume of the pool and the concentration of TOC per gram of coffee to achieve a pool concentration of 3 ppm as TOC using equation 3.5 below.

$$C = \frac{1}{5.12\times10^{-4}} \times \frac{m_I}{V} \tag{3.5}$$

Where: C= Concentration of TOC
V= Volume of swim spa
C_I= Mass of instant coffee added to swim spa

TOC experiments were conducted using the above equation for TOC concentration, and it was found that the TOC consumption within the pool was 1 ppm of TOC per week. TOC was then added at the concentration of 1 ppm of TOC per week during the TOC experiments.

2.9 Lab-Scale Regeneration of Ceramic Media

2.9.1 Configuration

Lab-scale experiments were performed using a 2-inch diameter PVC column. A 200-gallon spa was used for the pool water. The filter was supplied with water using a 3/8-inch outer diameter polyethylene tubing connected to a PVC pipe after the pool pump. The microspheres were supplied using a T-junction after the pump and before the filter column. Effluent samples were taken using the 3/8-inch discharge line. Flow rate was measured using a Coriolis flowmeter and verified by using a 1000 mL graduated cylinder (determining how long it took to fill it). The pool chemicals were added 24 hours prior to the experiment and verified 1 hour prior to the experiment start. A diagram of the lab-scale configuration can be seen below in Figure 2.2.

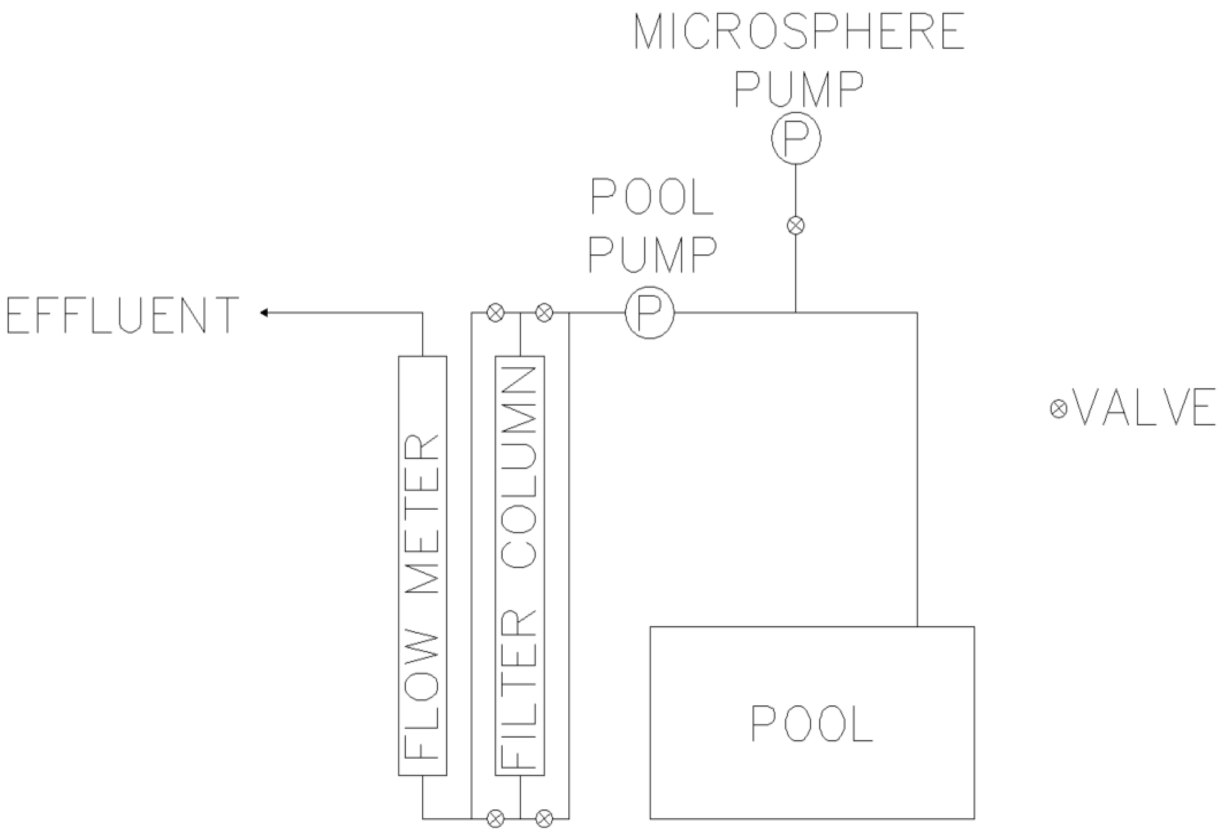

Figure 2.2: Lab-scale configuration

Media regeneration experiments were performed on the Ceraflow-70 ceramic media after 8 weeks of TOC loading. Nine experiments and one control experiment were performed using varying individual procedures or a combination of two procedures and can be seen in Appendix A.

2.8.2 Acid Soak

The ceramic media was soaked in a 5-gallon bucket (The Home Depot Inc., Atlanta, Georgia) using 2 liters of a 1:10 solution of hydrochloric acid (Thermo Fisher Scientific Co LLC, Waltham, Massachusetts) and mixed using a rubber spatula for 1 minute and soaked for 2 hours. After 2 hours, the acid-soaked media was rinsed 10 times by filling the remaining volume in the bucket and pouring it in a sink. Caution was taken to not allow media to escape the bucket by pouring the rinse water over a period of 2 minutes.

2.8.3 Base Soak

The ceramic media was soaked for 2 hours using a 1-liter jar test container (Phipps & Bird, Inc., Richmond, Virginia) using a 1% NaOH solution (Thermo Fisher Scientific Co LLC, Waltham Massachusetts) and adjusted to a pH of 12 using a 1:10 solution of hydrochloric acid (Thermo Fisher Scientific Co LLC, Waltham Massachusetts)

2.8.4 Chlorine Soak

The ceramic media was soaked for 2 hours using a 1-liter jar test container (Phipps & Bird, Inc., Richmond, Virginia) using a 1:20 dilution of bleach (The Clorox Company, Oakland California). For experiments where the pH was adjusted a 1:10 solution of hydrochloric acid (Thermo Fisher Scientific Co LLC, Waltham Massachusetts) was added until the pH was between 8 – 9 and verified using a pH probe (Hayward, CAT PRO-15, Charlotte, North Carolina).

2.8.5 Sodium Percarbonate Soak

The ceramic media was soaked in a 5-gallon bucket (The Home Depot Inc., Atlanta, Georgia) 3 times for 1 hour using a 2% solution of sodium percarbonate (Active Element, Kansas City, Missouri) and immediately mixed using a rubber spatula. After each soak the media was rinsed by filling the remaining volume in the bucket and pouring it in a sink. Caution was taken to not allow media to escape the bucket by pouring the rinse water over a period of 2 minutes.

2.8.6 Salt Soak

The ceramic media was soaked for 2 hours using a 1-liter jar test container (Phipps & Bird, Inc., Richmond, Virginia) using a 1% solution of sodium chloride (Thermo Fisher Scientific Co LLC, Waltham Massachusetts).

2.8.7 Blast Furnace

The ceramic media was placed in a blast furnace (model # 550-126, Fisher Scientific Co LLC., Waltham, Massachusetts) at 510 degrees Celsius for two hours and remained in the furnace to cool for 24 hours prior to starting the experiment.

2.8.8 HTH Pool Cleaner

HTH Pool Care Filter Cleaner (Innovative Water Care LLC., Alpharetta, Georgia) was added using the label instructions option 2: adding through pool skimmer using 4 liters of DI water and 32 fluid ounces of HTH Pool Care Filter Cleaner mixed in a 5-gallon bucket (The Home Depot Inc., Atlanta, Georgia) during the backwash cycle in the lab scale configuration. The entire solution from the bucket was passed through the filter and the pump was turned off allowing the media in the filter to remain submerged in the solution for 12 hours. The filter was then backwashed 5 times using pool water before the experiment started.

2.9 Calculations and Statistics

2.9.1 Calculation

The recorded number of microspheres on each filter was divided by the total volume of the sample that passed through the filter. This determined the concentration for each sample. At each time interval for the influent and effluent, the sample concentrations were averaged. A percentage removal was calculated using the average influent and effluent at each time interval using equation 3.6 below.

$$R = \frac{I-E}{I} \times 100\% \qquad (3.6)$$

Where: R= Percent removal
I=Influent sphere concentration
E= Effluent sphere concentration.

The standard deviation for each experiment was calculated based on the averaged removal at each time interval using Microsoft Excel's standard deviation function. An overall average for each experiment was calculated using Microsoft Excel based on the average removal at each time interval. A summary of all the experiments can be seen in Appendix B.

2.9.2 Statistics

All statistics were calculated using Microsoft Excel on the three calculated removals for each time interval. When the experiments were duplicated, the 6 removals were combined into one overall removal for that experiment. Each group of values were tested using the Ryan-Joiner normality test to determine if the data were normally distributed. Data collection can be seen in Appendix C. Once the data groups were determined to be normally distributed a two-sample, two-tailed, heteroscedastic t-test was performed to determine if the experiments resulted in a statistically significant difference using a 95% confidence interval.

CHAPTER 3: RESULTS

3.1 12-inch sand filter

A 12-inch deep sand filter achieved only 22.6% removal of 4.5-micron microspheres from pool water but changing the sand depth to 36-inches increased the removal to 51.8% as shown in Figure 3.1. These experiments were identical other than media depth filter with a constant filter loading of 10 gpm/ft^2 and a 20/40 mesh sand. The table inset in Figure 3.1 lists the values for media (sand) depth, total organic carbon (TOC) concentration, coagulant (Polyaluminum chloride or PACl) dose, and the number of pool turnovers prior to sample collection. A t-test showed a statistically significant difference with 95% confidence (p-value of 0.002) between the experiments at the two sand depths.

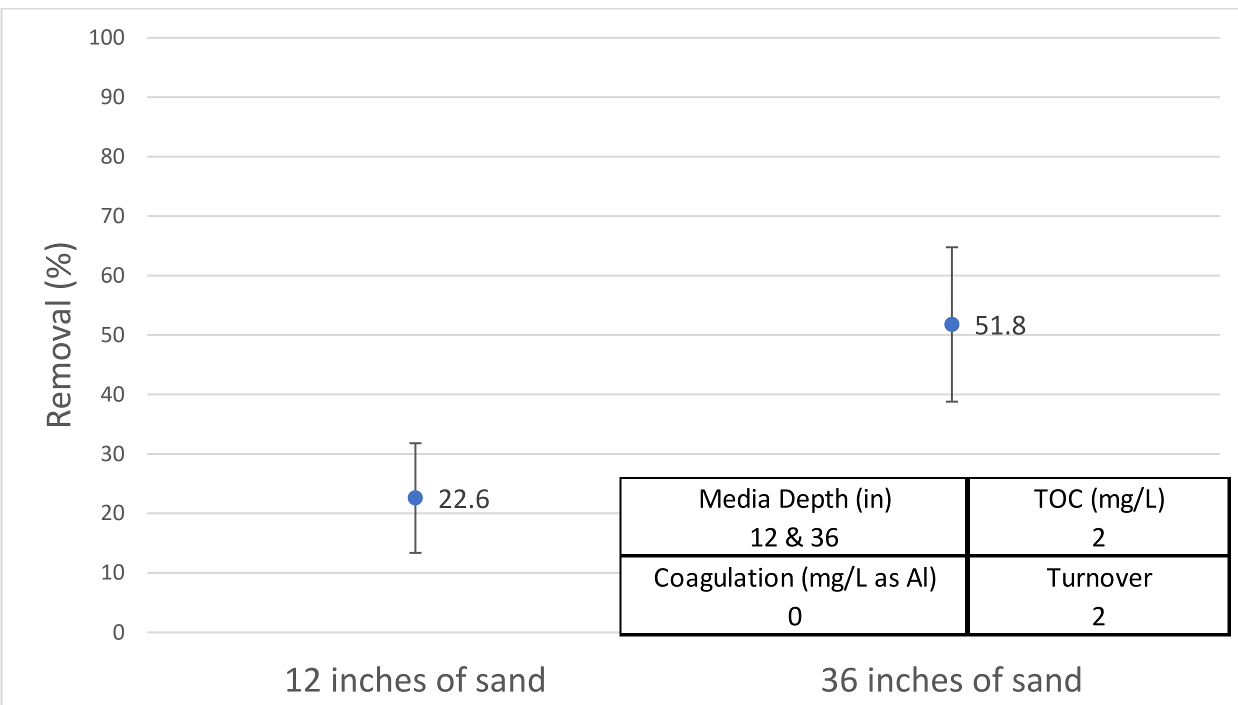

Figure 3.1: Comparison of 12-inch silica sand depth versus 36-inch silica sand depth

Figure 3.2 shows the microsphere removal by 12-inches of sand was increased from 22.6% (s.d.=9.22) to 63.9% (n = 1) by adding 0.005 mg/L as Al of PACl at 2 turnovers with 2 ppm of added TOC, as indicated on the graph inset, used to simulate bather load. This experiment was not replicated, so a statistical comparison is not possible. These results indicate that coagulant addition has potential to significantly increase filter removal efficiency.

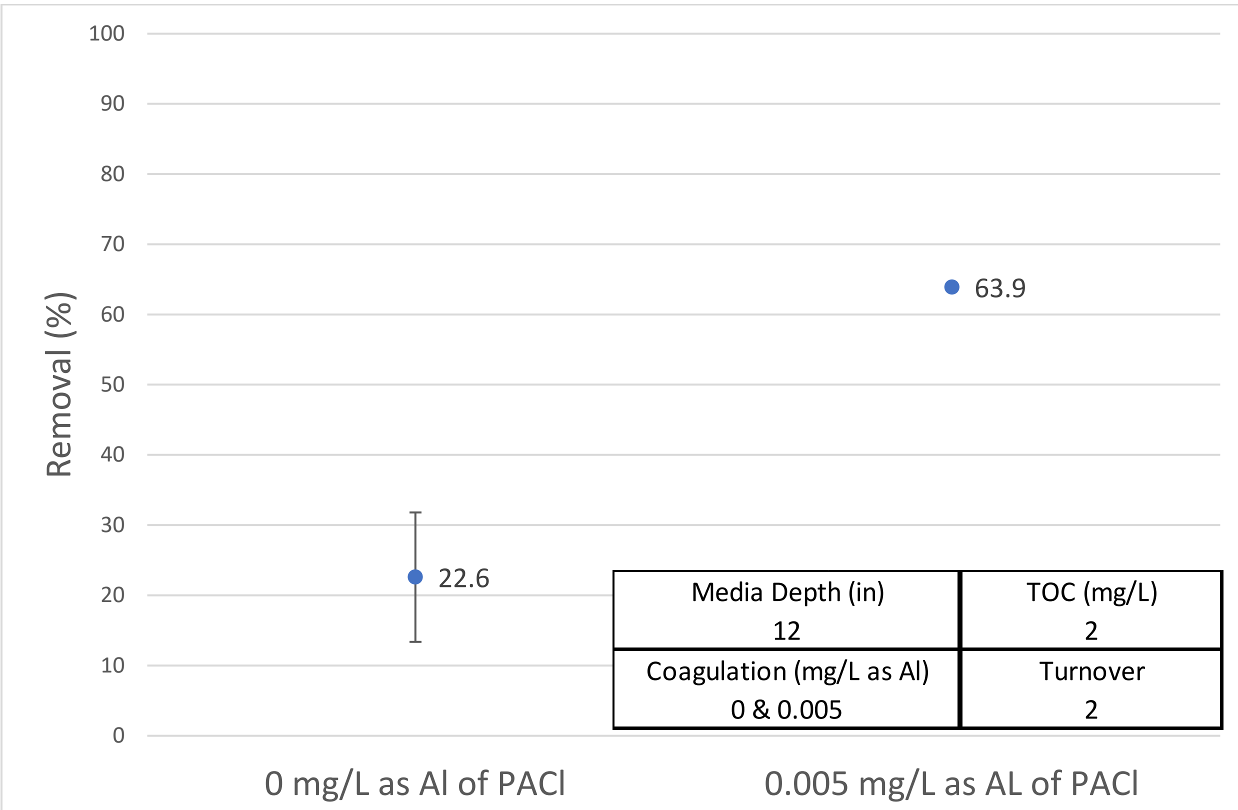

Figure 3.2: 12-inch Sand filter versus 12-inch sand filter with 0.005 mg/L as Al of PACl at 1 turnover

While a 12-inch depth of sand achieved a removal of 22.6% (s.d.=9.22) microsphere removal without coagulant, the addition of 0.005 mg/L as Al of PACl at 48 turnovers achieved microsphere removal of 98.1% (s.d.=0.74) as shown in Figure 3.3. A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 4.9×10^{-6}).

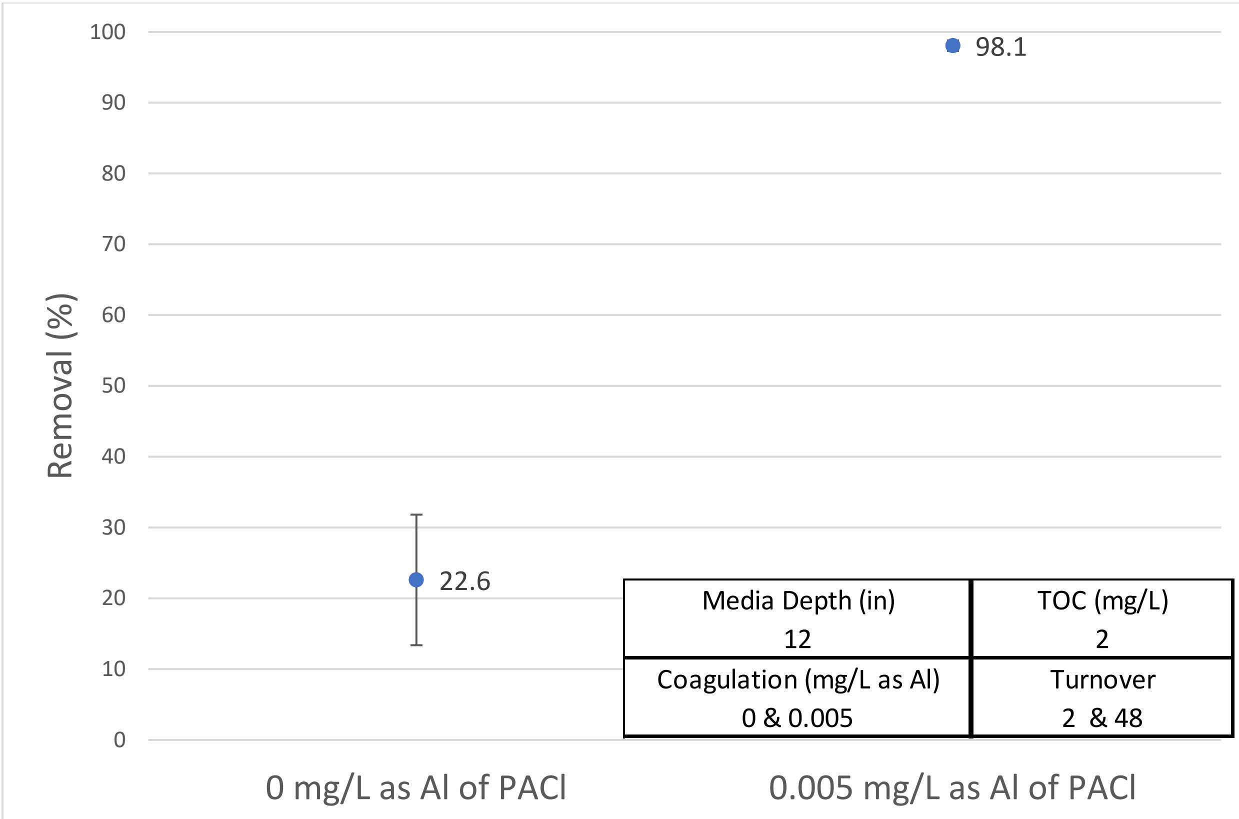

Figure 3.3: 12-inch Sand filter versus 12-inch sand filter with 0.005 mg/L as Al of PACl at 48 turnovers

Figure 3.4 shows microsphere removal of a 12-inch sand filter at 0.005 mg/L as Al of PACl at 2 turnover and 48 turnovers compared to microsphere removal of the 12-inch sand filter with no coagulant added. A t-test was not performed between the 2 turnover and 48 turnover experiments due to the 2 turnover experiment not being replicated.

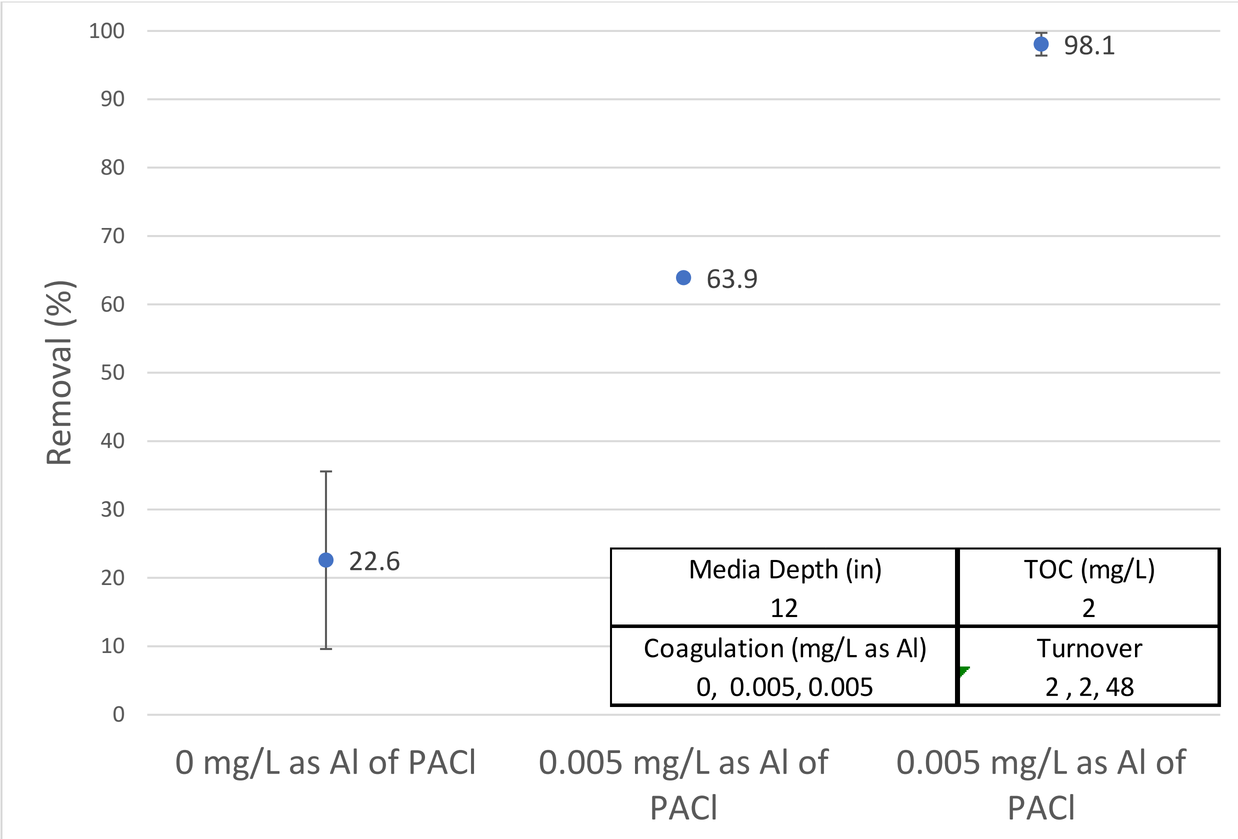

Figure 3.4: 12-inch sand filter versus 12-inch sand filter with 0.005 mg/L as Al of PACl at 2 turnovers versus 12-inch sand filter with 0.005 mg/L as Al of PACl at 48 turnovers

Figure 3.5 shows the microsphere removal of 12-inches of sand was increased from 22.6% (s.d.=9.22) to 74.9% (s.d.=2.36) with the addition of 0.05 mg/L as Al of PACl at 2 turnover. A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 5.5×10^{-5}) between the two experiments.

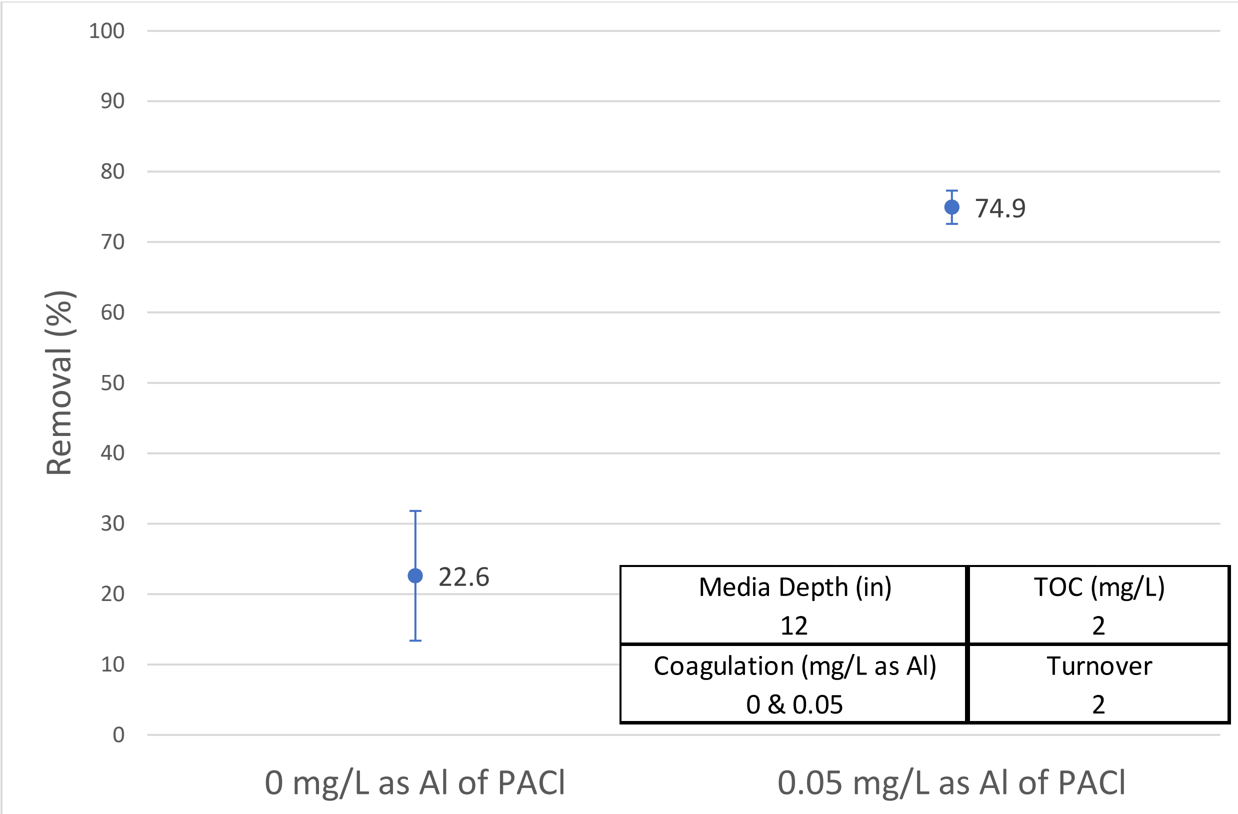

Figure 3.5: 12-inch Sand filter versus 12-inch Sand Filter with 0.05 mg/L as Al of PACl at 2 Turnover

Figure 3.6 shows the microsphere removal of 12-inches of sand was increased from 22.6% (s.d.=9.22) to 97.0% (s.d.=0.53) with the addition of 0.05 mg/L as Al of PACl at 48 turnover. A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 5.3×10^{-6}) between the two experiments.

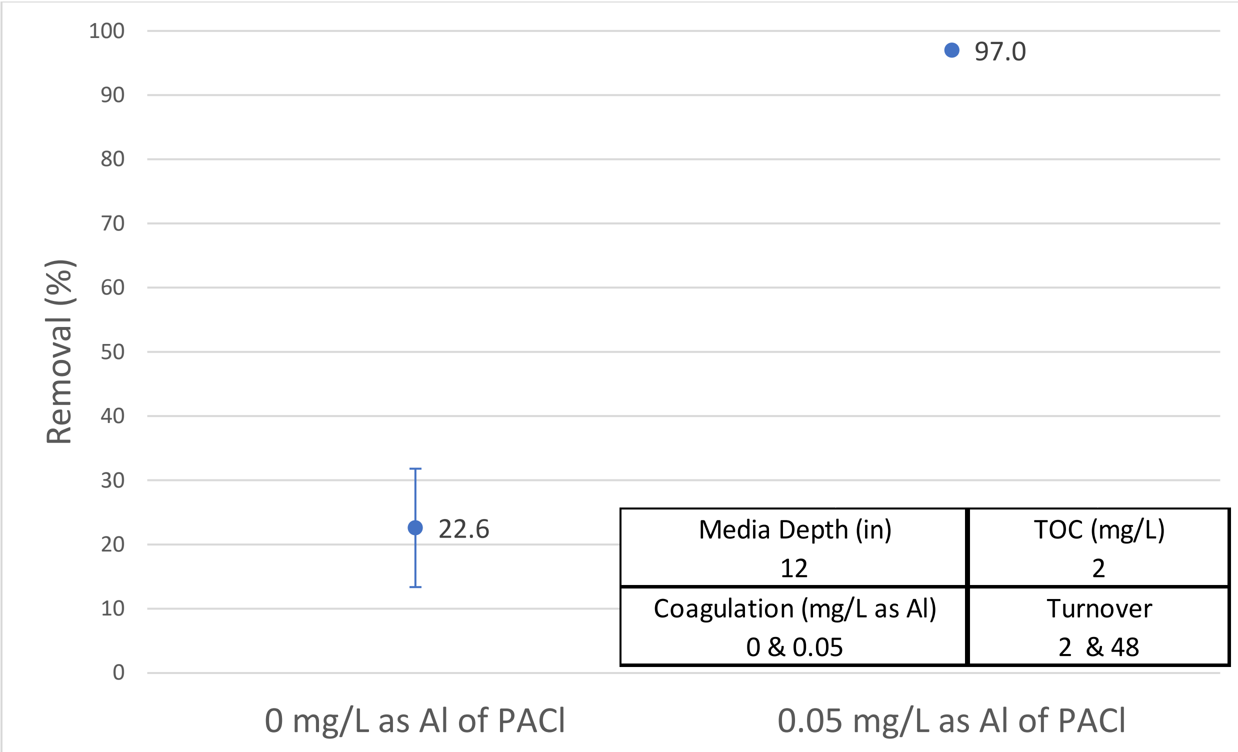

Figure 3.6: 12-inch Sand filter versus 12-inch Sand Filter with 0.05 mg/L as Al of PACl at 48 Turnovers

Figure 3.7 shows microsphere removal of a 12-inch sand filter at 0.05 mg/L as Al of PACl at 2 turnover and 48 turnovers compared to microsphere removal of the 12-inch sand filter with no coagulant added. A t-test was performed between the 2 turnover and 48 turnover experiments and showed a statistically significant difference with 95% confidence (p-value of 6.08×10^{-5}) between the two experiments. So, while coagulant addition can significantly increase filter efficiency, the removal efficiency still varies significantly over time under the tested conditions.

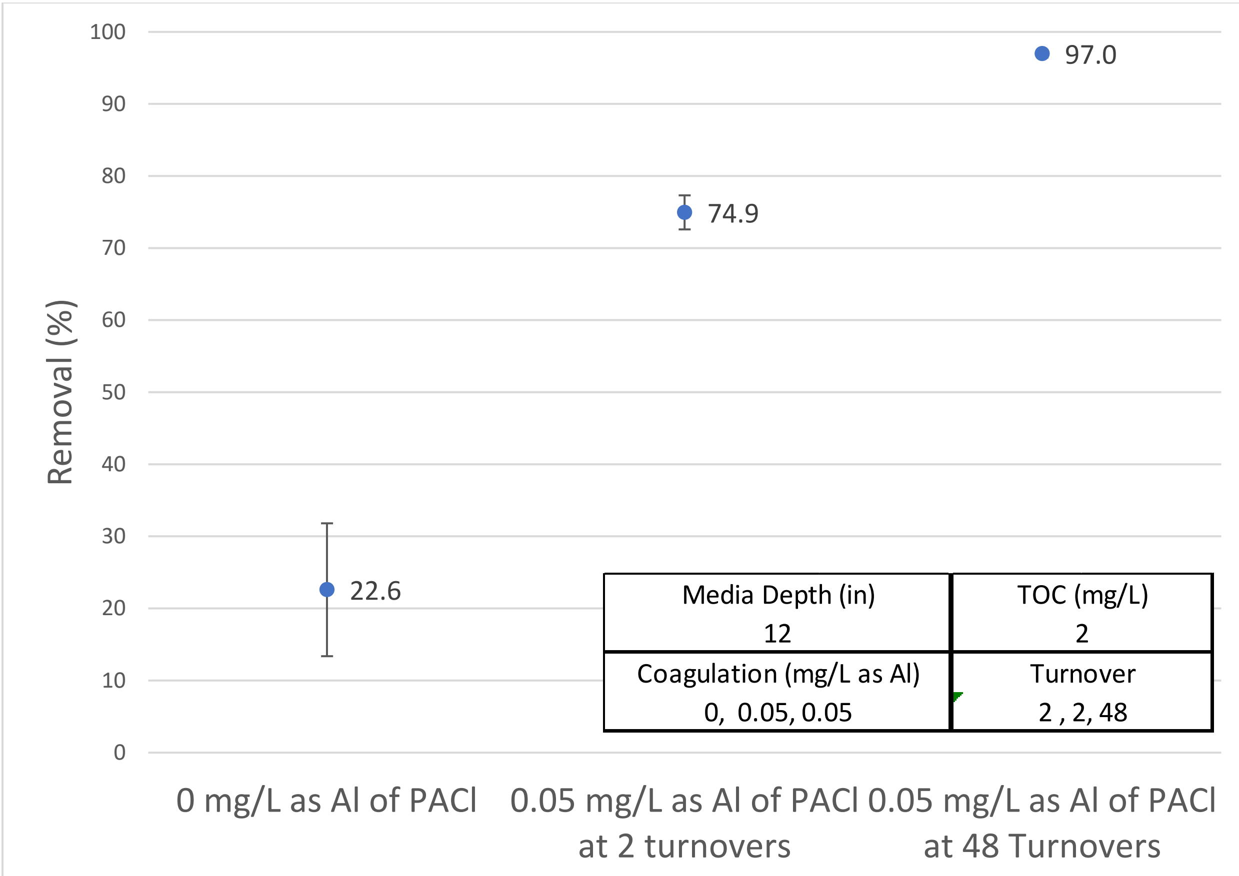

Figure 3.7: 12-inch sand filter versus 12-inch sand filter with 0.05 mg/L as Al of PACl at 2 turnovers versus 12-inch sand filter with 0.05 mg/L as Al of PACl at 48 turnovers

3.2 12-inch sand filter without TOC loading

The effect of total organic carbon (TOC) addition on microsphere removal was measured using the 12-inch sand filter. Based on previous research, the effect of TOC on sand filters does not significantly change filter performance without coagulation as sand filters do not remove TOC. Figure 3.8 shows the 12-inch filter with TOC loading at 2 ppm of TOC at 2 turnovers with a removal of 22.6% (s.d. = 9.22) as compared to the 12-inch sand filter without TOC loading using 0.05 mg/L as Al of PACl at 2 turnovers with a removal of 99.8% (s.d. = 0.02). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 4.13 x 10^{-6}) between the two experiments.

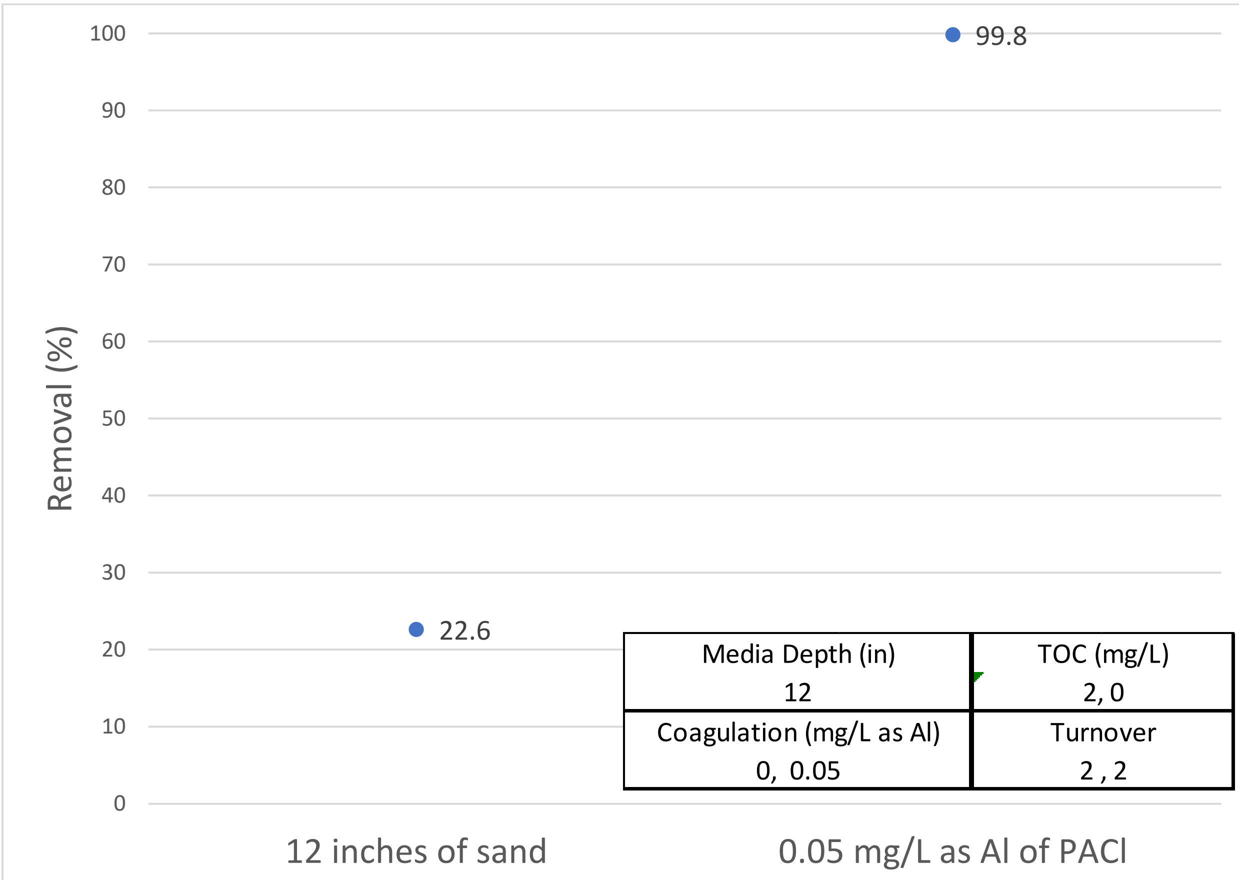

Figure 3.8: 12-inch sand filter with TOC loading versus 12-inch sand filter without TOC loading using 0.05 mg/L as Al of PACl

Figure 3.9 shows the 12-inch filter with TOC loading at 2 ppm of TOC at 2 turnovers with a removal of 22.6% (s.d. = 9.22) as compared to the 12-inch sand filter without TOC loading using 0.05 mg/L as Al of PACl at 48 turnovers with a removal of 99.9% (s.d. = 0.02). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 4.07 x 10^{-6}) between the two experiments.

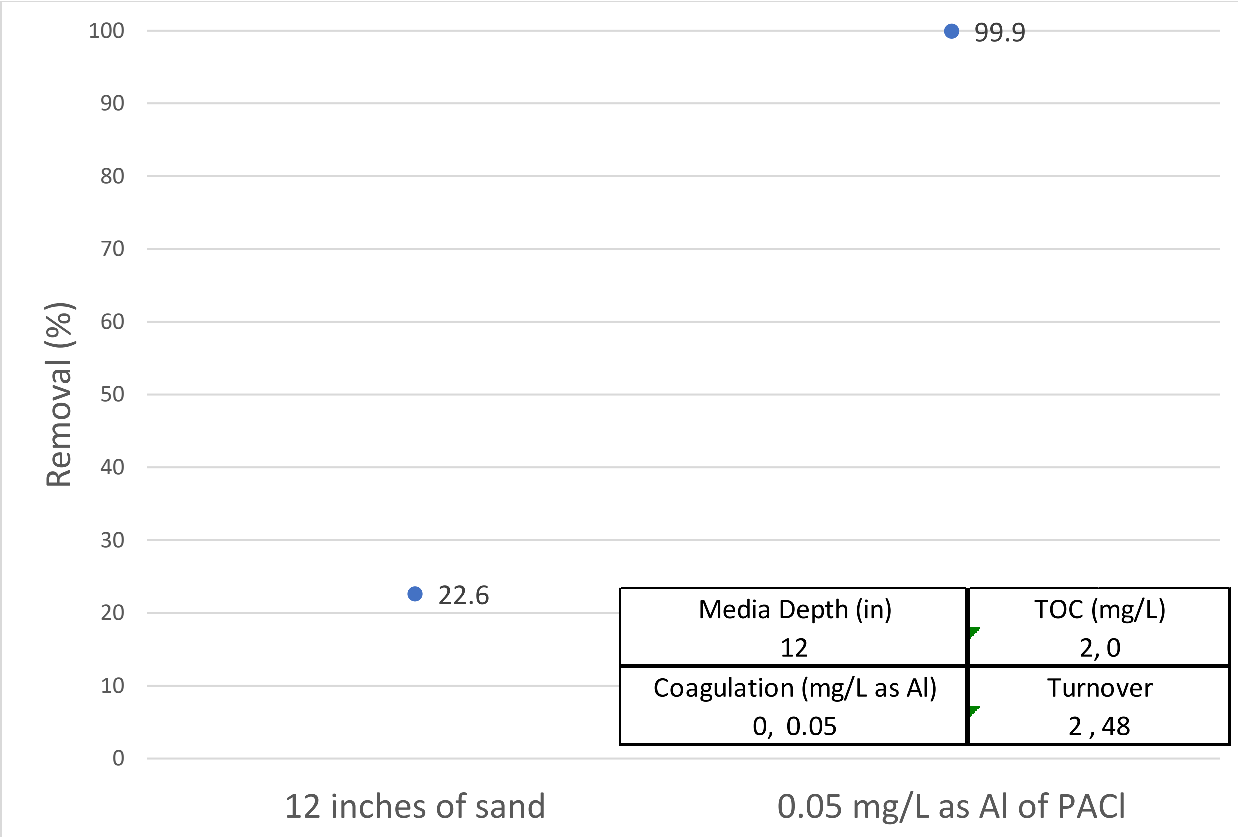

Figure 3.9: 12-inch sand filter with TOC loading versus 12-inch sand filter without TOC loading using 0.05 mg/L as Al of PACl

Figure 3.10 shows the 12-inch sand filter with a TOC loading at 2 ppm of TOC at 2 turnovers with a removal of 22.6% (s.d. = 9.22) as compared to the 12-inch sand filter without TOC loading using 0.05 mg/L as Al of PACl at 2 turnovers with a removal of 99.8% (s.d. =0.02) and 48 turnovers with a removal of 99.9% (s.d. = 0.02). A t-test was performed between the two experiments without TOC loading and showed a statistically significant difference with 95% confidence (p-value of 6.08 x 10^{-5}) between the two experiments.

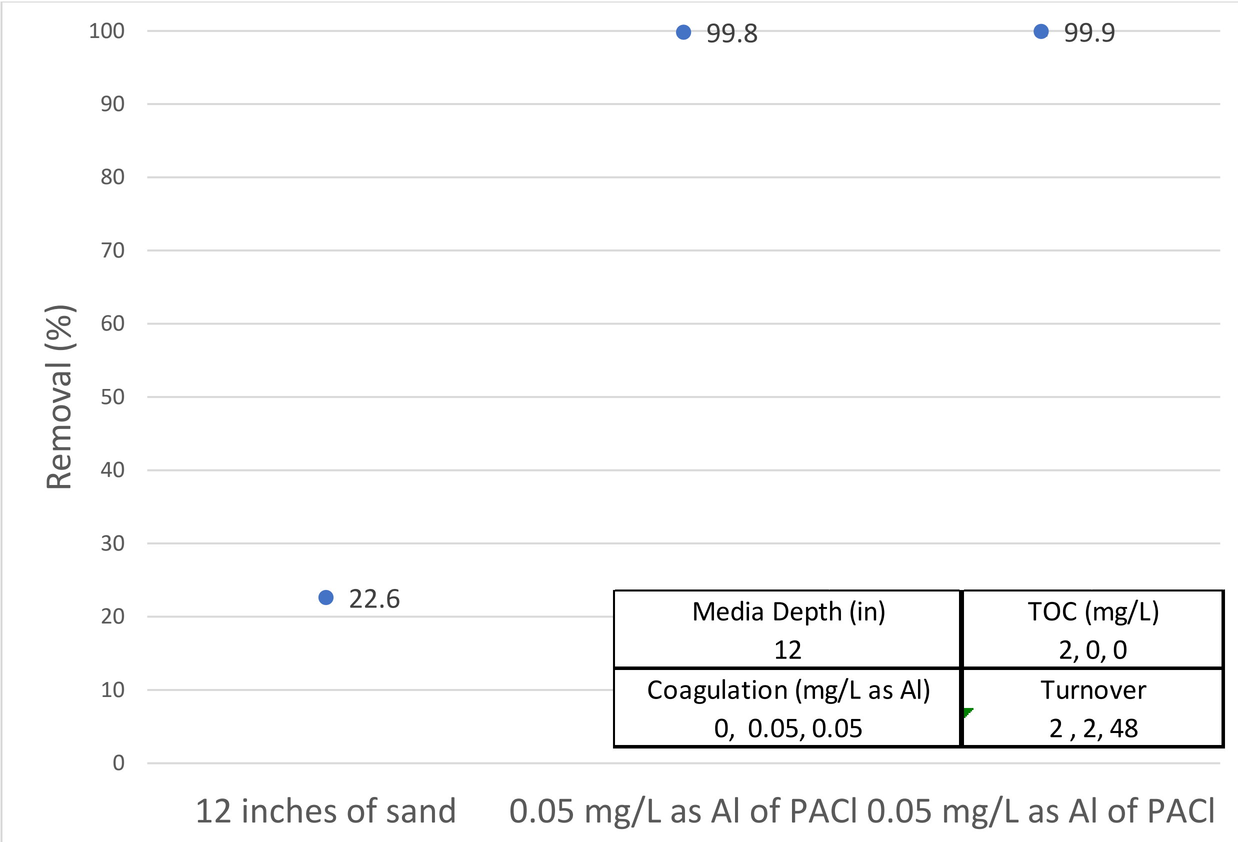

Figure 3.10: 12-inch sand filter with TOC loading versus 12-inch sand filter without TOC loading using 0.05 mg/L as Al of PACl at 2 and 48 turnovers

While adding coagulant increased the sand filter efficiency by more than 340% under these conditions, testing filter performance without TOC addition does not reflect real-world conditions where swimmers are continuously introducing organic contaminants (e.g., sweat, personal care products, and skin cells) as they swim. So, subsequent experiments were performed with TOC addition, and caution should be used when interpreting filter testing data performed without TOC addition.

3.3 36-inch sand filter

The microsphere removal in the 36-inch sand filter was 51.8% (s.d. = 12.99) without coagulant addition, but it increased to 86.5% (s.d. = 5.58) removal with the addition of 0.005 mg/L as Al of PACl at 1 turnover. A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.67 x 10^{-4}) between the two experiments and can be seen in Figure 3.11.

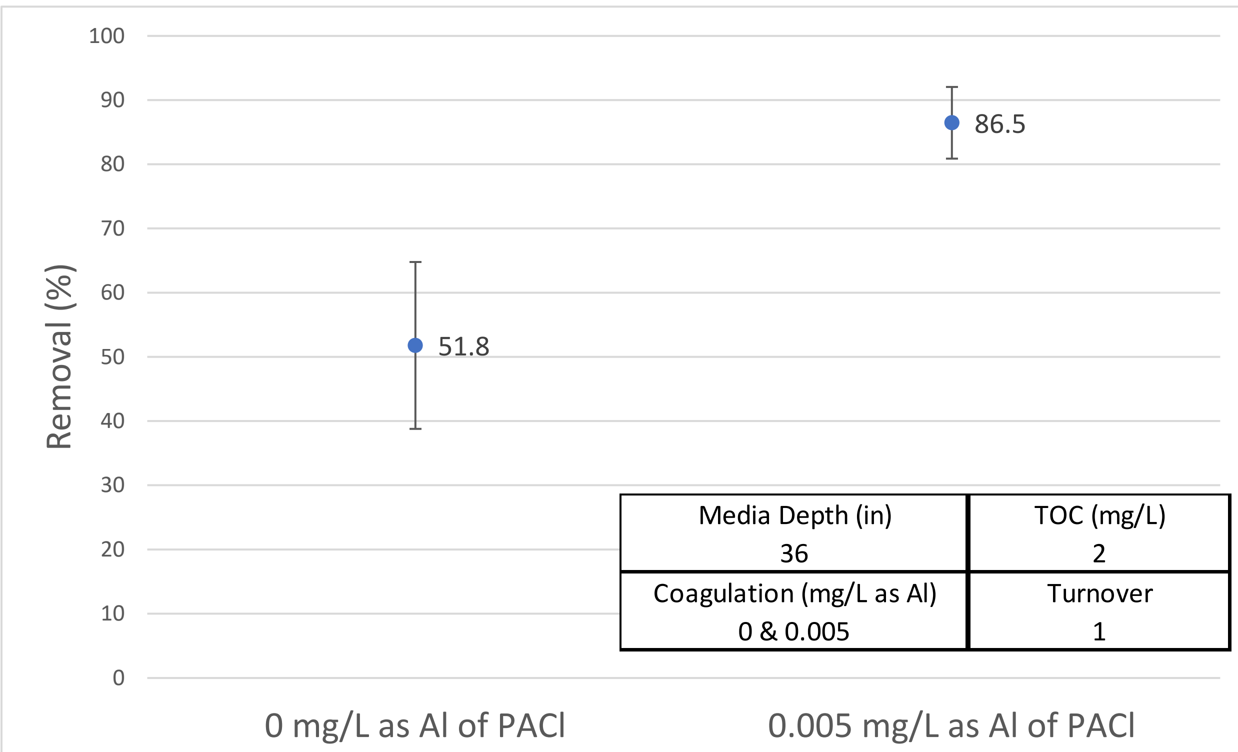

Figure 3.11: 36-inch sand filter versus 36-inch sand filter with 0.005 mg/L as Al of PACl at 1 turnover

Figure 3.12 shows the microsphere removal of a 36-inch sand filter was 51.8% (s.d. = 12.99) without coagulation, but the microsphere removal increased to 94.3% (s.d. = 1.11) with the addition of 0.005 mg/L as Al of PACl at 3 turnovers. A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.60×10^{-5}) between the two experiments.

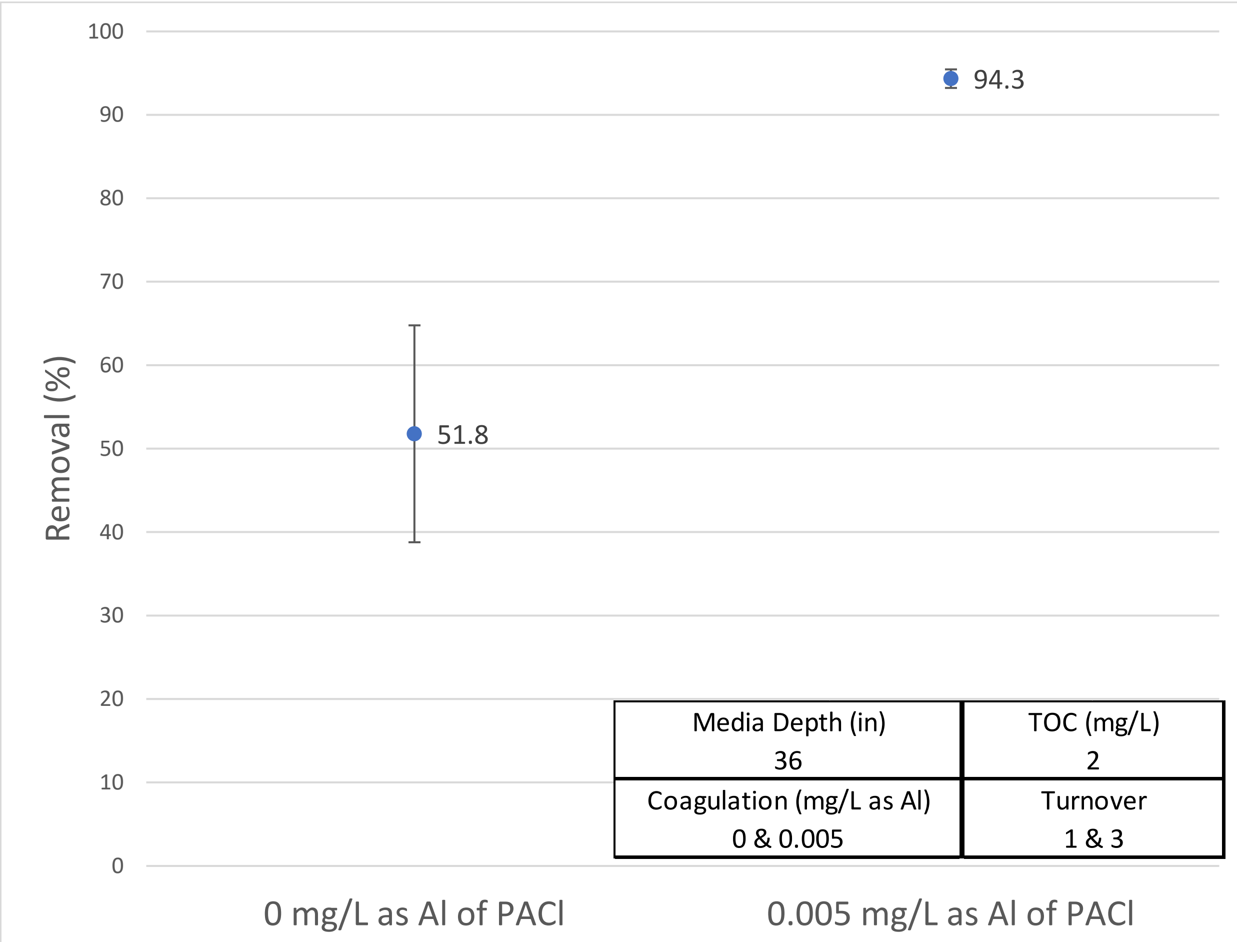

Figure 3.12: 36-inch sand filter versus 36-inch sand filter with 0.005 mg/l as Al of PACl at 3 turnovers

Figure 3.13 shows the microsphere removal of the 36-inch sand filter with no coagulation was 51.8% (s.d. = 12.99), which increased to 86.5% (s.d. = 5.58) microsphere removal with 0.005 mg/L as Al of PACl at 1 turnover and then to 94.3% (s.d. = 1.11) removal at 3 turnovers at the same coagulant dose. A t-test was performed and did not show a statistically significant difference with 95% confidence (p-value of 9.14×10^{-1}) between the 1 turnover and 3 turnover experiments with 0.005 mg/L as Al of PACl.

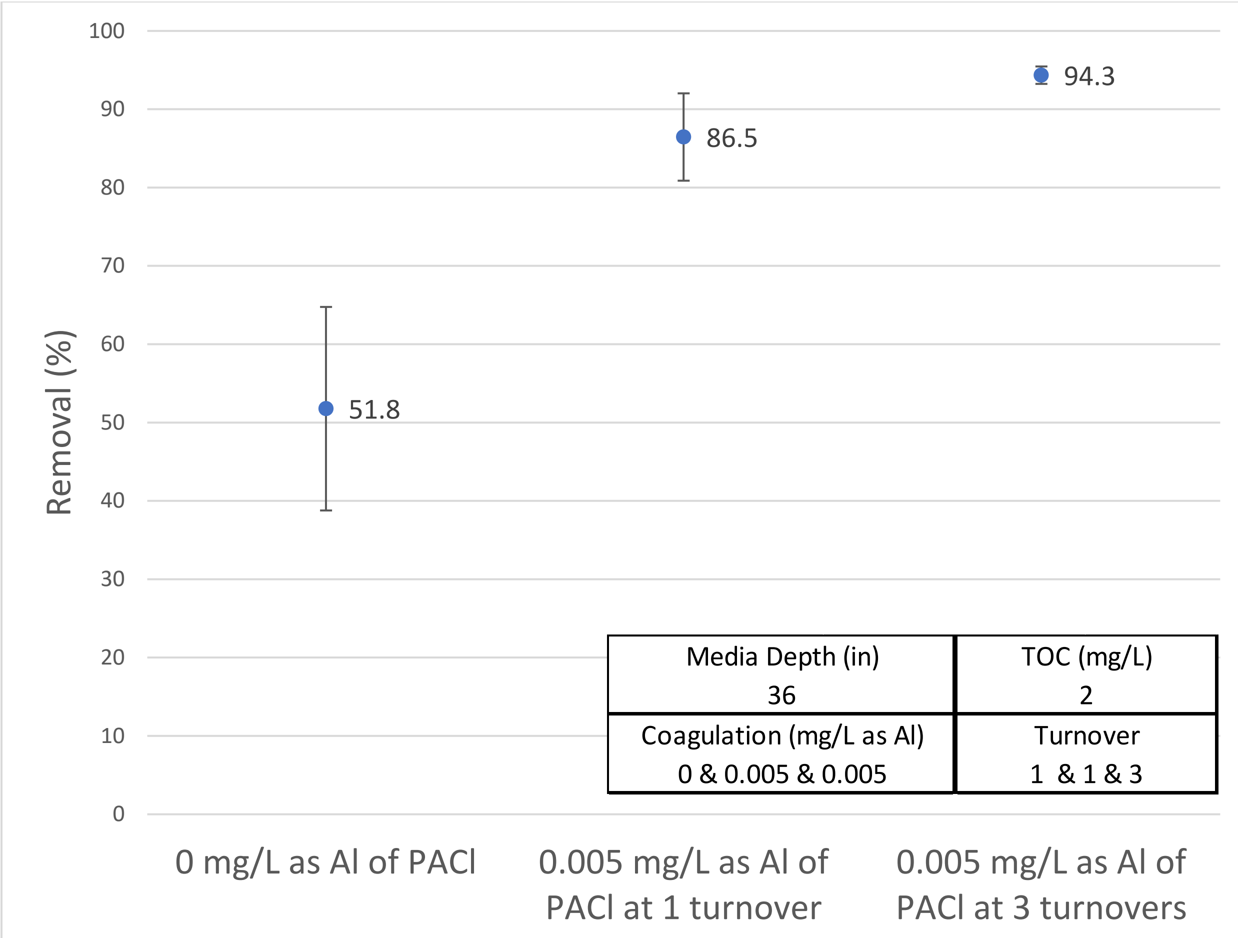

Figure 3.13: 36-inch sand filter versus 36-inch sand filter with 0.005 mg/L as Al of PACl at 1 and 3 turnovers

Figure 3.14 shows the microsphere removal in a 36-inch sand filter was 51.8% (s.d. = 12.99) without coagulant, which increased to 90.6% (s.d. = 0.56) removal with the addition of 0.05 mg/L as Al of PACl at 1 turnover. A t-test showed a statistically significant difference with 95% confidence (p-value of 2.60 x 10^{-3}) between the two experiments.

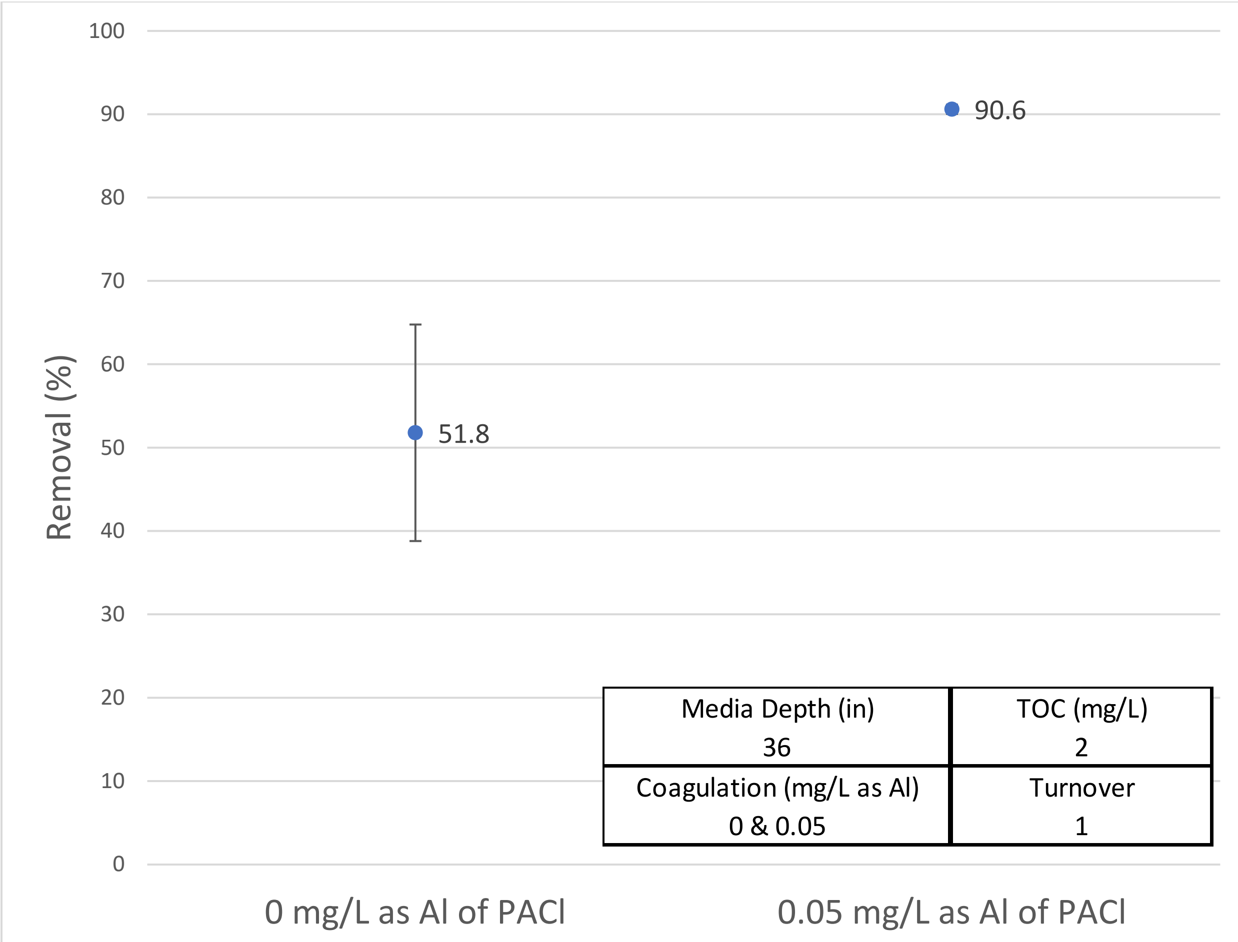

Figure 3.14: 36-inch sand filter versus 36-inch sand filter with 0.05 mg/l as Al of PACl at 1 turnover

Figure 3.15 shows the microsphere removal a 36-inch sand filter was 51.8% (s.d. = 12.99) without coagulant, which increased to 90.7% (s.d. = 1.67) removal with the addition of 0.05 mg/L as Al of PACl at 3 turnovers. A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.60 x 10^{-3}) between the two experiments.

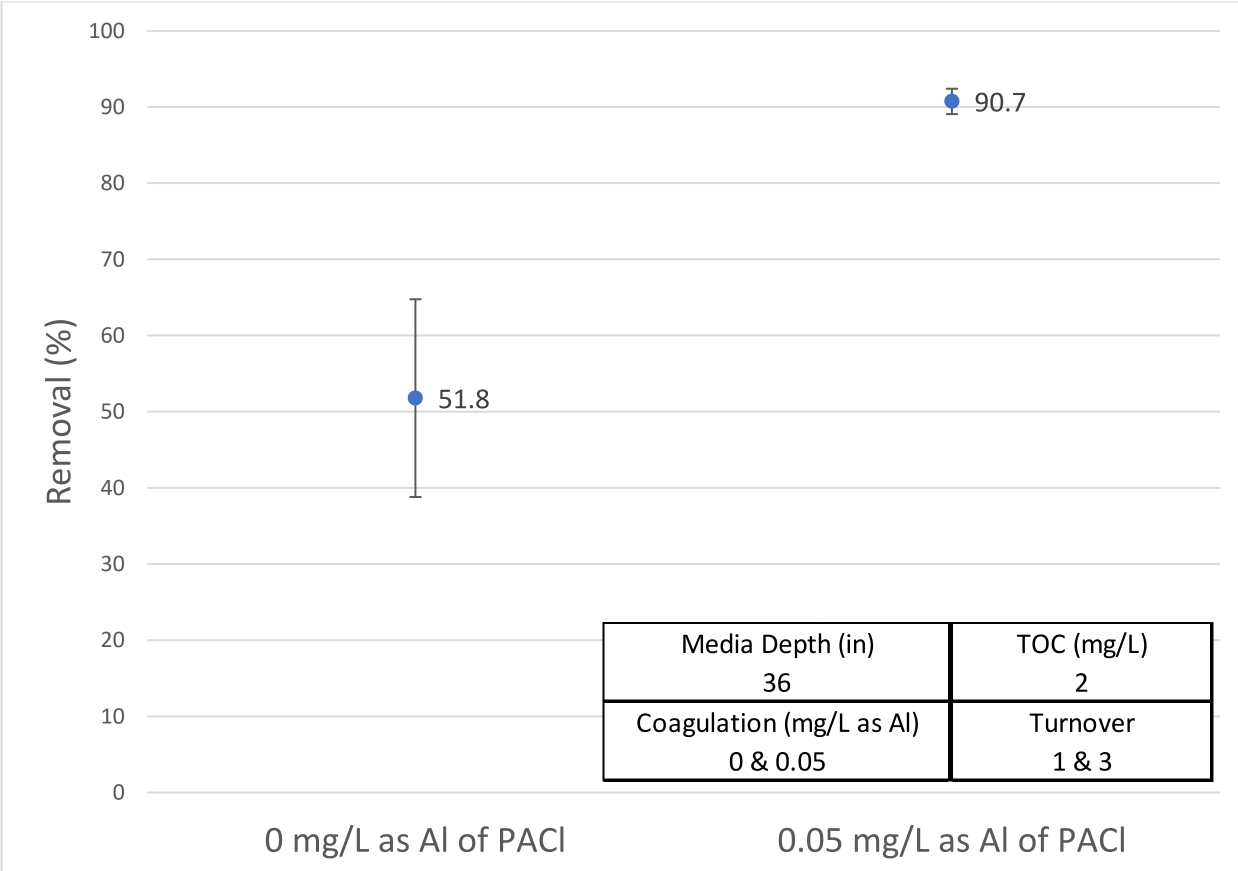

Figure 3.15: 36-inch sand filter versus 36-inch sand filter with 0.05 mg/l as Al of PACl at 3 turnovers

Figure 3.16 shows the microsphere removal of a 36-inch sand filter with no coagulation of 51.8% (s.d. = 12.99), but the microsphere removal with 0.05 mg/L as Al of PACl at 1 turnover increased to 90.6% (s.d. = 0.56) and then 90.7% (s.d. = 1.67) removal at 3 turnovers. A t-test was performed and did not show a statistically significant difference with 95% confidence (p-value of 9.14×10^{-1}) between the 1 turnover and 3 turnover experiments with 0.05 mg/L as Al of PACl.

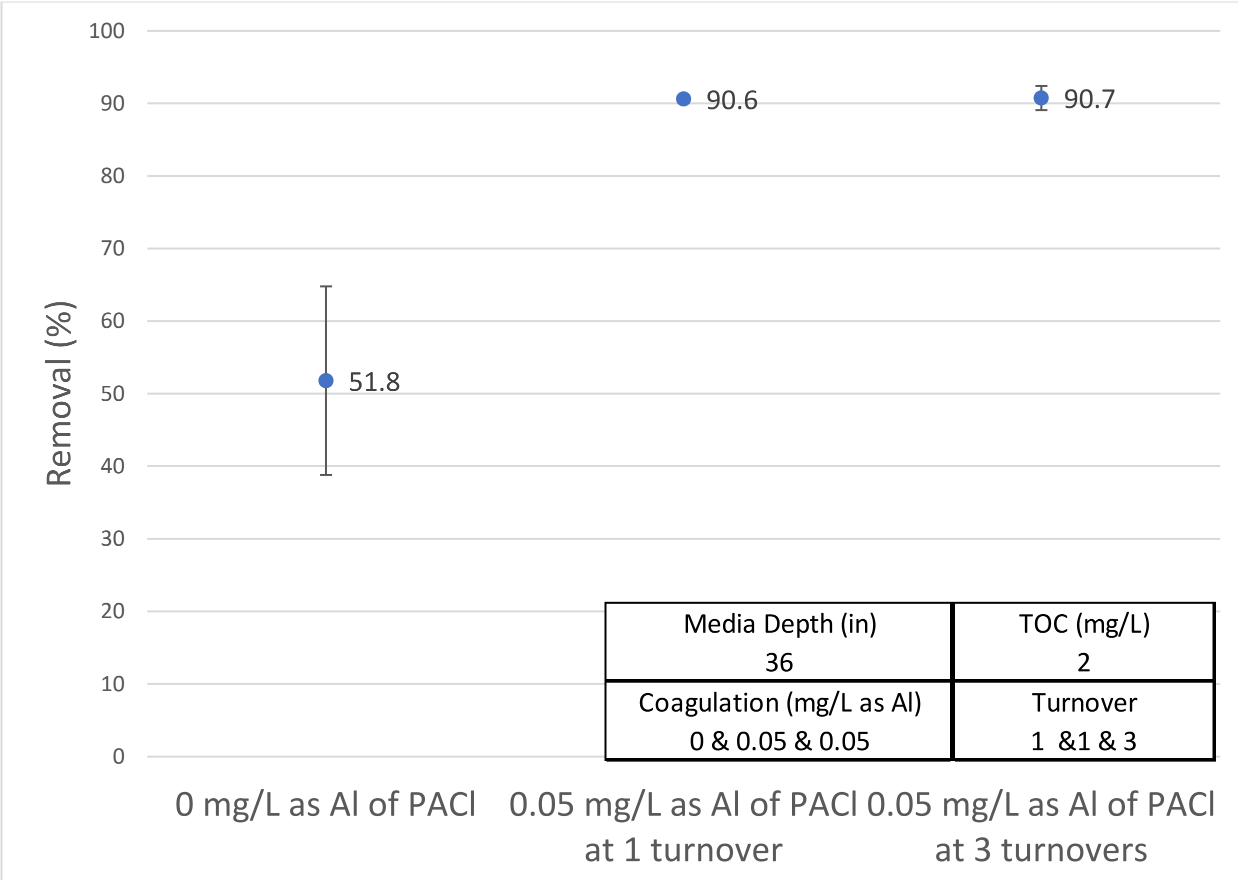

Figure 3.16: 36-inch sand filter versus 36-inch sand filter with 0.05 mg/L as Al of PACl at 1 and 3 turnovers

Adding coagulant to a 36-inch sand filter showed a significant increase in filter efficiency without significant variations in removal over time. These results indicate that adding coagulant to 36-inch sand filters could lead to better pathogen removal than if not using coagulant. This has potential practical significance since most U.S. pools and pool codes do require coagulant addition and allow sand filter depths of less than 12 inches.

3.4 Vortisand® filter

Two experiments using the Vortisand® filter were performed in accordance with the manufacturers standard operating procedures and resulted in microsphere removals of 51.2% (s.d. = 5.56) and 73.9% (s.d. = 3.34). Combining the two experiments resulted in a combined average removal of 62.6% (s.d. = 11.84) for the Vortisand filter that will be used in later comparisons.

Compared to the combined initial test of the Vortisand filter with a microsphere removal of 62.6% (s.d. = 11.84), the Vortisand filter was left in operation for 24 hours and tested again for microsphere removal, which resulted in a microsphere removal of 87.4% (s.d. = 2.34). A t-test was performed between the combined initial experiments and the 24 hours after operation experiment and showed a statistically significant difference with 95% confidence (p-value of 1.47×10^{-2}) as can be seen in Figure 3.17.

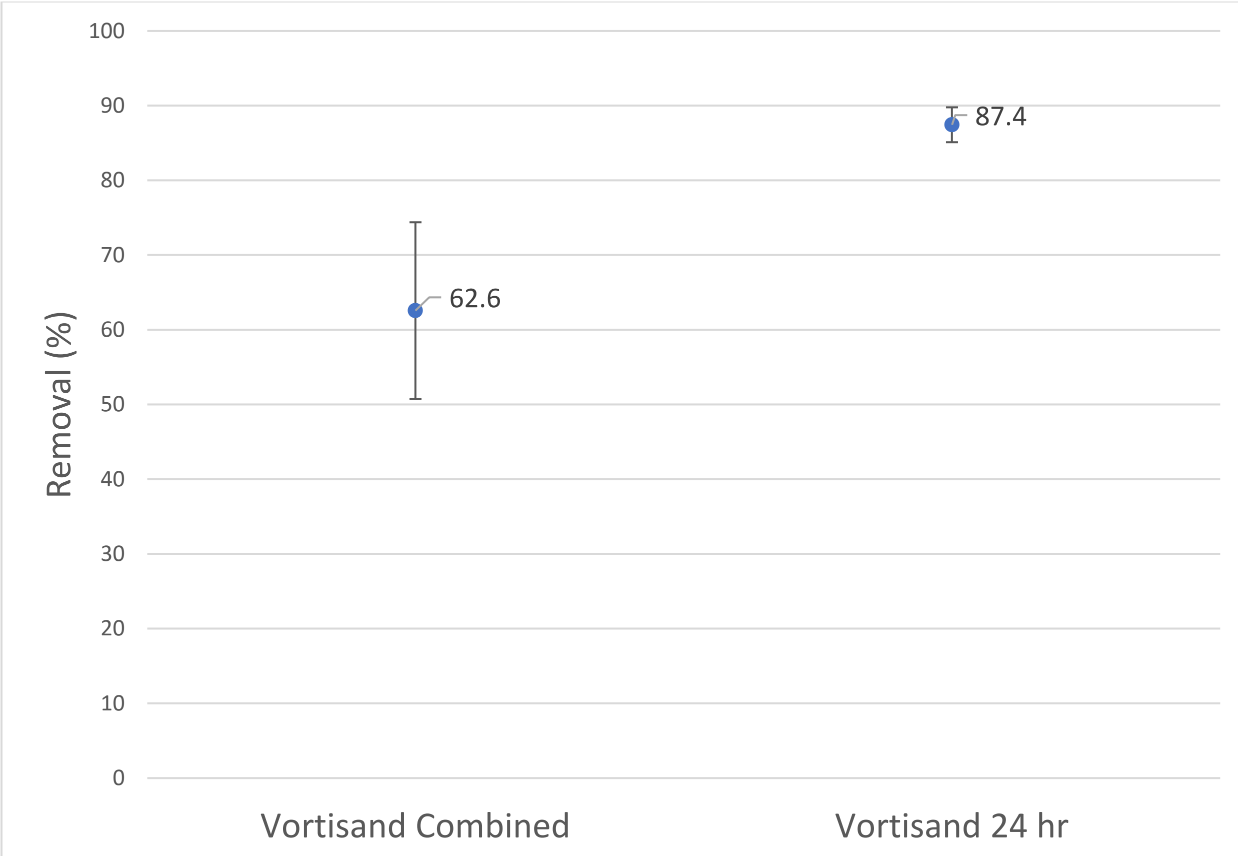

Figure 3.17: Initial Vortisand experiments vs 24 hours after operation experiment

The Vortisand filter was then tested at a high pH (pH = 8.1) as compared to standard tests (pH range 7.5 – 7.6) and compared to the initial combined microsphere removal of 62.6% (s.d. = 11.84) the microsphere removal of the high pH experiment resulted in a removal of 94.2% (s.d. = 0.94). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 4.69×10^{-3}) and can be seen in Figure 3.19. While the high-pH results look promising, the pH used was outside of the range required in most U.S. pool codes (7.2 to 7.8) and could have been enhanced by the precipitation of calcium in the filter bed.

3.5 Ceramic Data Testing

Testing was performed between a ceramic media sourced from Japan and the other sourced from the United States. The Ceraflow-70 ceramic media, according to the manufacturer, was identical other than the location in which manufacturing took place. The Japanese sourced media showed a microsphere removal of 78.2% (s.d. = 5.93), and the USA sourced media showed a microsphere removal of 99.6% (s.d. = 0.23). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 1.12×10^{-5}) between the two experiments and can be seen in Figure 3..

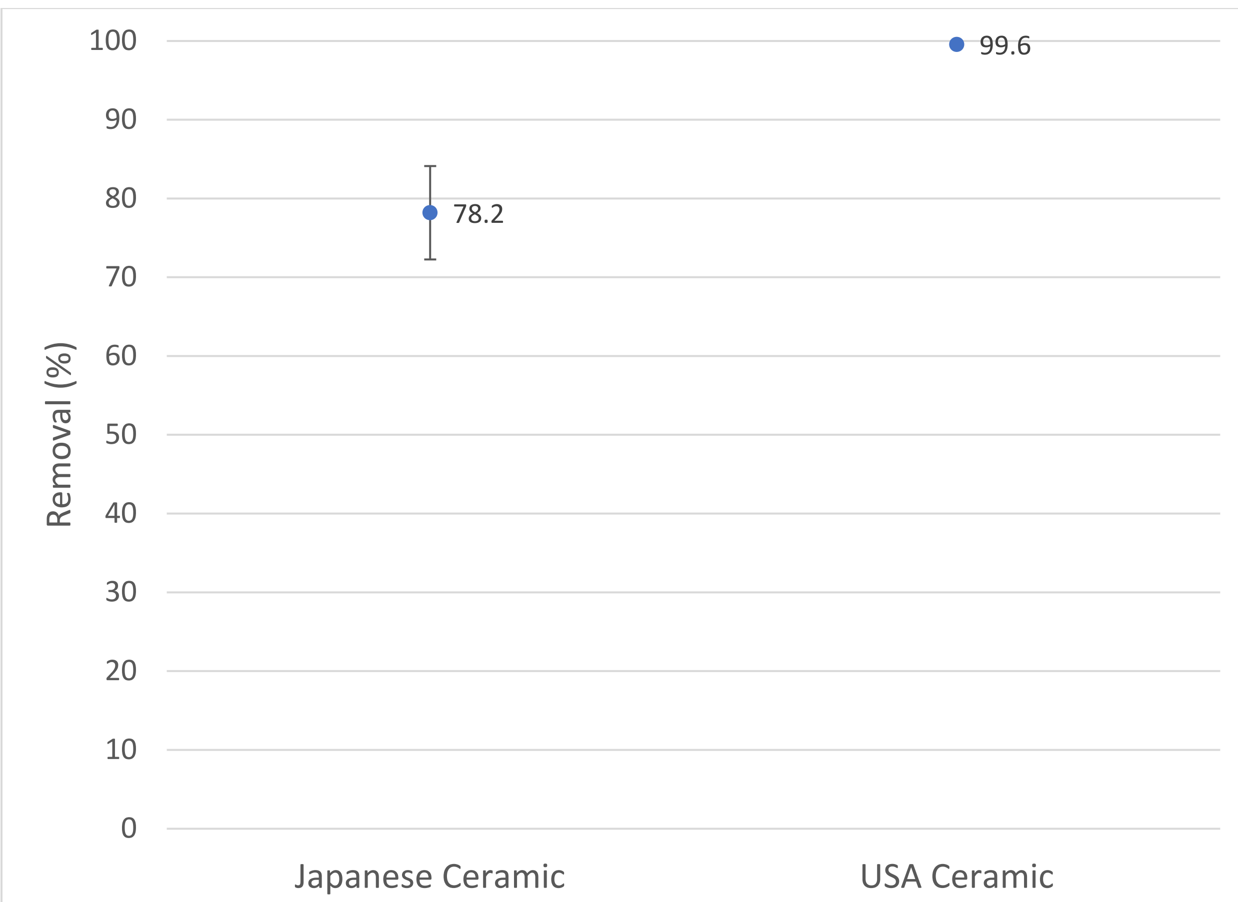

Figure 3.18: Japanese sourced ceramic versus USA sourced ceramic

Total organic carbon (TOC) challenge testing was performed on the 22-inch ceramic media filter depth sourced from the US to attempt to determine if the ceramic media had an initially positive surface charge that might be eliminated by TOC exposure, and after 7 days of continual loading of TOC of 2 ppm as TOC resulted in a microsphere removal of 99.3% (s.d. = 0.21) as compared to the microsphere removal initially of 99.6% (s.d. = 0.23). A t-test was performed and did not show a statistically significant difference with 95% confidence (p-value of 1.53×10^{-1}) between the two experiments and can be seen in Figure 3.19.

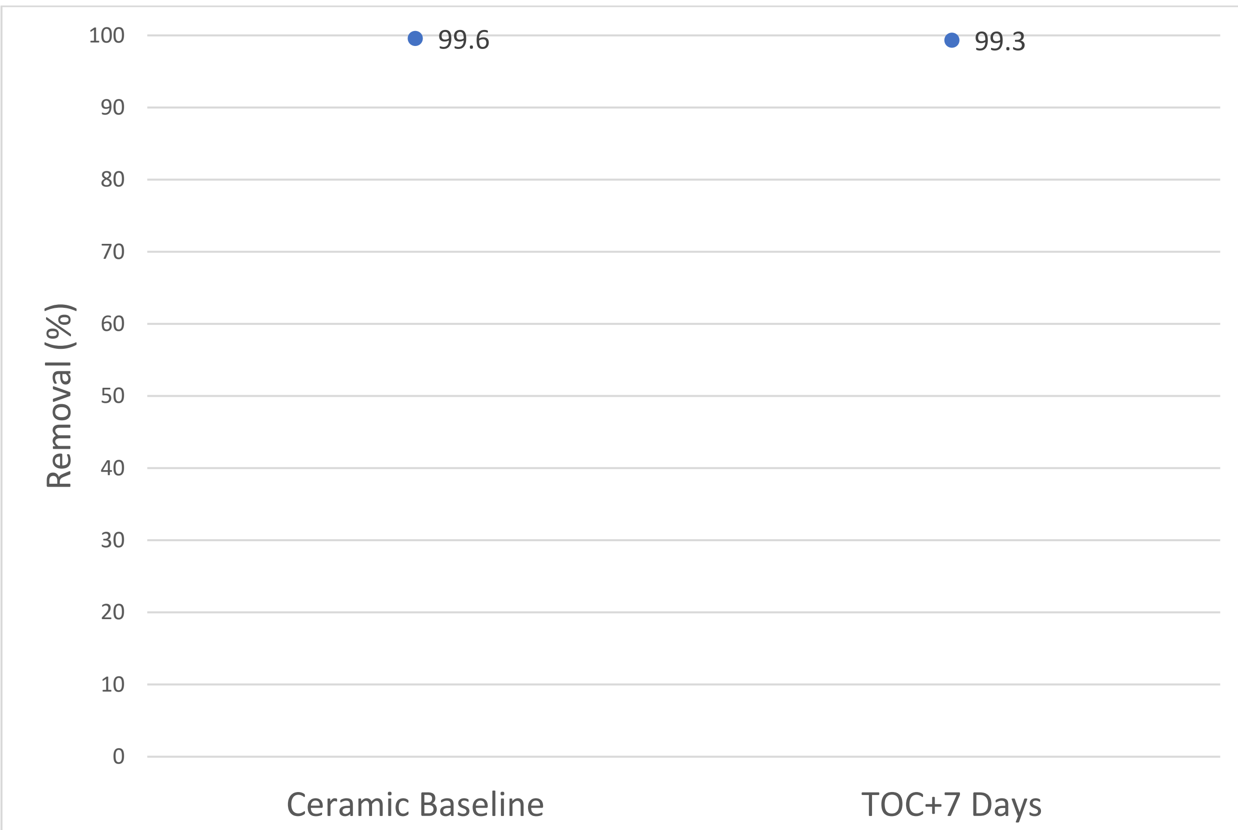

Figure 3.19: Initial microsphere removal versus 7 days TOC loading at 2 ppm of TOC

Total organic carbon (TOC) challenge testing was continued on the 22-inch ceramic media sourced from the US, and after 8 weeks of continual loading of TOC at 2 ppm the microsphere removal dropped from 99.3% (s.d. = 0.21) to 49.8% (s.d. = 9.88). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.86×10^{-6}) between the two experiments and can be seen in Figure 3.20.

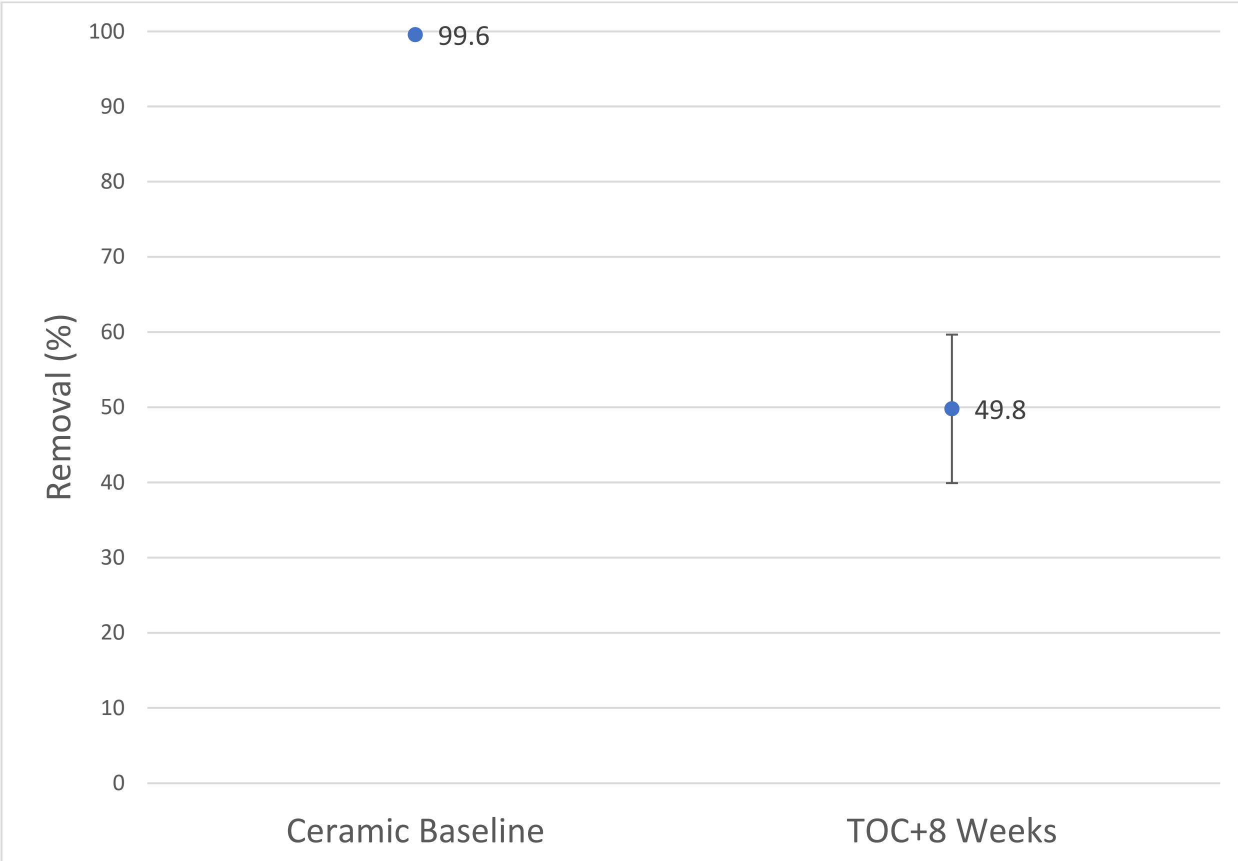

Figure 3.20: Initial microsphere removal versus 8 weeks TOC loading at 2 ppm of TOC

Regeneration of the ceramic media was attempted in smaller pilot-scale filter and resulted in a removal of 93.2% (s.d. = 0.47) after regeneration with pool filter cleaner: Universal Pool Filter Cleaner as compared to the initial removal of 99.3% (s.d. = 0.21). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.69×10^{-10}) between the two experiments and can be seen in Figure 3.21. There is still significant room for improvement in regenerating the performance of the ceramic media, and duration of the improvement resulting from regeneration was not tested in this study.

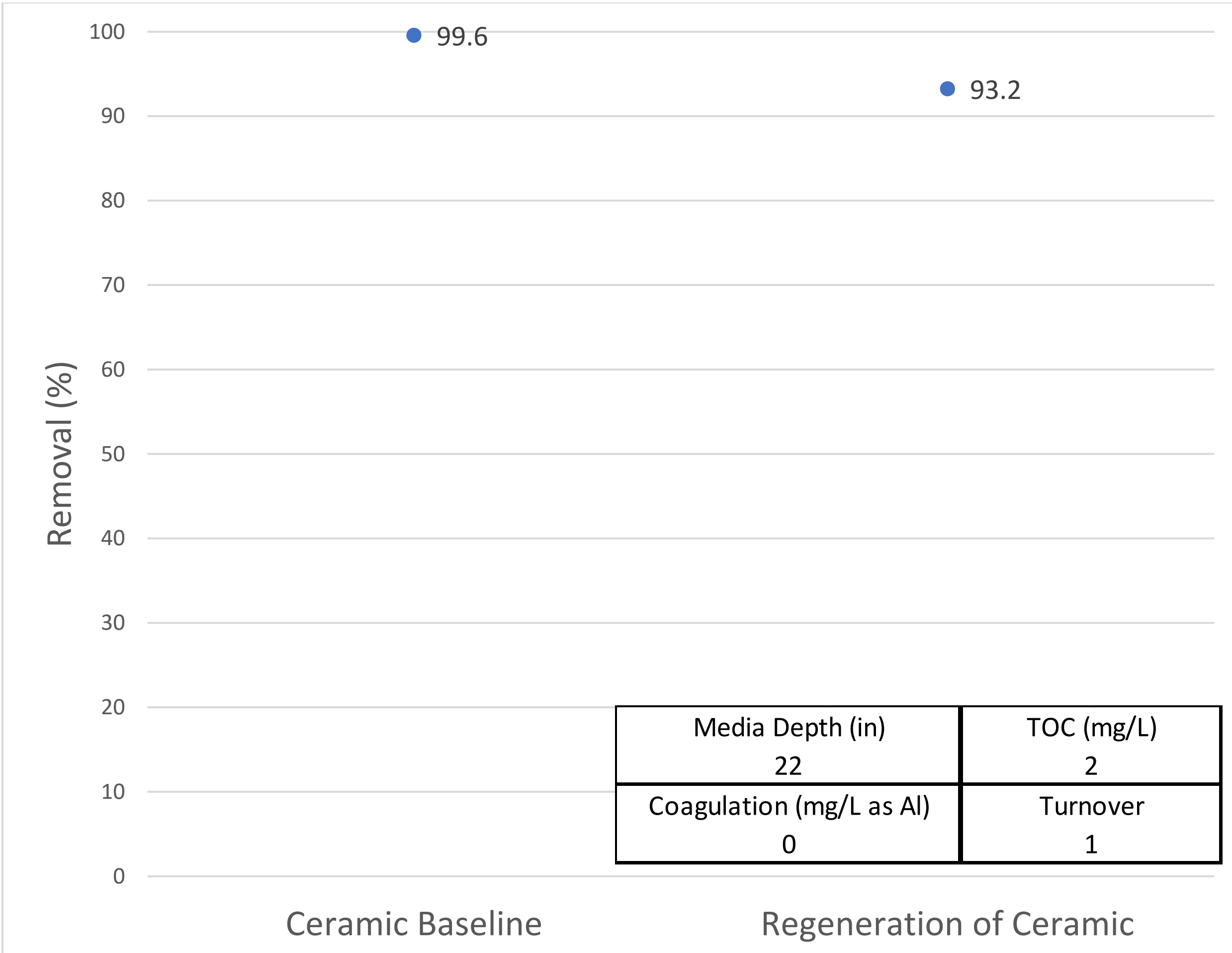

Figure 3.21: Microsphere removal of 22-inch ceramic filter after regeneration experiment using pool filter cleaner

3.6 Combined Data Analysis

Figure 3.22 shows the microsphere removal of a 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) to the microsphere removal of a 12-inch sand filter without TOC loading with 0.05 mg/L as Al of PACl at 2 turnovers with a removal of 99.8% (s.d. = 0.02). A t-test was performed and did not show a statistically significant difference with 95% confidence (p-value of 1.30×10^{-1}) between the two experiments.

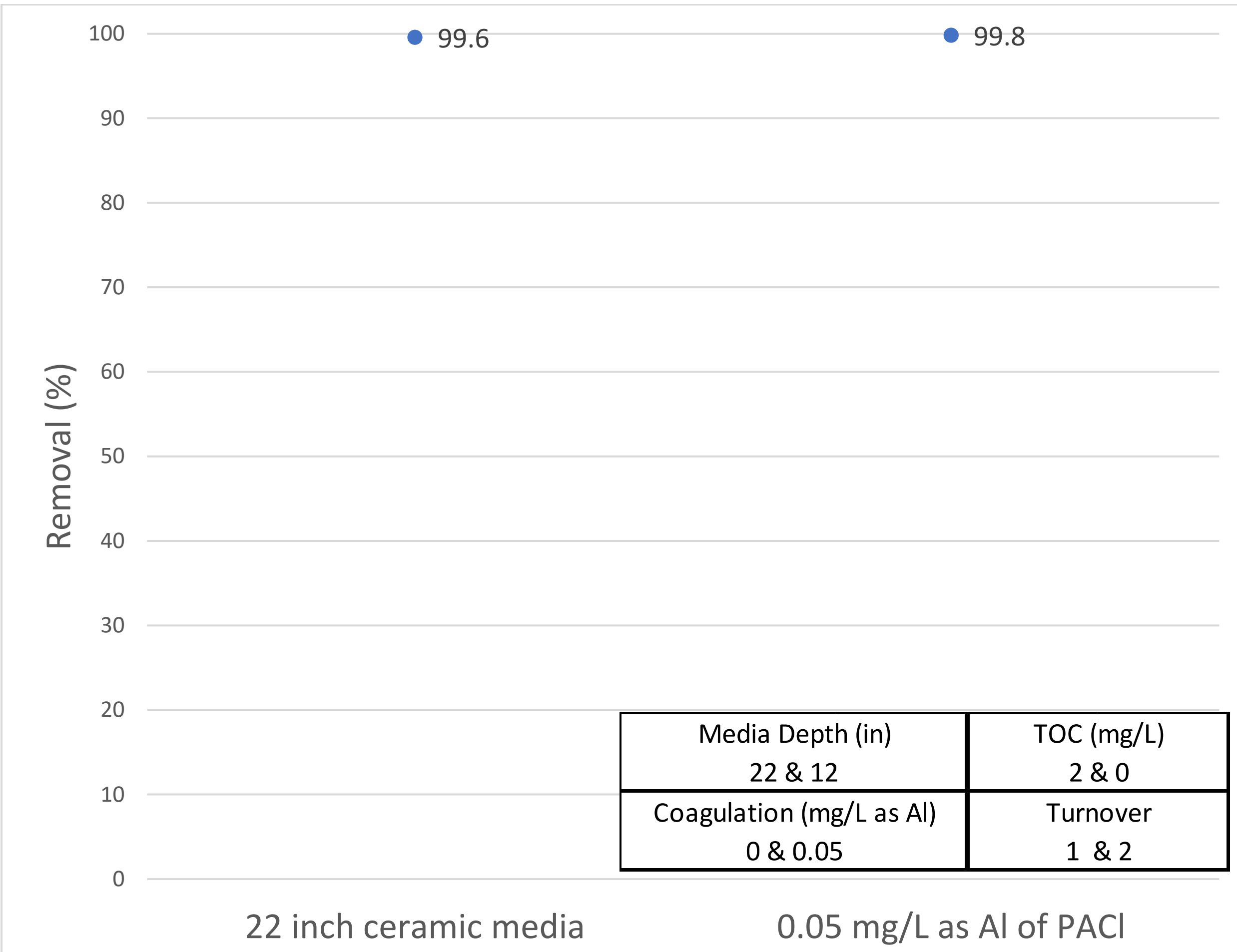

Figure 3.22: 22-inch ceramic media filter versus 12-inch sand filter 0.05 mg/L as Al of PACl without TOC at 2 turnovers

Figure 3.23 shows the microsphere removal of 22-inches of ceramic media filter to be 99.6% (s.d. = 0.23) versus the microsphere removal of 12-inches sand filter without TOC loading with 0.05 mg/L as Al of PACl at 48 turnovers with a removal of 99.8% (s.d. = 0.02). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.72×10^{-2}) between the two experiments. While the sand filter with coagulation performed slightly better than ceramic media without coagulation, the sand filter could only achieve these removals without TOC in the water, and operating pools without bathers or bather load defeats the purpose of having pools.

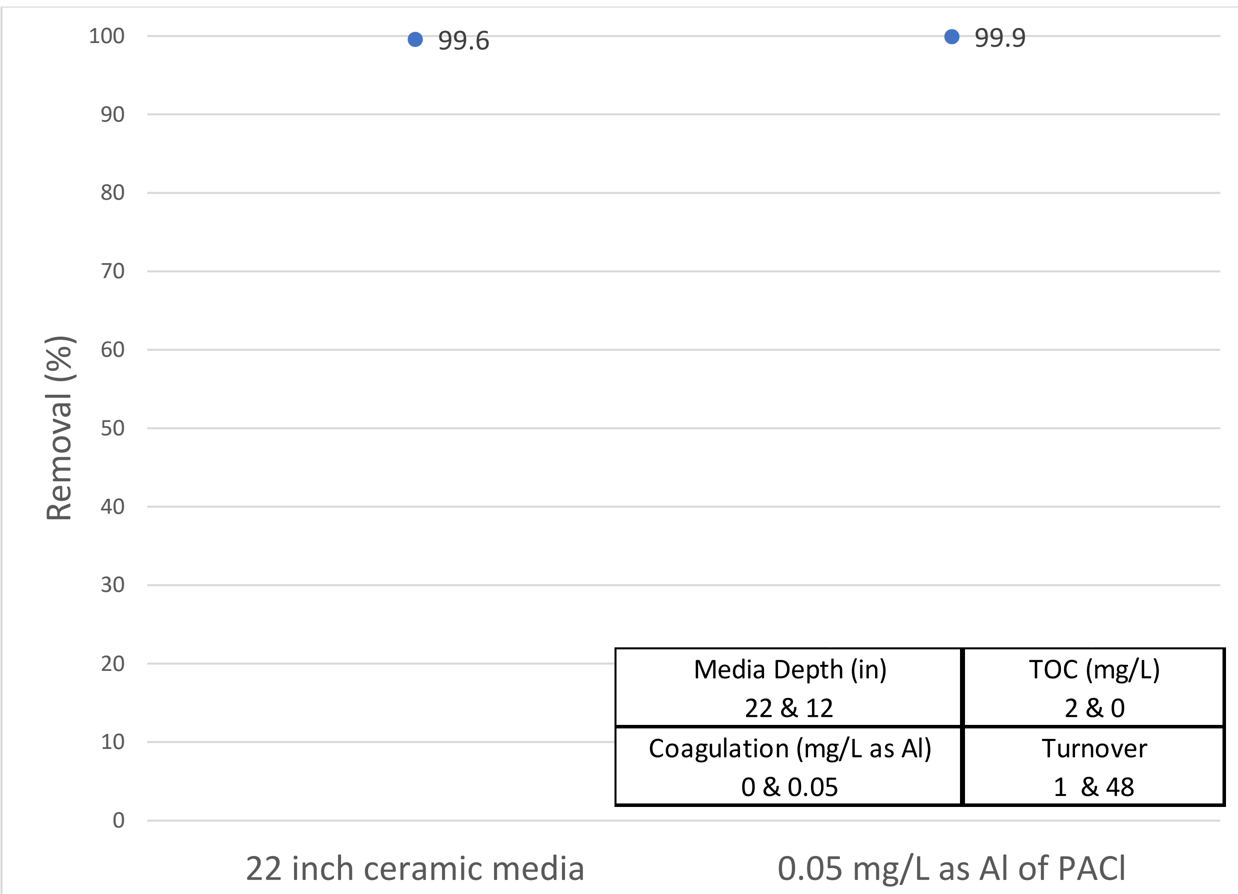

Figure 3.23: 22-inch ceramic media filter versus 12-inch sand filter 0.05 mg/L as Al of PACl without TOC at 48 turnovers

Figure 3.24 shows the microsphere removal of 22-inches of ceramic media to be 99.6% (s.d. = 0.23) versus 12-inches of sand filter loading with 0.05 mg/L as Al of PACl at 2 turnovers with a removal of 74.9% (s.d. = 2.36). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.48×10^{-10}) between the two experiments.

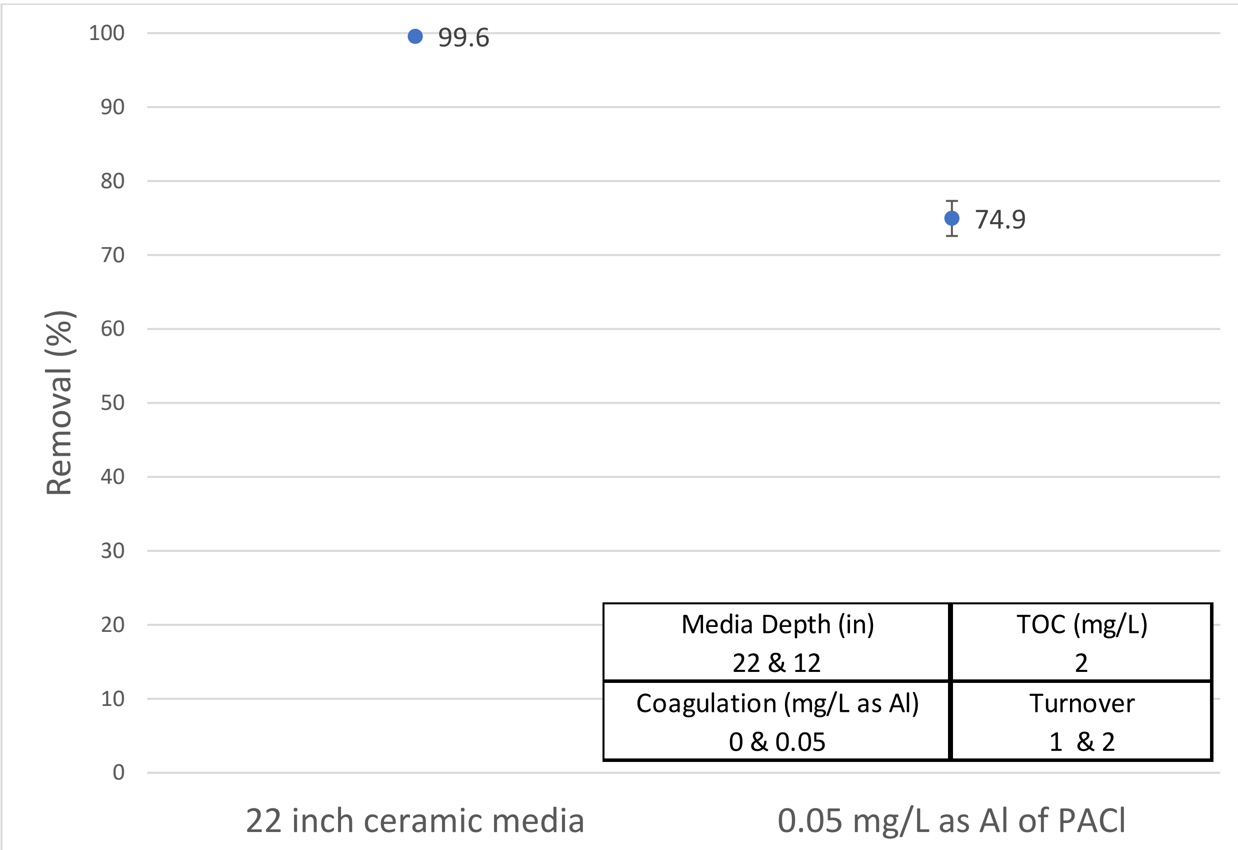

Figure 3.24: 22-inch ceramic media filter versus 12-inch sand filter 0.05 mg/L as Al of PACl at 2 turnovers

Figure 3.25 shows the microsphere removal of a 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) relative to the 12-inch sand filter with 0.05 mg/L as Al of PACl at 48 turnovers with a removal of 98.1% (s.d. = 0.74). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.11×10^{-3}) between the two experiments. While the 12-inch sand filter does perform better with coagulant than without it, the sand filter removals at 2 turnovers were much lower than the ceramic filter without coagulant. Inconsistent filter performance has significant public health implications.

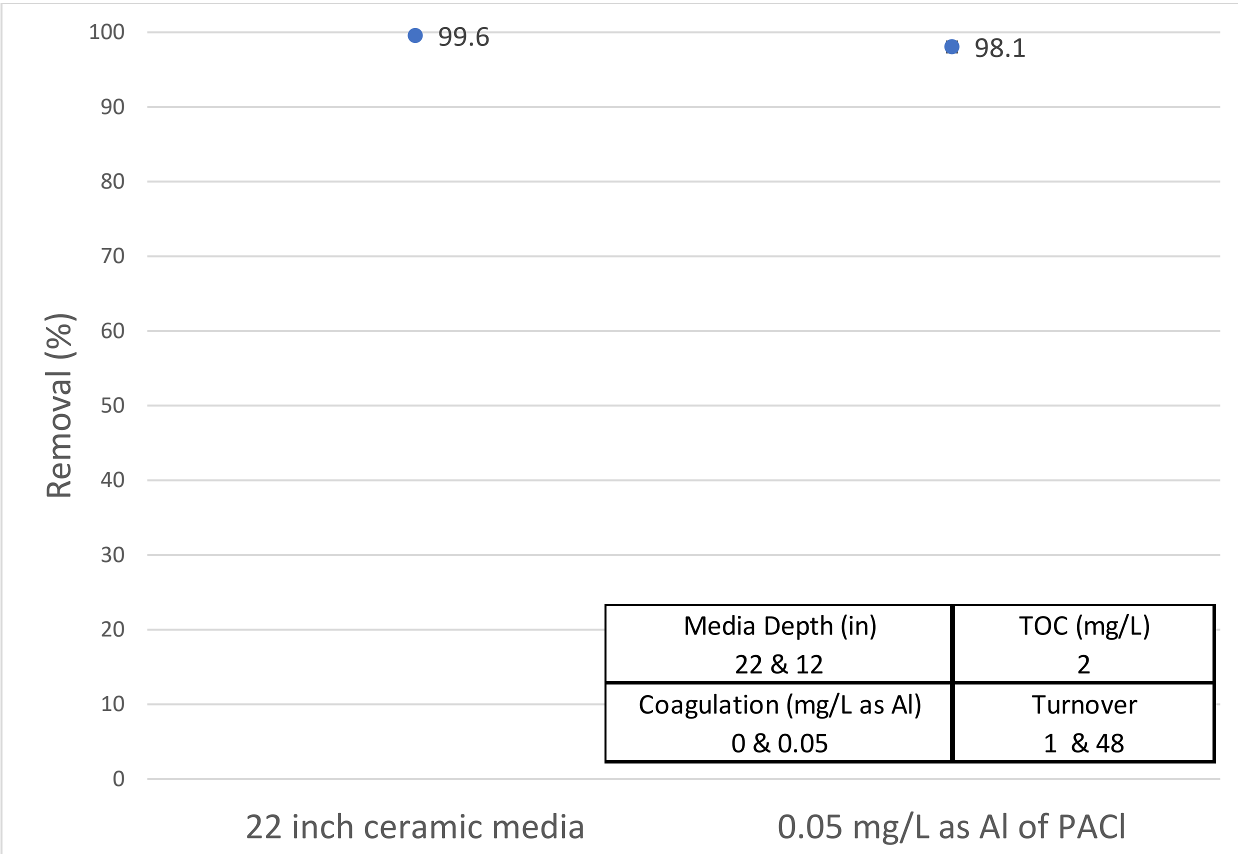

Figure 3.25: 22-inch ceramic media filter versus 12-inch sand filter 0.05 mg/L as Al of PACl at 48 turnovers

Figure 3.26 compares the microsphere removal of the 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) to the microsphere removal of the12-inch sand filter with 0.005 mg/L as Al of PACl at 2 turnovers with a removal of 63.9% (n = 1).

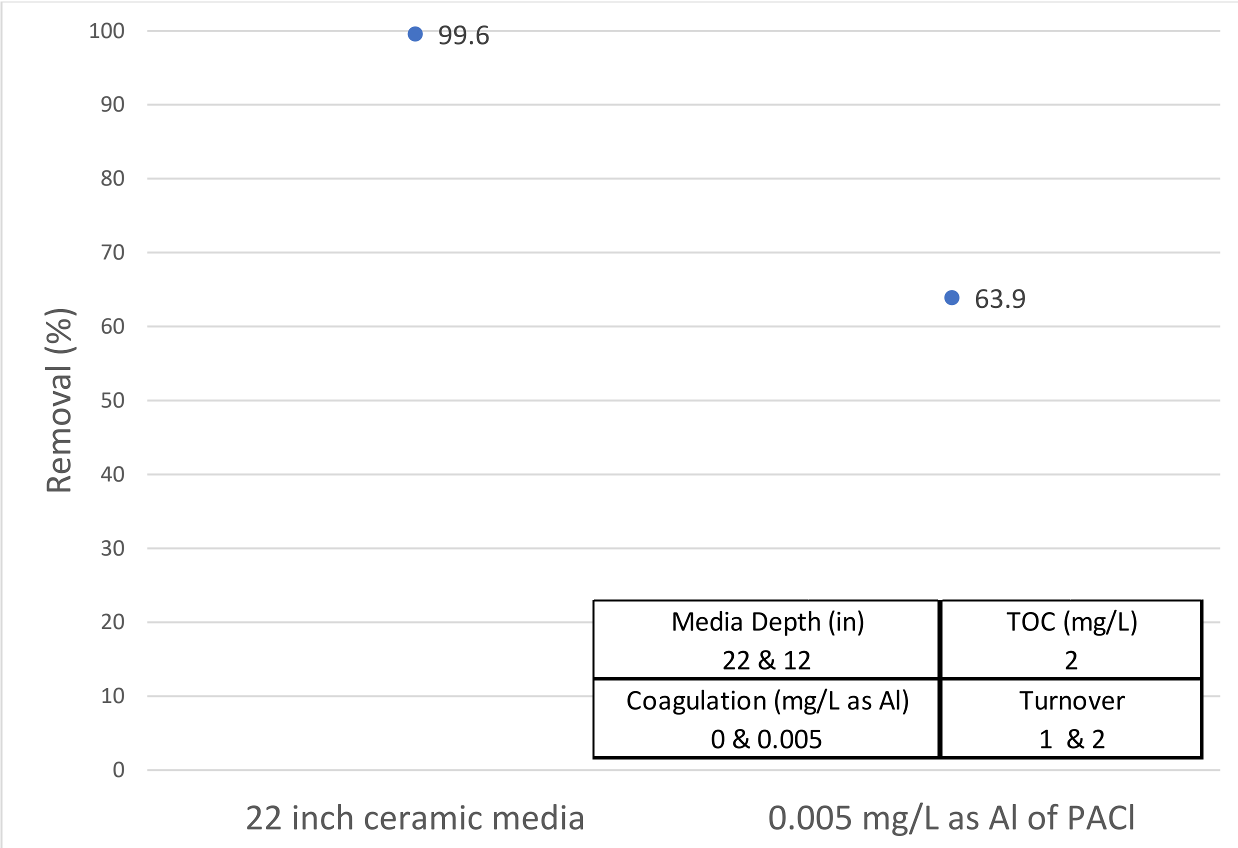

Figure 3.26: 22-inch ceramic media filter versus 12-inch sand filter 0.005 mg/L as Al of PACl at 2 turnovers

Figure 3.27 compares the microsphere removal of the 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) to the microsphere removal of 12-inch sand filter with 0.05 mg/L as Al of PACl at 48 turnovers with a removal of 98.1% (s.d. = 0.74). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 2.11 x 10^{-3}) between the two experiments. At a lower coagulant dose, the sand filter removals at 2 turnovers were even lower. Inconsistent filter performance and its public health implications are exacerbated by the lower coagulant dosage.

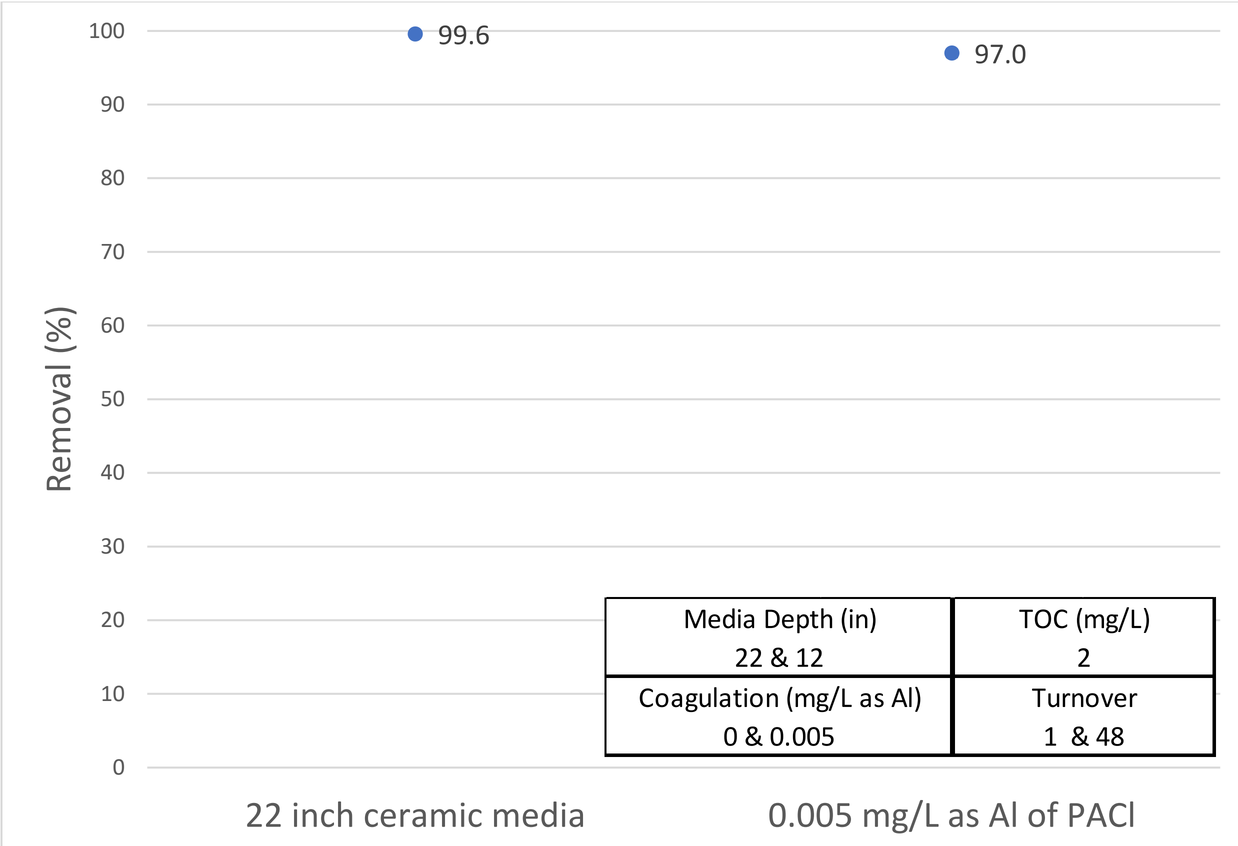

Figure 3.27: 22-inch ceramic media filter versus 12-inch sand filter 0.005 mg/L as Al of PACl at 48 turnovers

Figure 3.28 compares the microsphere removal of the 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) to the microsphere removal of 36-inch sand filter with 0.05 mg/L as Al of PACl at 1 turnover with a removal of 90.6% (s.d. = 0.56). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 3.76×10^{-4}) between the two experiments.

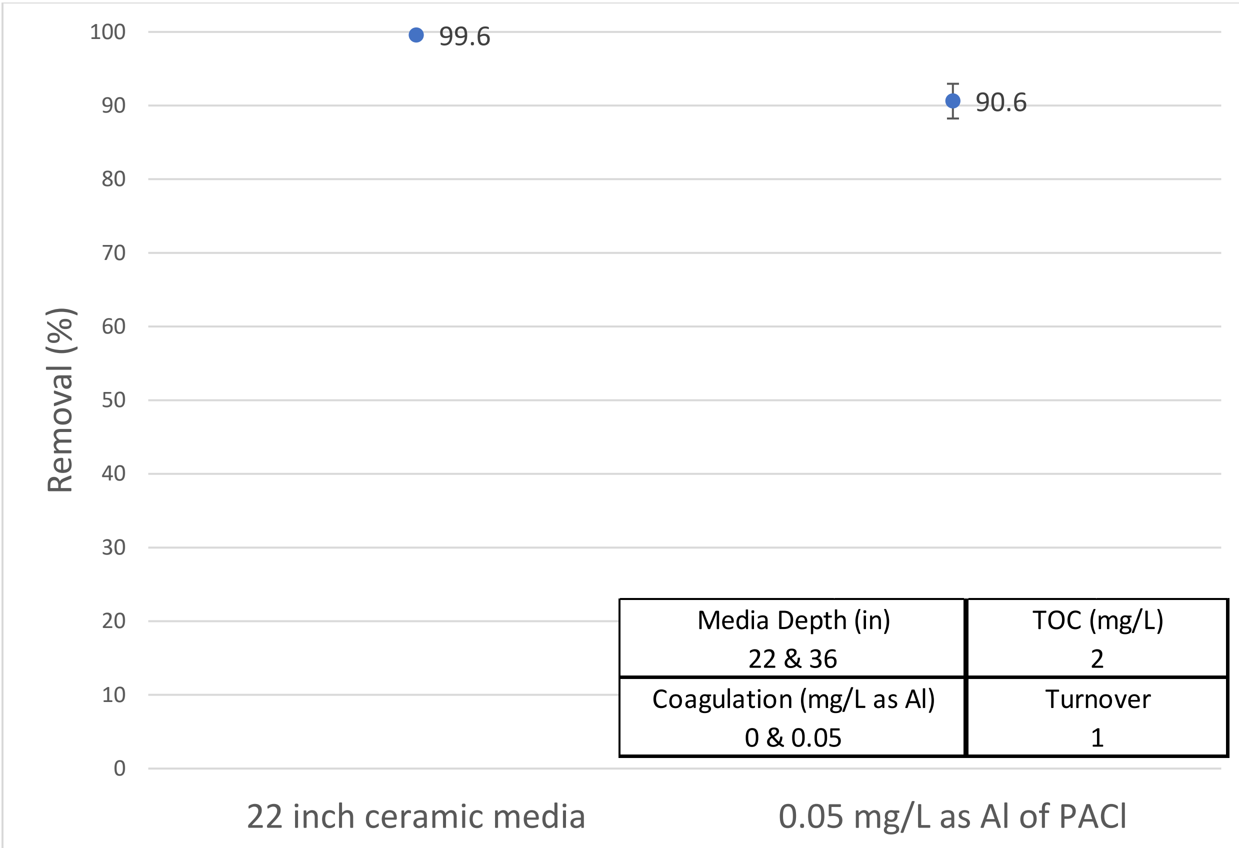

Figure 3.28: 22-inch ceramic media filter versus 36-inch sand filter 0.05 mg/L as Al of PACl at 2 turnovers

Figure 3.29 compares the microsphere removal of the 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) to the microsphere removal of the 36-inch sand filter loading with 0.05 mg/L as Al of PACl at 48 turnovers with a removal of 90.7% (s.d. = 1.67). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 1.28 x 10^{-6}) between the two experiments. While the 36-inch sand filter with coagulant does perform better than 12-inch sand filter at 2 turnovers, the ceramic filter without coagulant still performs significantly better.

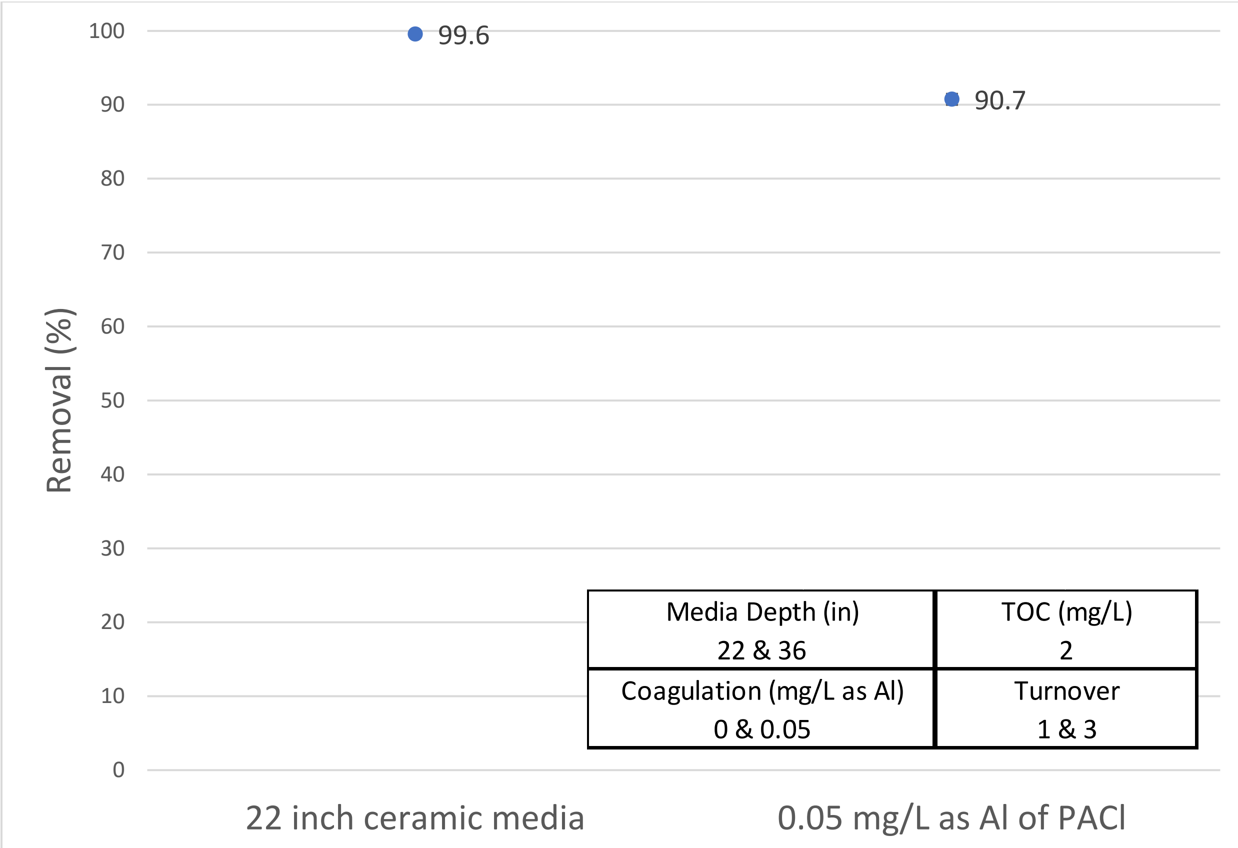

Figure 3.29: 22-inch ceramic media filter versus 36-inch sand filter 0.05 mg/L as Al of PACl at 3 turnovers

Figure 3.30 shows the microsphere removal of 22 inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) to the microsphere removal of 36-inch sand filter loading with 0.005 mg/L as Al of PACl at 1 turnover with a removal of 86.5% (s.d. = 5.58). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 1.48×10^{-8}) between the two experiments.

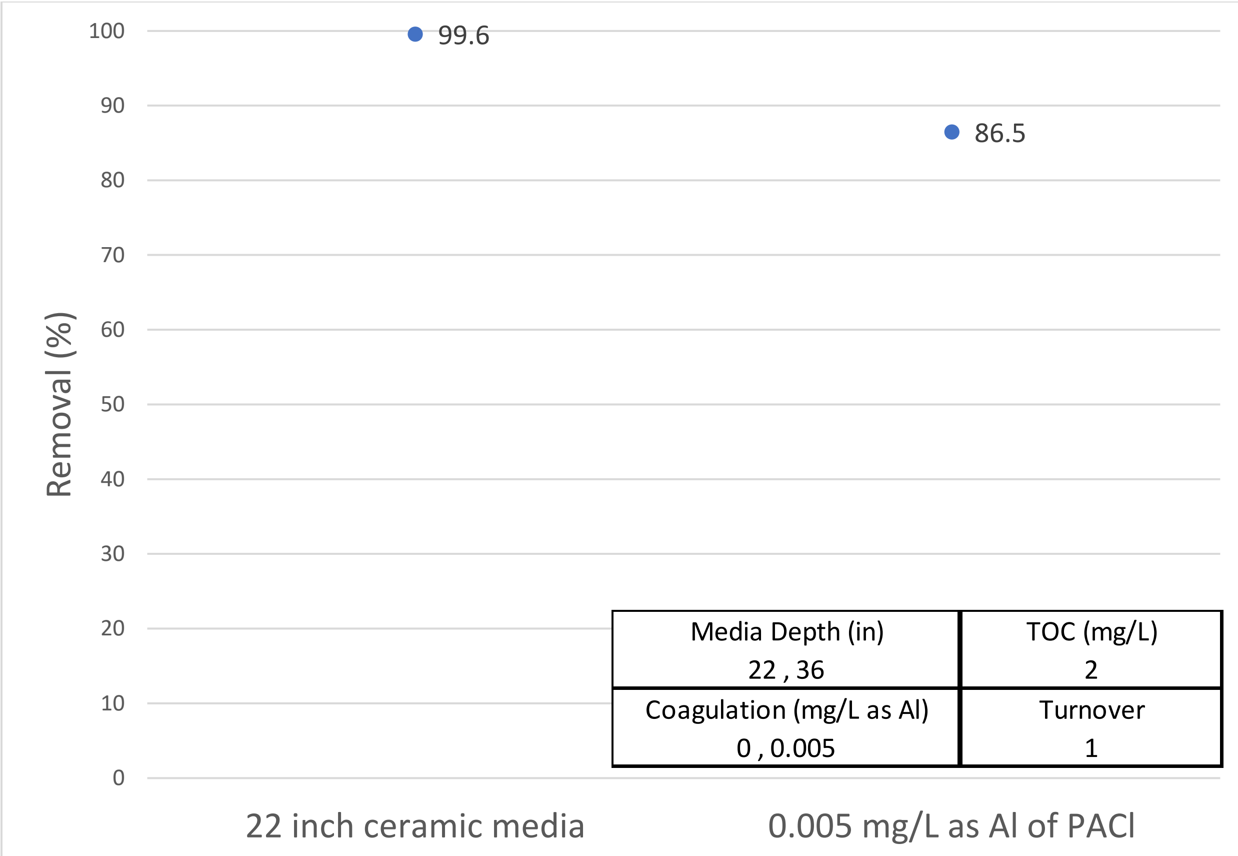

Figure 3.30: 22-inch ceramic media filter versus 36-inch sand filter 0.005 mg/L as Al of PACl at 1 turnover

Figure 3.31 shows the microsphere removal of 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) to the microsphere removal of 36-inch sand filter with 0.005 mg/L as Al of PACl at 3 turnovers with a removal of 94.3% (s.d. = 1.11). A t-test was performed and showed a statistically significant difference with 95% confidence (p-value of 1.01×10^{-5}) between the two experiments. Lowering the coagulant dosage in the 36-inch sand filter had a small yet inconsistent impact on filter performance, but the ceramic filter without coagulant still performs significantly better.

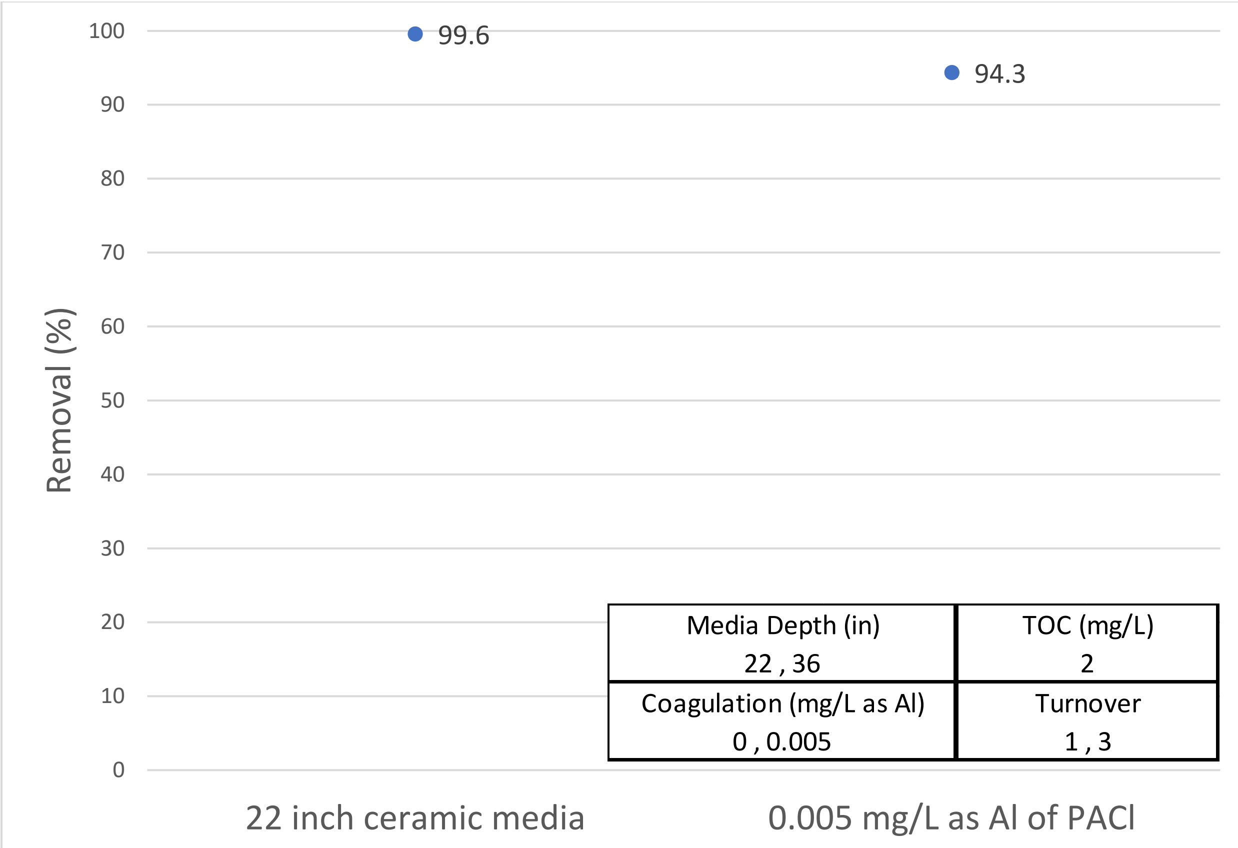

Figure 3.31: 22-inch ceramic media filter versus 36-inch sand filter 0.005 mg/L as Al of PACl at 3 turnovers

A comparison of all the initial experiments (no coagulant dosing) of the filters using the data from the US source ceramic with a microsphere removal of 99.6% (s.d. = 0.23), 12-inch media depth of sand with a microsphere removal of 22.6% (s.d. = 9.22), 36-inch media depth of sand with a microsphere removal of 51.8% (s.d. = 12.99), and the Vortisand filter with a combined initial microsphere removal of 62.6% (s.d. = 12.84) and can be seen in Figure 3.32.

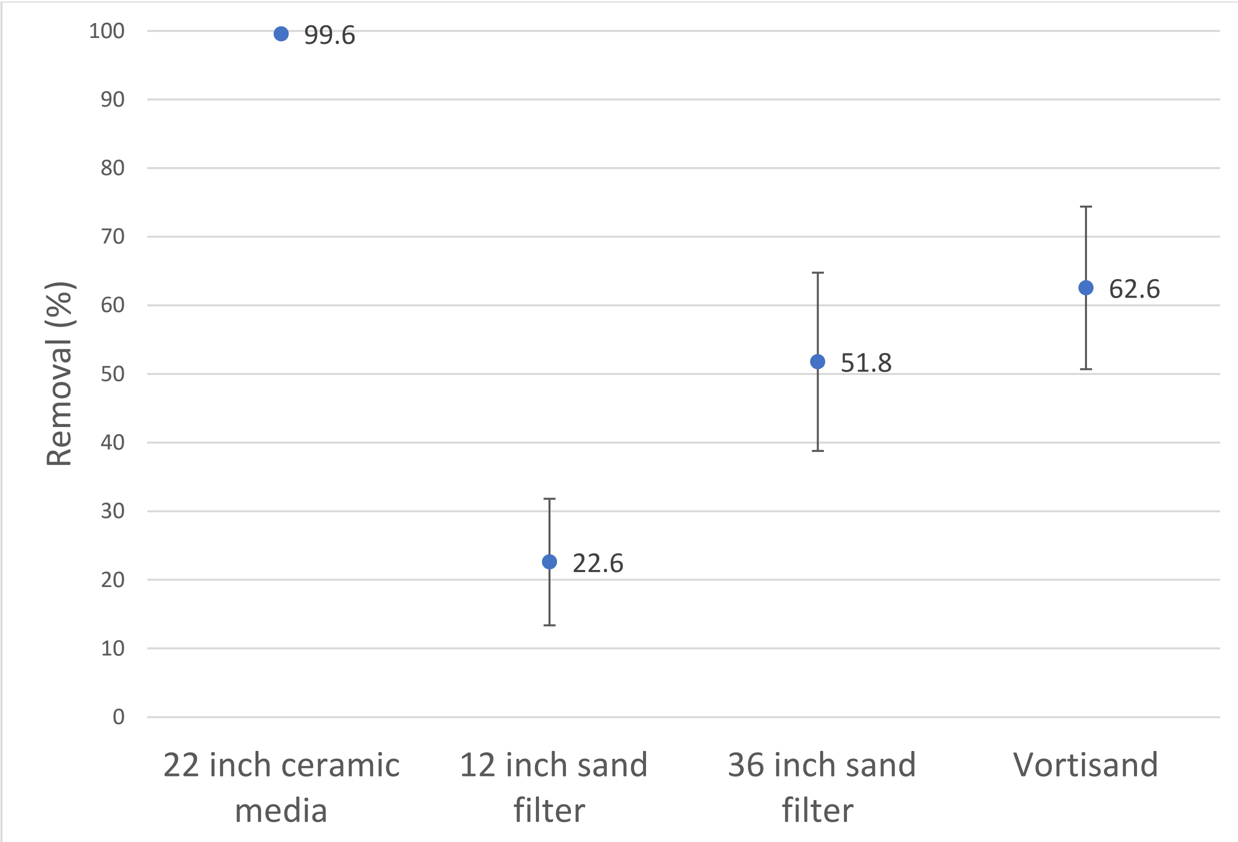

Figure 3.32: Comparison of 22-inch ceramic media versus 12-inch sand filter versus 36-inch sand filter versus Vortisand

A comparison of the microsphere removal of the 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) and the Vortisand filter with a removal of 62.6% (s.d. = 11.84) versus the 12-inch with 0.05 mg/L of Al as PACl at 48 turnovers with a removal of 97.0% (s.d.= 0.53) and 36-inch filter with 0.05 mg/L as Al of PACl at 3 turnover with a removal of 90.7% (s.d. = 1.67) and can be seen in Figure 3.33. With coagulant dosing, the ceramic filter offers a smaller improvement in filter removal efficiency. Depending on the situation and regulations, there could be multiple viable filtration options for pools based on this study.

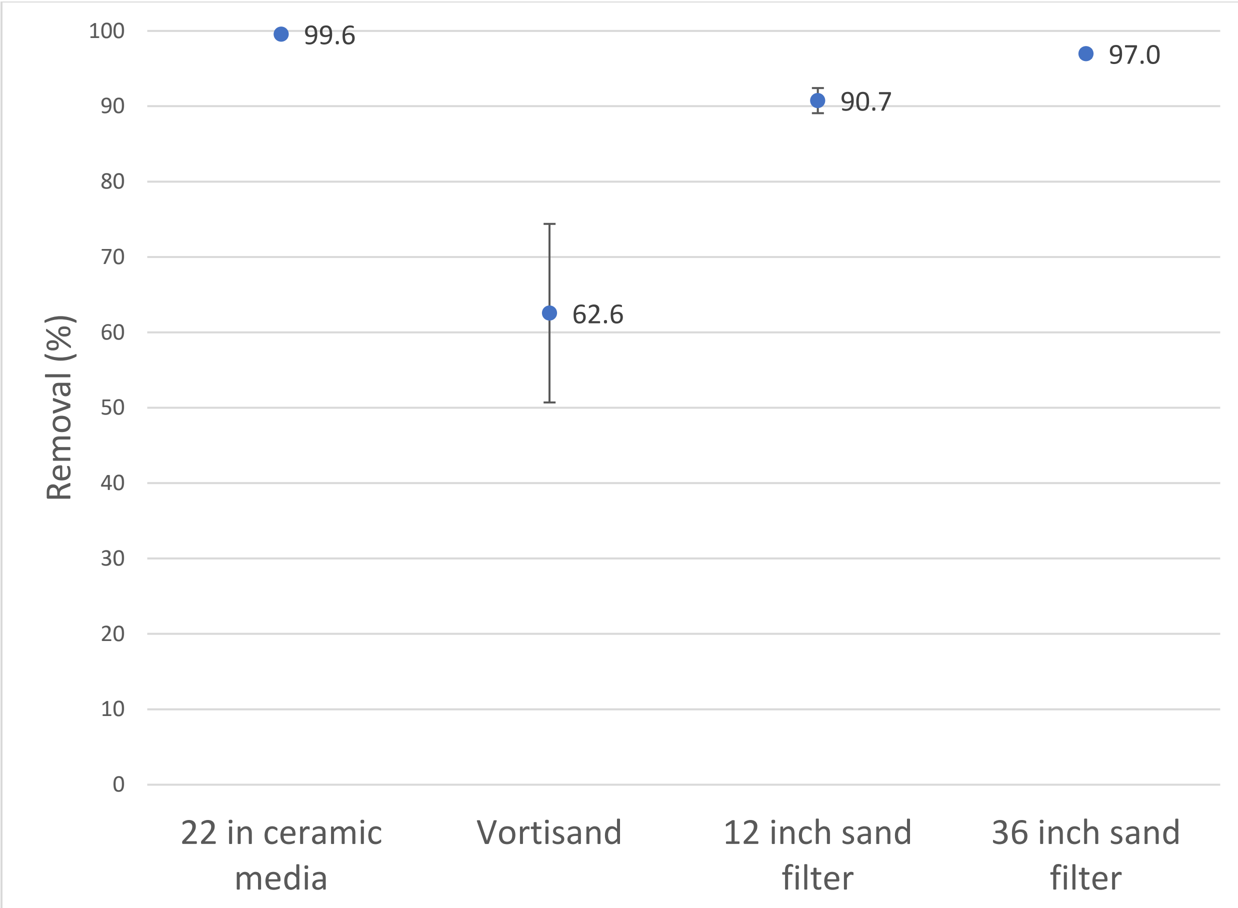

Figure 3.33: Comparison of 22-inch ceramic media filter and Vortisand filter versus 12-in sand filter with 0.05 mg/L as Al of PACl at 48 turnovers and 36-inch sand filter with 0.05 mg/L as Al of PACl at 3 turnovers

A comparison of the microsphere removal of the 22-inch ceramic media filter with a removal of 99.6% (s.d. = 0.23) and the Vortisand filter with a removal of 62.6% (s.d. = 11.84) versus the 12-inch with 0.05 mg/L of Al as PACl at 2 turnovers with a removal of 97.0% (s.d.= 0.53) and 36-inch filter with 0.05 mg/L as Al of PACl at 1 turnover with a removal of 90.7% (s.d. = 1.67) and can be seen in Figure 3.34. With coagulant dosing, sand filters still experienced periods of decreased filter removal efficiency. Ceramic filters also experienced periods of decreased filter removal efficiency in the timescale of weeks (not hours like sand filters) and would require periodic cleaning to restore performance.

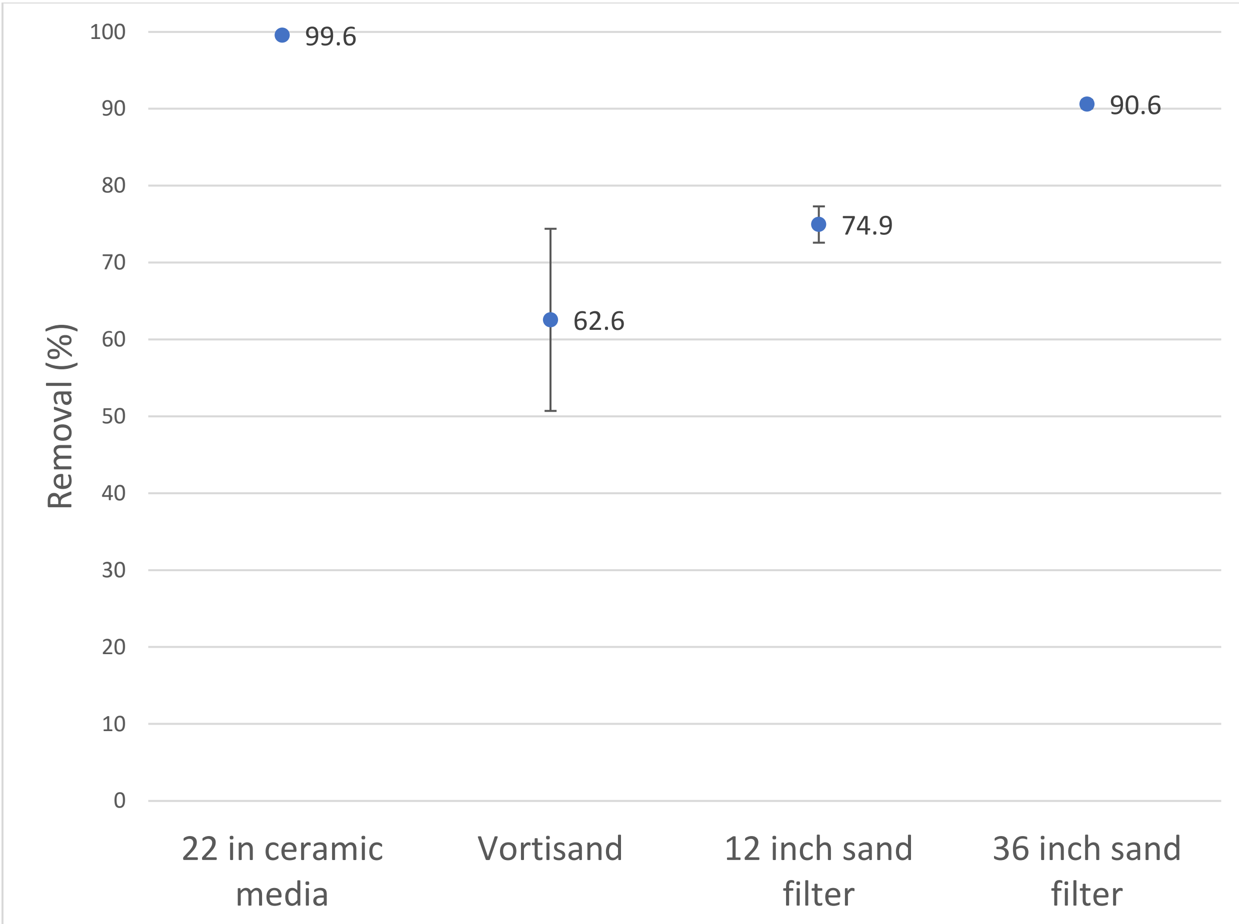

Figure 3.34: Comparison of 22-inch ceramic media filter and Vortisand filter versus 12-in sand filter with 0.05 mg/L as Al of PACl at 2 turnovers and 36-inch sand filter with 0.05 mg/L as Al of PACl at 1 turnover

Figure 3.35 compares the microsphere removal of the 36-inch sand filter with 0.005 mg/L as Al of PACl at 1 and 3 turnovers with a removal of 86.5% (s.d. = 5.58) and 94.3% (s.d. = 1.11) respectively to the microsphere removal with 0.05 mg/L as Al of PACl at 1 and 3 turnovers with a removal of 90.6% (s.d. = 0.56) and 90.7% (s.d. = 1.67) respectively. A t-test was performed between both coagulant doses at 1 turnover and did not show a statistically significant difference with 95% confidence (p-value of 0.295) between the two experiments. A t-test was performed between both coagulant doses at 3 turnovers and showed a statistically significant difference with 95% confidence (p-value of 1.16×10^{-2}) between the two experiments.

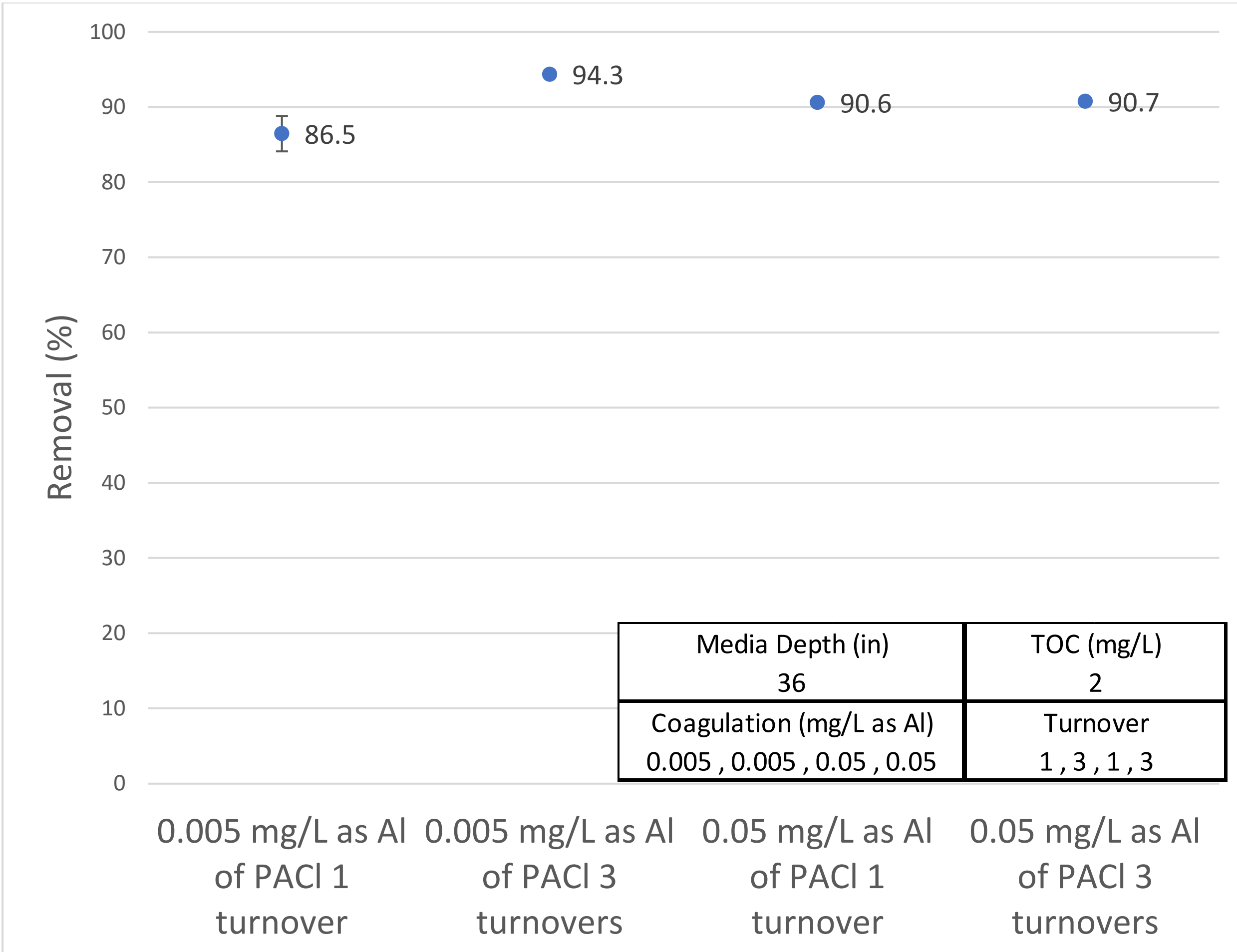

Figure 3.35: Comparison of 36 -inch sand filter with 0.005 mg/L as Al of PACl at 1 and 3 turnovers and 36-inch sand filter with 0.05 mg/L as Al of PACl at 1 and 3 turnovers

CHAPTER 4: CONCLUSIONS & RECOMMENDATIONS

4.1 Conclusions

The following conclusions were drawn based on the experimental results obtained in the laboratory under the specified testing conditions.

1. The 12-inch swimming pool sand filter operated at 10 gpm/ft^2 had an initial removal of 22.6% without coagulant addition, but the addition of 0.05 mg/L as Al of PACl significantly increased the removal to 99.8% at 2 turnovers and 99.9% at 48 turnovers, but there was no total organic carbon (TOC) added to the water in these experiments to simulate the effect of bather load. The addition of 2 ppm of TOC to the water decreased the removal at the same coagulant dose to 74.9% at 2 turnovers and 97.0% at 48 turnovers. This indicates that TOC should be added to future pool filtration experiments to simulate realistic operating conditions.

2. The 12-inch sand filter removal at 2 turnovers with 2 ppm of added TOC and a coagulant dose of 0.005 mg/L as Al of PACl (was 63.9%) and 0.05 mg/L as Al of PACl (was 74.9%) and increased at 48 turnovers with a coagulant dose of 0.005 mg/L as Al of PACl (to 98.1%) and 0.05 mg/L as Al of PACl (to 97.0%). The performance of a 12-inch sand filter operating at 10 gpm/ft2 with coagulant addition varies significantly with time and would not be recommended for use in recreational water due to public health risks associated with Cryptosporidium passage in the early stage of the filter run after backwashing after backwashing procedures.

3. The 36-inch sand filter with the coagulant performed at above 1 log (90%) removal with a coagulant dose of 0.05 mg/L as Al of PACl (90.6%) at 1 turnover and (90.8%) at 3 turnovers. After lowering the coagulant dose to 0.005 mg/L as Al of PACl, the removals varied only slightly at 86.5% and 94.4% at 1 and 3 turnovers, respectively. The performance of a 36-inch sand filter operating at 10 gpm/ft^2 with coagulant addition was much more efficient than without coagulant addition and did not vary significantly with time.

4. Ceramic media (Cerafow-70) with a 22-inch media depth initially had a microsphere removal of 99.6%, but after 8 weeks of a constant TOC loading of 3 ppm of TOC the microsphere removal dropped to 49.8%. Media regeneration (chemical cleaning) experiments were performed to increase microsphere removals, but the chemically cleaned media was only able to removal at maximum of 93.2% of microspheres. Additional experiments will be required to determine how to maximize the performance of this type of filter.

5. The Vortisand filter had an initial microsphere removal of 62.6% and 87.4% after 24 hours of operation which does not appear to be well-suited to swimming pool water treatment and would not be recommended for use in recreational water due to public health risks after backwashing.

6. Initial microsphere removal in the 36-inch sand filter with 0.005 mg/L as Al of PACL at 1 turnover (86.5%) and an increase in removal at 3 turnovers (94.3%) was the highest initial removal after backwashing and is the recommended recreational water treatment method in this research. Future research on the Ceraflow-70 ceramic media to regenerate performance to initial removals would be recommended.

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APPENDIX A: CERAMIC MEDIA REGENERATION EXPERIMENTS

Experiment	Removal (%)
Control	80.4
Base	80.1
Chlorine	82.9
Chlorine then Base	83.3
Chlorine (pH 8-9)	75.4
HTH Pool Filter Cleaner	93.2
Bleach then Salt	65.5
Base then Salt	77.0
Sodium Percarbonate	75.9
Blast Furnace	85.4

APPENDIX B: EXPERIMENTAL SUMMARY

	Experiment	Media Depth (in)	Media Type	Removal (%)	Removal (log)	Std. Dev.	2 Std. Dev.	Loading Rate (GPM/Ft2)	Coagulation (Y/N)	Coagulation Dose (mg/L as Al of PACl)	TOC (ppm of TOC)
1	12-inch sand 1	12	Sand	22.28	0.11	8.70	17.40	10	N	N/A	3
2	12-inch sand 2	12	Sand	22.92	0.12	15.02	30.03	10	N	N/A	3
3	2-TO, high 0.05	12	Sand	99.81	2.72	0.02	0.04	10	Y	0.05	0
4	48-TO, high 0.05	12	Sand	99.97	3.50	0.02	0.04	10	Y	0.05	0
5	2-TO, high 0.05	12	Sand	74.95	0.60	2.36	4.73	10	Y	0.05	3
6	48-TO, high 0.05	12	Sand	96.97	1.52	0.53	1.05	10	Y	0.05	3
7	2-TO, low 0.005	12	Sand	63.89	0.44	N/A	N/A	10	Y	0.005	3
8	48-TO, low 0.005	12	Sand	98.05	1.73	0.74	1.49	10	Y	0.005	3
9	36-inch 1	36	Sand	40.08	13.18	0.23	0.45	10	N	N/A	3
10	36-inch 2	36	Sand	63.48	3.76	0.44	0.88	10	N	N/A	3
11	1-TO, low 0.005	36	Sand	83.63	0.83	6.68	13.36	10	Y	0.005	3
12	3-TO, low 0.005	36	Sand	94.07	1.24	1.86	3.71	10	Y	0.005	3
13	1-TO low 0.005 (2)	36	Sand	89.29	0.99	2.99	5.98	10	Y	0.005	3
14	3-TO, low 0.005 (2)	36	Sand	94.63	1.28	1.47	2.93	10	Y	0.005	3

15	1-TO. High 0.05	36	Sand	90.61	1.03	1.05	2.10	10	Y	0.05	3
16	3-TO, high 0.05	36	Sand	90.75	1.89	1.04	2.08	10	Y	0.05	3
17	Vortisand 1	N/A	Vortisand	51.20	0.31	5.56	11.12	16	N	N/A	3
18	Vortisand 2	N/A	Vortisand	73.91	0.59	3.34	6.68	16	N	N/A	3
19	Vortisand 24 hr	N/A	Vortisand	87.44	0.91	2.34	4.68	16	N	N/A	3
20	Vortisand High Ph	N/A	Vortisand	94.20	1.24	0.94	1.88	16	N	N/A	3
21	22-inch Japanese Ceramic 1	22	Ceramic	72.55	0.56	3.88	7.76	10	N	N/A	3
22	22-inch Japanese Ceramic 2	22	Ceramic	83.84	0.80	4.02	8.05	10	N	N/A	3
23	22-inch USA Ceramic 1	22	Ceramic	99.78	2.66	0.04	0.08	10	N	N/A	3
24	22-inch USA Ceramic 2	22	Ceramic	99.33	2.18	0.25	0.51	10	N	N/A	3
25	22-inch ceramic TOC +7 day	22	Ceramic	99.32	2.17	0.21	0.43	10	N	N/A	3
26	22-inch ceramic +8 Wk TOC	22	Ceramic	49.80	0.30	9.88	19.76	10	N	N/A	3

APPENDIX C: EXPIRIMENTAL DATA SHEET EXAMPLE

Exp. Name	48-TO, high 0.05
Date of Exp.	6/15/2023
counts:	WAG

Influent samples

made slides	time (min)	sample number	dose (mL)	count	#/mL	average
WAG	3	1	10	122	12.20	
WAG	3	2	10	118	11.80	12.20
WAG	3	3	10	126	12.60	
WAG	5	1	10	112	11.20	
WAG	5	2	10	137	13.70	12.70
WAG	5	3	10	132	13.20	
WAG	9	1	10	129	12.90	
WAG	9	2	10	125	12.50	12.10
WAG	9	3	10	109	10.90	

Effluent samples

made slides	time (min)	sample number	dose (mL)	count	#/mL
WAG	3	1	50	14	0.28
WAG	3	2	50	19	0.38
WAG	3	3	50	23	0.46
WAG	6	1	50	19	0.38
WAG	6	2	50	22	0.44
WAG	6	3	50	14	0.28
WAG	9	1	50	17	0.34
WAG	9	2	50	21	0.42
WAG	9	3	50	19	0.38

results of each sample

ample (Time-Replica	time (min)	sample number	percent removal	LRV	% AVG	LRV AVG
3-1	3	1	97.70	1.64		
3-2	3	2	96.89	1.51	**96.94**	**1.51**
3-3	9	3	96.23	1.42		
6-1	6	1	97.01	1.52		
6-2	6	2	96.54	1.46	**97.11**	**1.54**
6-3	9	3	97.80	1.66		
9-1	9	1	97.19	1.55		
9-2	9	2	96.53	1.46	**96.86**	**1.50**
9-3	9	3	96.86	1.50		

Summary:

Average of Samples Taken at Each Time

time	% removal	LRV
3	96.94	1.52
6	97.11	1.55
9	96.86	1.50

blank slide counts

1 (Eff.)	0
2 (between)	0
3 (Inf.)	0

samples taken before experiment

name	size	count
effluent	500	3
influent	50	0

average influent #/ml

expected:	12
experimental:	12.33

Backwash procedure: backwash for 6 minutes alternating with filtering for 5 minutes, 5 times repeated.

After backwashing the filter one hour passed and then the coagulant feed was started. One hour after the coagulant was started the seeding solution was started and samples took. 24 hours after the first seeding was started the second seeding was started.

.05 mg Al/L

TOC: 2 mg/L as TOC

dilution 1:100
49 ml PAX-19
4907 ml DI water
Coagulant feed rate: 3.408 ml/min
Coffee added 2 mg/L

Filter rate: 30.05 gpm

water chemistry
pH: 7.4
ORP: 820
Temp: 86 deg. F

Pressure Data
before experiment : 11/3 psi
after 1 hour of coagulant: 11/3 psi
after experimment: 11/3 psi
after 24 hour of coagulant: 11/3 psi

Notes on samples
The filter was backwashed, 45 minutes later coffee was added to the pool with the jets on. 15 minutes later the coagulant pump was started. 1 hour after the coagulant pump was started, the seeding pump was started and samples took.

Average of Samples Taken at Each Time					95% Conf Int
time	**% removal**	Std. Dev.	**LRV**	Std. Dev.	2*SD
3	96.94	0.74	1.51	0.11	0.22
6	97.11	0.64	1.54	0.10	0.20
9	96.86	0.33	1.50	0.05	0.09
OVERALL AVERAGE:	**96.97**	**0.53**	**1.52**		