

ARSENIC AND BACTERIOPHAGE MS2 REMOVAL
FROM GROUNDWATER BY NANOPARTICULATE ALUMINUM OXIDE
COATED GRANULAR FILTER MEDIA: A PILOT-SCALE EVALUATION ON THE
EFFECT OF pH AND COATING DENSITY

by

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Disclaimer

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1 Abstract

Adsorptive filtration is a technique based on the coating of a filter medium with adsorbents, resulting in modified media that can act simultaneously as a filter and as an adsorbent (Zouboulis and Katsoyiannis, 2002). Numerous studies have demonstrated that adsorptive filtration is a promising technology for removal of inorganic and microbiological contaminants. While previous studies have demonstrated the ability to coat granular media by precipitation of metallic salts, this study applied nanoscale materials as coatings. This study involved the development of an innovative physico-chemical adsorptive filtration technology for removal of bacteriophage MS2 and arsenic in groundwater. The effects of pH and coating density on contaminant removal were evaluated through coated and uncoated anthracite and granular activated carbon. Lowering pH and increasing coating density resulted in higher arsenic and MS2 removal. This study not only demonstrated the benefits of nanoparticulate aluminum oxide coated filter media but also characterized the potential risks associated with their implementation.

2 Introduction

According to the USEPA (2005), there were 145,498 public water systems that used ground water as their sole source of drinking water in 2004. Most of these ground water systems were small, with 94% of the systems serving 3,300 or fewer people and 98% serving 10,000 or fewer people. The USEPA recently established a maximum contaminant level of 10 $\mu\text{g/L}$ for arsenic in drinking water and estimated that this new standard would annually prevent 37 to 56 cases of bladder and lung cancer in the United States (USEPA, 2001). When finalizing this standard, the USEPA (2001) estimated that 5.3 percent of ground water systems would exceed the 10 $\mu\text{g/L}$ standard. Of the 2302 community ground water systems that would exceed the 10 $\mu\text{g/L}$ standard, 2226 (97%) had service populations of 10,000 or less. All of the 1040 non-transient, non-community ground water systems that would exceed the 10 $\mu\text{g/L}$ standard had service populations of 10,000 or less.

The extent of groundwater contamination with human enteric viruses was recently shown by Abbaszadegan *et al.* (1999) and Borchardt *et al.* (2004). Abbaszadegan *et al.* (1999) conducted a national occurrence study with 150 samples collected from wells in 35 states. They found that 30.1% of the wells were positive for human enteric viruses. Among 48 municipal well samples tested in La Crosse, Wisconsin, 50% were positive for enteric viruses (Borchardt *et al.*, 2004). The USEPA is currently developing a groundwater rule that may require virus control in systems considered vulnerable to virus contamination. MS2 is a male-specific, unenveloped, icosahedral, single-stranded RNA bacteriophage with a size of 26 nm and an isoelectric point of 3.9 (Dowd *et al.*, 1998; Zhuang and Jin, 2003). MS2 is often used as a surrogate for human enteric viruses in filtration studies because they are morphologically similar (Redman *et al.*, 1999). Moreover, surface chemical properties of MS2 are well-known, offering the potential to determine the factors controlling the degree of adsorption (Bales *et al.*, 1991). A study performed by Redman *et al.* (1997) supported the use of MS2 as a “conservative” indicator of fecal contamination in sandy aquifers because this bacteriophage exhibited less removal by filtration than the recombinant Norwalk virus at both pH 5 and pH 7.

This report presents a systematic study of viral and anionic contaminant removal using pilot-scale columns containing granular media that were coated with nanoparticulate aluminum oxide. Previous studies have examined the possibility of modifying granular media to improve their ability to remove pathogens, natural organic matter (NOM), and metals (Stenkamp and Benjamin, 1994; Chang *et al.*, 1997; Chen *et al.*, 1998; Truesdail *et al.*, 1998; Shaw *et al.*, 2000). While previous studies have demonstrated the ability to coat filter media by precipitation of metallic salts, no studies have used nanoparticle suspensions for coating. This work is an attempt to apply nanoscale materials as coatings for the simultaneous removal of particulate and inorganic contaminants from water.

This study not only demonstrated the benefits of nanoparticulate aluminum oxide coated filter media but also characterized the potential risks associated with their implementation. According to the USEPA’s National Secondary Drinking Water Regulations, an aluminum concentration of less than 0.2 mg/L has been recommended for aesthetic reasons and to minimize color, turbidity, and postprecipitation in water systems

(USEPA, 2004). Contradictory findings can be observed in the literature regarding the link between aluminum and Alzheimer's disease. Flaten (2001) reported that nine out of 13 published epidemiological studies of Alzheimer's disease and aluminum in drinking water have shown statistically significant positive relationships. However, regular consumers of antacids ingest gram amounts of aluminum daily, thousands of times the amount taken in through drinking water, and epidemiological studies of antacid exposure and Alzheimer's disease have been largely negative (Flaten, 2001).

The objective of this report was to investigate the use of nanoparticulate aluminum oxide coated filter media for removal of arsenic and bacteriophage MS2 during drinking water filtration. This study was designed to answer the following questions:

1. How do arsenic and MS2 removal vary with pH (5.3 and 7.3) and coating density (0%, 7.5%, and 15%)?
2. Is there any evidence that aluminum is released from the coated anthracite?

3 Methods

3.1 Preparation of Coated Granular Filter Media

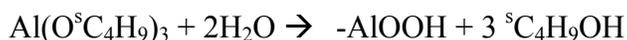
Solution-gelation (sol-gel) has been applied in this study for the production of granular filter media coating. The sol-gel process typically involves four-stages: dispersion, gelation, drying, and sintering.

Dispersion – Synthesis of a stable nanoparticle suspension

A stable suspension of boehmite (γ -AlOOH) was prepared by generating colloidal particles in situ by chemical methods described in Giesemann (1991). The following paragraphs summarize the method.

Aluminum tri-sec-butoxide (ATSB) was used as a starting material in the preparation of boehmite sol. The advantages of preparing the materials from metal

alkoxides include the high purity of the starting materials and the small size of the polymers or particles in the colloidal sol (Gieselmann and Anderson, 1989). ATSB undergoes the following reaction to form boehmite.



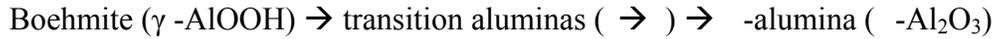
A volume of 187 mL of 2.0 M ATSB solution (in 2-BuOH) was quickly added, with vigorous stirring, to 750 mL water preheated to 83 C. This addition resulted in the immediate formation of a heavy white precipitate which was maintained in suspension only by stirring. After 1-2 hours, 16.5 mL of 1.6 M HNO₃ was added to disperse the particles. In a few minutes, the appearance of the suspension changed from opaque white to nearly clear. Heating and stirring continued for another 1-2 hours. Two of the ports of the reaction kettle were then opened and 2-BuOH was boiled off as its azeotrope with water (bp = 87 C). When the 2-BuOH was completely removed, as indicated by an increase in the temperature of the suspension and by the absence of its characteristic odor, water was added to the kettle until the total volume reached 750 mL. The 2 open ports were then closed and the sol was gently refluxed overnight. After cooling to room temperature, the sol was filtered and stored in a clear glass bottle at room temperature until used. The sol prepared according to the above procedures yielded an average particle size of 47 nm and an isoelectric pH of 10.

Gelation, Drying, and Sintering

Filter medium was mixed with boehmite sol in 500 mL Pyrex beakers with agitation provided by stirring. After mixing, gelation started to take place when the sol was “polymerized” to form a solid dispersion or gel. The mixture was then put into a 70 C furnace for overnight drying to evaporate the water contained inside the gel.

After no observable liquid sol was seen in the beaker, the coated filter medium was subjected to sintering. Filter medium was sintered in a furnace that could be programmed with two ramp/dwell cycles (Model F46128C, Thermolyne Corp., Dubuque, IA). In each sintering experiment, the ramp rate was 3 C per minute up to the target

sintering temperature and the furnace was programmed to remain at the target sintering temperature of 500 C for 3 hours before cooling. On heating, boehmite sol will undergo the following phase transformations:



The phase transformation of boehmite into $\text{-Al}_2\text{O}_3$ has been investigated by different researchers (Yoldas, 1975; Clark and Lannutti, 1984; Gieselmann, 1991). The aluminum monohydroxide (-AlOOH) converts into $\text{-Al}_2\text{O}_3$ between 90 C and 475 C. $\text{-Al}_2\text{O}_3$ converts partially into $\text{-Al}_2\text{O}_3$ between 900 C and 1100 C, and fully converts into $\text{-Al}_2\text{O}_3$ above 1200 C. Given the results of these studies, the alumina coating used in this study was expected to be in the $\text{-Al}_2\text{O}_3$ form.

3.2 *Characterization Studies*

Surface Charge Analysis

Surface charge is an important variable affecting particle and ion interactions with granular media. Zeta potential, which approximates surface charge, was estimated from electrophoretic mobility measurements.

Electrophoretic mobility was measured with a Malvern ZetaSizer 3000HSA (Malvern Instruments Ltd., Malvern, England). The sample was injected into a cell to which an electric potential was applied. Within the cell, particles with a negatively charged diffuse layer move towards the positively charged electrode. Laser beams cross the cell and illuminate particles at a particular point in the cell. The intensity of the light reflected by the particles fluctuates with a frequency that is related to particle velocity. The photons detected by a photomultiplier are fed to a digital correlator which analyzes the frequency spectrum from which the electrophoretic mobility is calculated. Electrophoretic mobility is the velocity of a particle in a unit electric field, and is expressed in (m cm)/(Volt sec). The instrument software calculates zeta potential, in

mVolts, from the electrophoretic mobility by using the Smoluchowski approximation (Hunter, 1981). The performance of the instrument was checked several times throughout each run by measuring polystyrene latex standards (Malvern Instruments Ltd., Malvern, England) having a zeta potential of 50 mV \pm 5 mV at 25°C.

Samples were injected directly into the 1.5 mL quartz capillary electrophoresis measurement cell with 10 mL disposable plastic syringes. Prior to the measurement of each new sample, 10 mL of deionized water, followed by 5 mL of the sample to be measured, was rinsed through the capillary cell. Subsequent replicate measurements (typically 2 to 3 depending on sample volume) were made in 10 mL injection increments. Measurements were made at 25 \pm 1°C.

Surface Area Analysis

A Micromeritics ASAP 2010 Micropore Analyzer (Micromeritics Inc., Norcross, GA) was used to measure the BET surface area of filter media based on nitrogen adsorption analysis. This analysis was performed as described in Gieselmann (1991).

3.3 *Experimental Set-Up*

Experiments were carried out with fixed beds of granular media operated under continuous-flow conditions at a pilot plant located on the University of Wisconsin campus. The pilot plant includes six fixed-bed columns, each constructed of clear polyvinylchloride with a diameter of 3 inches. Dual media filtration with 18 inches of crushed anthracite or GAC over 12 inches of sand was used in all experiments. Two experiments were run and the plant was configured in the manner shown in Figure 1 for each of these experiments.

The raw water supply for this study was ground water used by the Madison Water Utility. In all experiments, a carbon block (Plymouth Products, Sheboygan, WI) was used to dechlorinate Madison tap water which was then stored in a 50 gallon plastic container. Effluent of the carbon block was tested using the DPD titration method to ensure that a nondetectable chlorine concentration was maintained throughout the experiments (APHA

et al., 1996). Before entering the fixed-bed columns, dechlorinated tap water was spiked

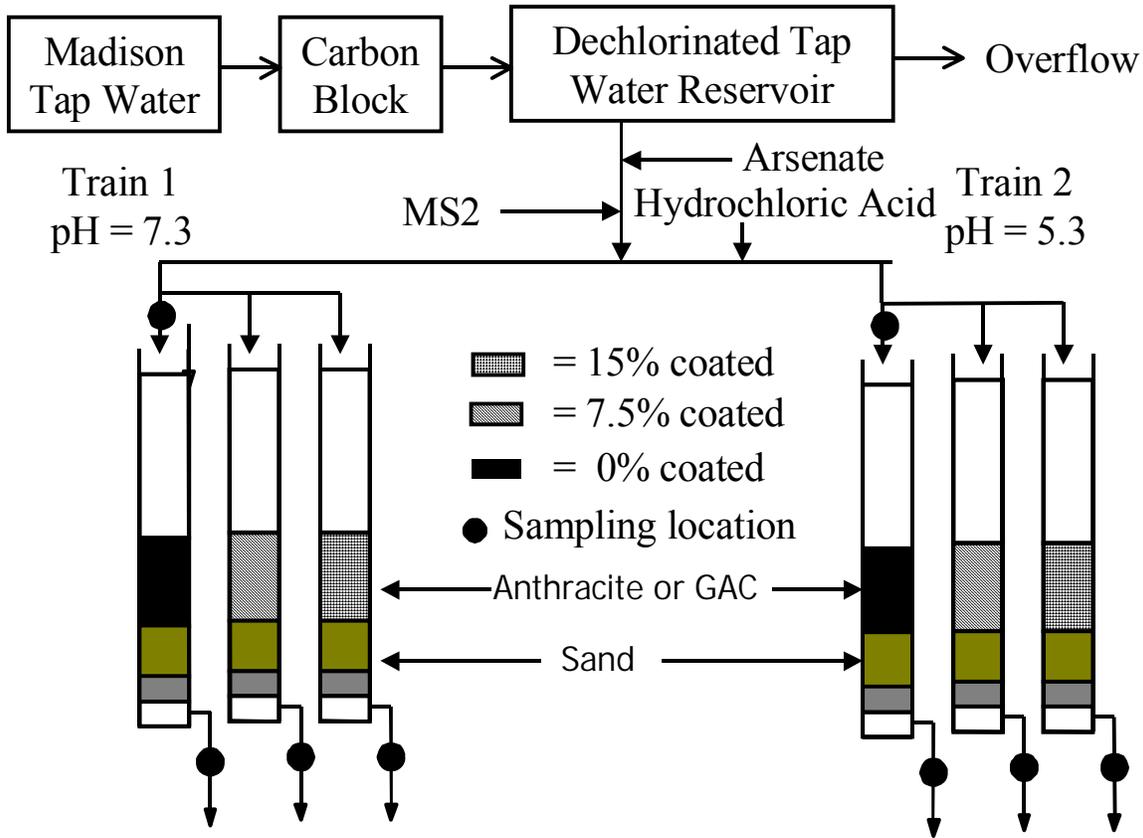


Figure 1 Schematic of pilot-scale experiments.

with 50 $\mu\text{g/L}$ of arsenic as a representative anionic contaminant and 10^8 PFU/L of bacteriophage MS2 as a representative virus. The arsenic and MS2 were added from separate feed containers to prevent potential problems with the MS2 detection method, where *E. coli* may lose its F pili due to high arsenic concentrations (O’Callaghan *et al.*, 1973). The F pili is required to attach MS2 onto *E. coli* for detection. A 0.2 mg/L arsenic stock solution was prepared by dissolving sodium arsenate into 10L L of DI water (Sigma Aldrich, Milwaukee, WI). The MS2 stock was enumerated according to the single agar layer procedure outlined in USEPA Method 1602 (USEPA, 2001). After calculating the concentration from the enumeration procedure, the MS2 stock was diluted in tryptic soy broth to obtain the target spiking concentration for each experiment. The diluted spiking suspensions were aliquoted and frozen at -80°C until use.

To characterize the effect of pH on contaminant removal through coated and uncoated filter media, experiments were conducted at pH 5.3 and pH 7.3. The ambient pH of Madison tap water was 7.3. 2 M hydrochloric acid was used to lower the pH to pH 5.3. These two pH values were chosen after considering the pK values of arsenic and surface charge on aluminum oxide surfaces. Moreover, the effect of coating density was examined by coating the media with three mass percentages. For all experiments, feeding of the contaminants was initiated at a desired time and, once steady-state was achieved after five hours of operation, each column was backwashed and placed back into service. A constant filtration rate of 4 gpm/ft² and an empty bed contact time of 5 minutes were maintained.

3.4 Analytical approach

A Varian SpectrAA 800 was used to analyze samples for arsenic using Standard Methods (APHA *et al.*, 1996). This method has a detection limit of 0.5 µg/L and provides procedures for the determination of arsenic by graphite furnace atomic absorption. A Perkin Elmer (Norwalk, CT) Model Optima 4300DV Inductively Coupled Argon Plasma Optical Emission Spectrometer was used to quantify the concentration of aluminum in the samples. Prior to analysis, arsenic and aluminum samples were acidified to pH 2 with 2 N nitric acid. Replicate measurements revealed an analytical error of 5 µg/L for arsenic and 1 µg/L for aluminum.

Bacteriophage MS2 samples were analyzed using the single agar layer procedure for male-specific (F⁺) and somatic coliphage in water. Procedural details are described in USEPA (2001).

4 Results and Discussion

4.1 Media Characterization

Figure 2 illustrates the effect of coating density on the anthracite's isoelectric pH, which increased with increasing coating density. The isoelectric pH values for anthracite

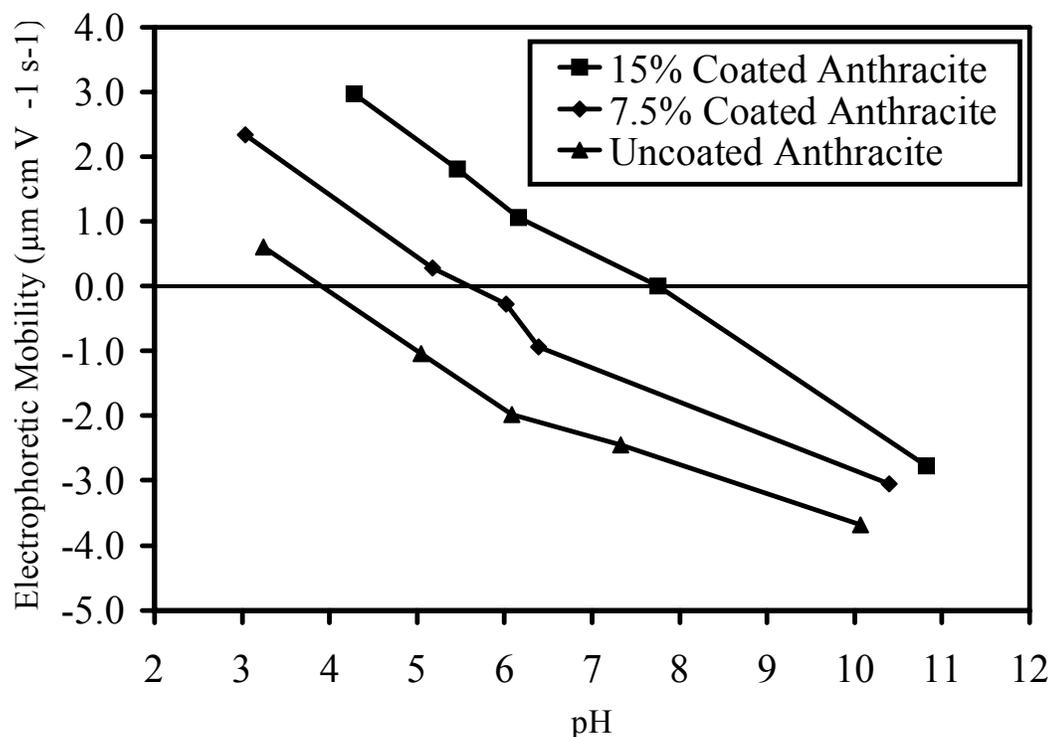


Figure 2 Electrophoretic mobility of anthracite at different coating densities.

with 0%, 7.5%, and 15% coating densities were 3.9, 5.5, and 7.8, respectively. The effect of coating density on the isoelectric pH of GAC is shown in Figure 3. As with anthracite, the isoelectric pH of GAC increased with increasing coating density. The isoelectric pH values for GAC with 0%, 7.5%, and 15% coating densities were 3.8, 7.3, and 8.8, respectively. The results on Figures 2 and 3 are consistent with the isoelectric pH of the boehmite (γ -AlOOH) coating suspension, which had an isoelectric pH of 10.

Table 1 summarizes BET surface area measurements on filter media with different coating densities. A major advantage of using nanoparticulate aluminum oxide is its ability to increase surface area by a factor of 100 over uncoated material. A 130-fold increase in surface area was observed between uncoated anthracite and 7.5% coated anthracite. When comparing uncoated anthracite with 15% coated anthracite, surface area was increased by a factor of 345. The increase was expected because the boehmite (γ -AlOOH) coating suspension had an average particle size of 47 nm and the average BET surface area of its xerogel when dried at 100 C was 225 2.5 m²/g. However, the

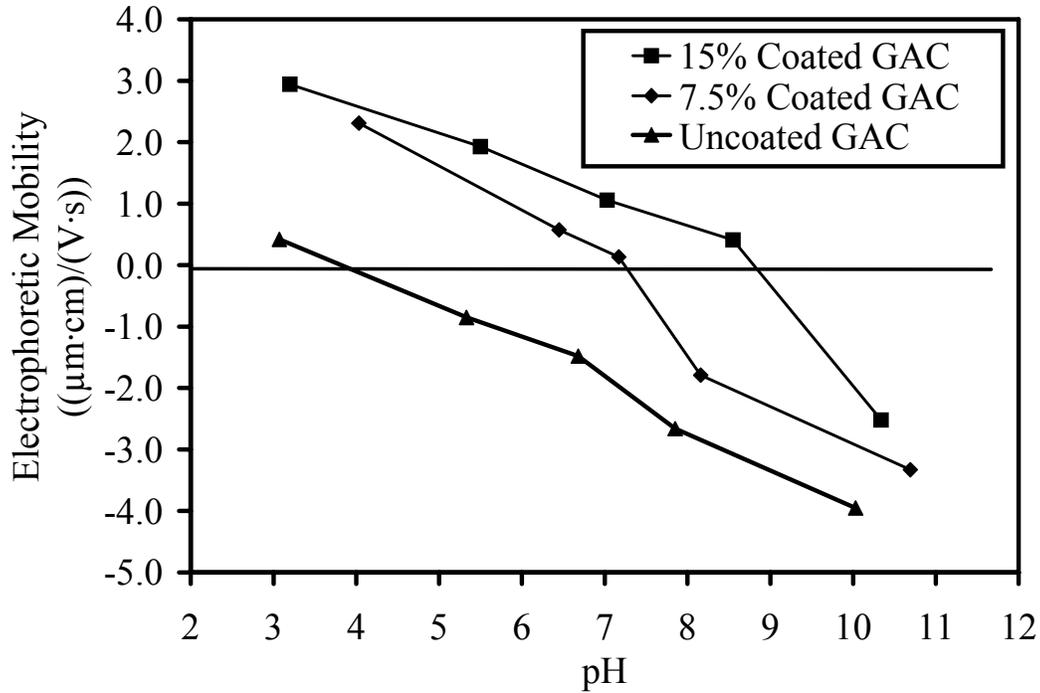


Figure 3 Electrophoretic mobility of GAC at different coating densities.

Table 1 Summary of BET surface area (m^2/g) of filter media at different coating quantities.

Support Medium	0% Coating	7.5% Coating	15% Coating
Anthracite	0.265 ± 0.05	34.5 ± 0.4	91.4 ± 0.7
GAC	1688 ± 22	964 ± 14	921 ± 13

coating decreased the GAC's surface area by 43% (7.5% coated) and 45% (15% coated). The cause of this reduction in surface area was not experimentally determined but it could possibly be due to a significant degree of micropore blockage by the coating.

4.2 Arsenic Removal

The effect of coating density on arsenic removal by anthracite is shown in Figures 4 and 5. In general, arsenic removal increased with increasing coating density. This coating density effect became more distinct when the pH was lowered to 5.3. The

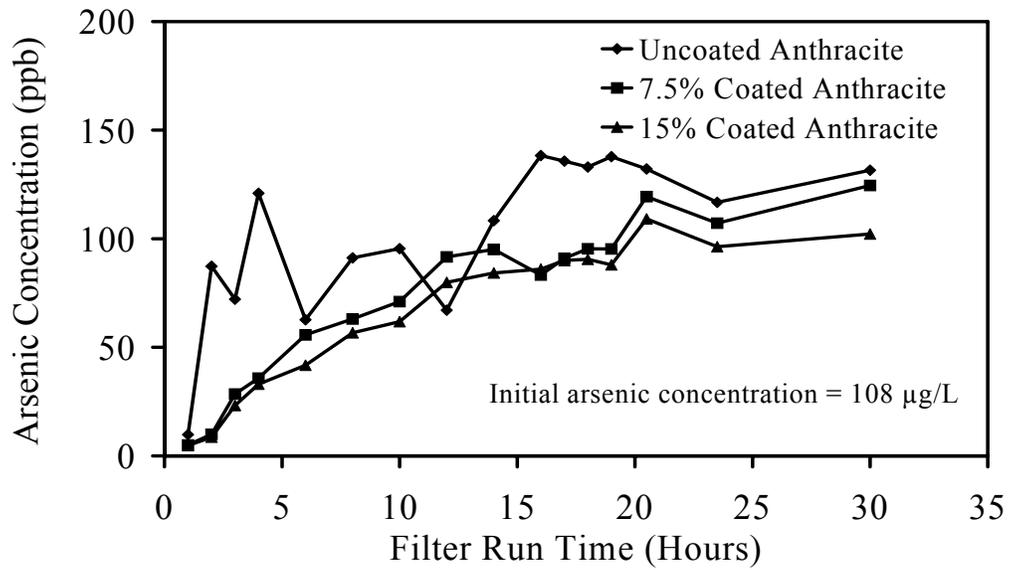


Figure 4 Effect of coating density on arsenic removal by anthracite at pH 7.3.

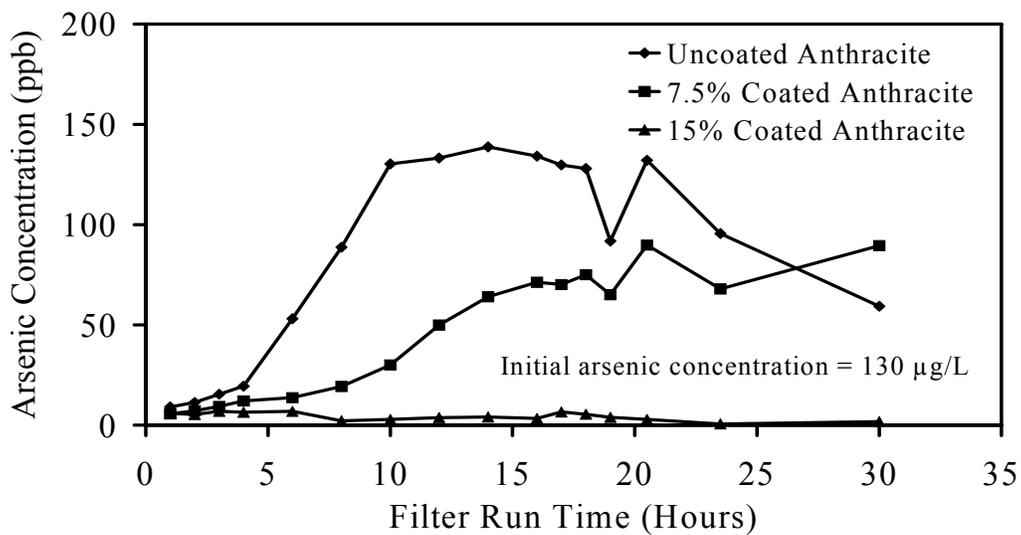


Figure 5 Effect of coating density on arsenic removal by anthracite at pH 5.3.

Table 2 Summary of electrostatic conditions of anthracite

Coating density (%)	Sign of charge at pH 7.3 (Train 1)	Presence of electrostatically favorable condition	Sign of charge at pH 5.3 (Train 2)	Presence of electrostatically favorable condition
0	-	-	-	-
7.5	-	-	+	+
15	+	+	+	+

electrostatic conditions observed for anthracite can be used to explain these observations (Table 2). Anthracite at different coating densities carried a different charge at each pH condition. Arsenate, the expected form of arsenic in this study, has three pK_a values: 2.7, 6.8, and 11.5 (Smith and Martell, 1976). At pH 5.3 and 7.3, arsenate is primarily present in water as a monovalent anion ($H_2AsO_4^-$) and divalent anion ($HAsO_4^{2-}$), respectively. Uncoated anthracite possessed a negatively charged surface at both pH conditions and, therefore, was electrostatically unfavorable for attracting negatively charged arsenic at both pH conditions. Anthracite coated at 7.5% density was also electrostatically unfavorable for attracting negatively charged species at pH 7.3. However, a favorable condition occurred at pH 5.3 for anthracite coated with a 7.5% density. The anthracite coated with a density of 15% carried a positively charged surface at both pH conditions, favoring electrostatic attraction of arsenic.

Figure 6 illustrates the effect of pH on arsenic removal by 15% coated anthracite. At pH 5.3, 15% coated anthracite was able to produce an effluent with less than 5 g/L of arsenic throughout the entire 30-hour run. However, 15% coated anthracite exceeded the 10 g/L standard at pH 7.3 after a filter run time of 2.3 hours.

The effect of coating density with respect to arsenic removal by GAC was more distinguishable at pH 7.3 than at pH 5.3. At pH 7.3, GAC coated at 0%, 7.5%, and 15% reached the 10 g/L breakthrough at 0.5 hours, 0.5 hours, and 6.5 hours respectively (Figure 7). At pH 5.3, GAC coated at all three coating densities was able to comply with the new EPA standard of 10 g/L for the entire 30-hour run (Figure 8). Uncoated GAC

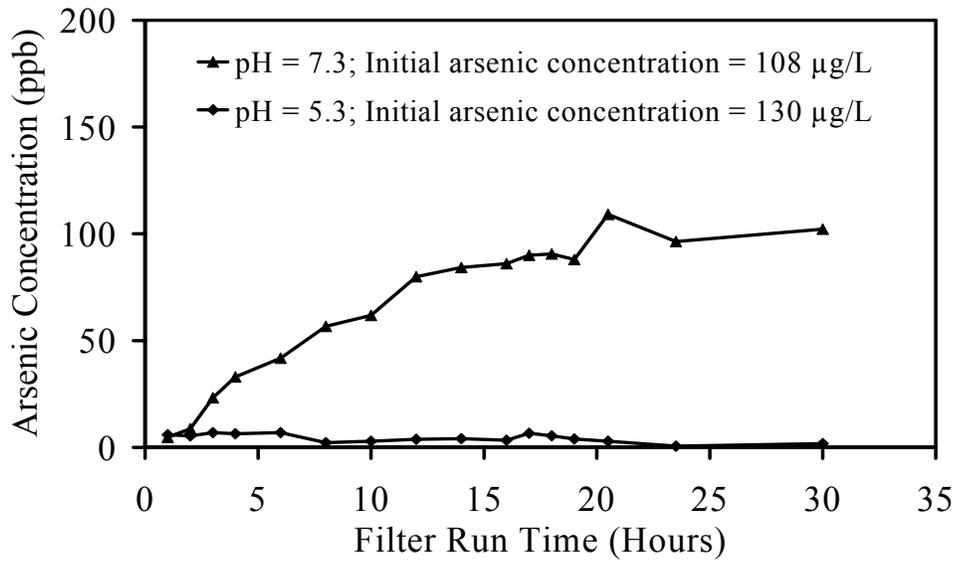


Figure 6 Effect of pH on arsenic removal by 15% coated anthracite.

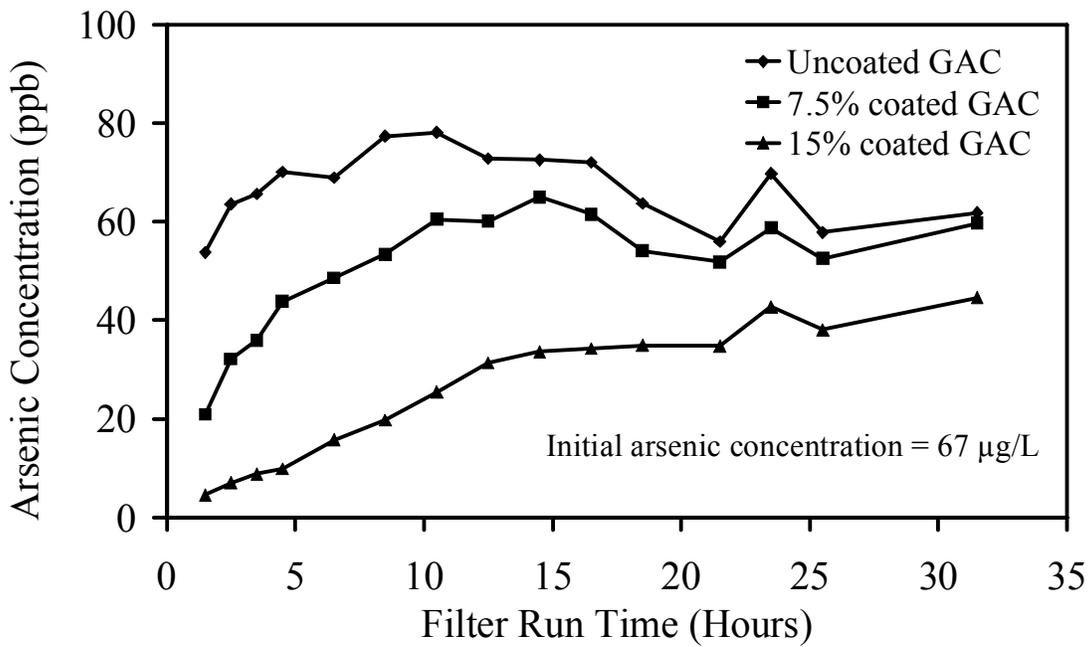


Figure 7 Effect of coating density on arsenic removal by GAC at pH 7.3.

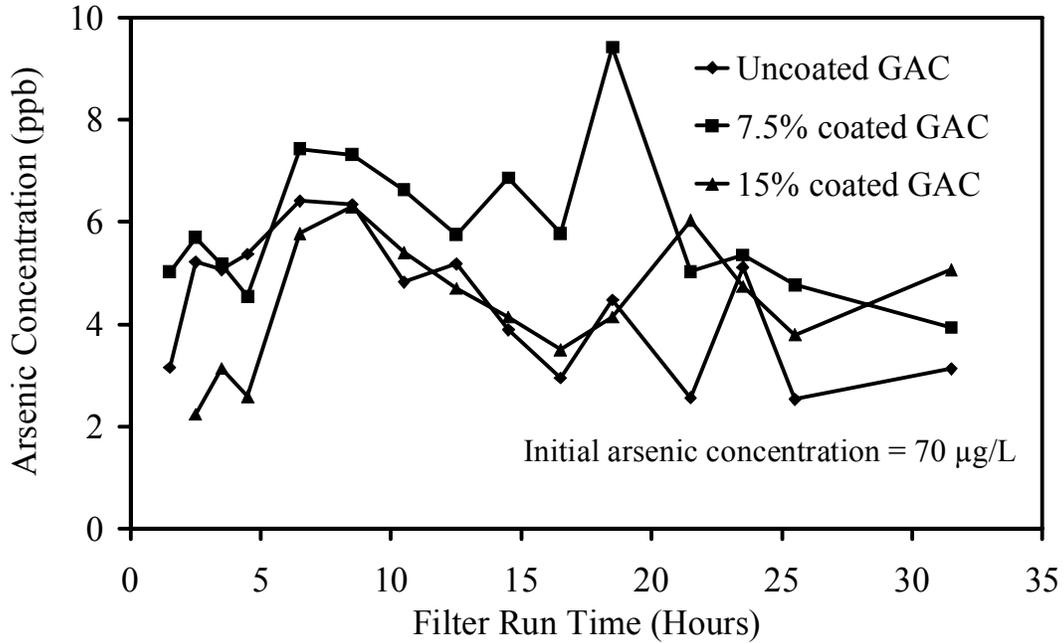


Figure 8 Effect of coating density on arsenic removal by GAC at pH 5.3.

Table 3 Summary of electrostatic conditions of GAC

Coating density of GAC (%)	Sign of charge at pH 7.3 (Train 1)	Presence of Electrostatically favorable condition	Sign of charge at pH 5.3 (Train 2)	Presence of Electrostatically favorable condition
0	-	-	-	-
7.5	Neutral	Neutral	+	+
15	+	+	+	+

was electrostatically unfavorable for attracting arsenic in both treatment trains because it possessed a negatively charged surface at both pH conditions (Table 3). This explanation is consistent with the result shown in Figure 7 that uncoated GAC produced the highest average effluent arsenic concentration. The 7.5% coated GAC was electrostatically neutral at pH 7.3, but provided a favorable condition at pH 5.3. The 15% coated GAC carried a positively charged surface in both conditions, favoring electrostatic attraction of arsenic.

Despite the fact that 7.5% coated GAC had a higher isoelectric pH and surface area than 7.5% coated anthracite, 7.5% coated GAC reached the 10 g/L standard four times faster than 7.5% coated anthracite. One of the possible explanations of this phenomenon is that the majority of the aluminum oxide might be coated onto the internal surface of the GAC and the EBCT in this study may not be enough for internal diffusion of arsenic to occur. Further study on the adsorption kinetics, identification and quantification of the mass transport processes that limit the rate of arsenic adsorption, and other media characterization techniques are necessary to explain this observation.

The effect of pH on arsenic removal by 15% coated GAC is shown in Figure 9. Arsenic removal was more significant at the lower pH, a result that was consistent with the anthracite results shown in Figure 6. As with the effect of coating density, the significance of the filter media effect on arsenic removal was pH dependent (see Figure 10). Both media performed well at pH 5.3, while the coated GAC performed better than the coated anthracite at pH 7.3.

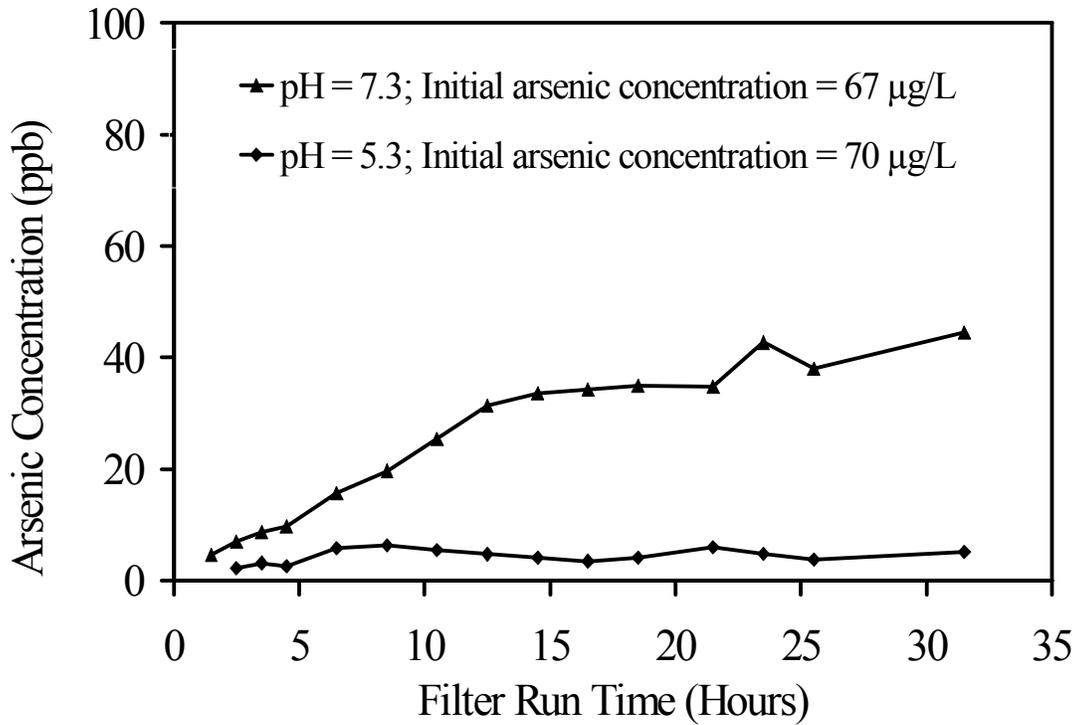


Figure 9 Effect of pH on arsenic removal by 15% coated GAC.

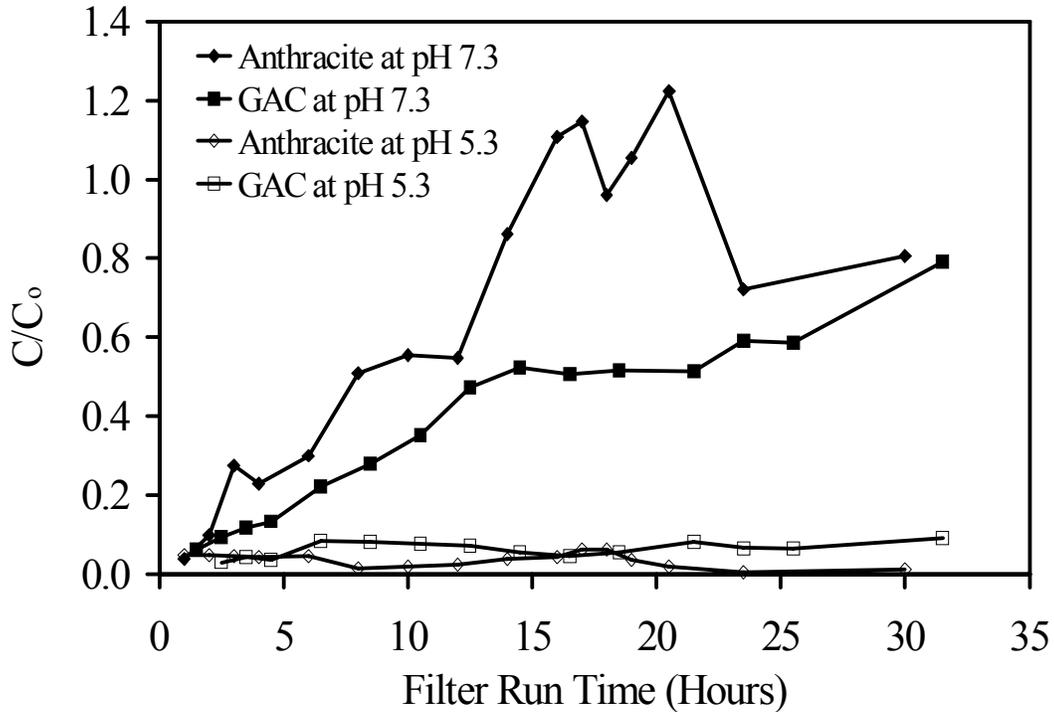


Figure 10 Effect of 15% coated filter media on arsenic removal.

4.3 MS2 Removal

With an isoelectric pH of 3.9, MS2 was negatively charged at pH 7.3 and pH 5.3. Figures 11 and 12 illustrate the effect of coating density on MS2 removal by anthracite and GAC at pH 7.3. In general, MS2 removal increased with increasing coating density. When the pH changed from 7.3 to 5.3, differences in log removal between uncoated and coated filter media were not always observed (Tables 4 and 5). In these cases, the initial MS2 concentration was not high enough to detect any difference in performance between the 7.5% and the 15% coated filter media. When there was an observable difference, coated anthracite and GAC removed MS2 at an average of 5.7 log and 4.7 log respectively, while uncoated anthracite and GAC had an average of 4.1 log and 3.0 log removal. Coated anthracite demonstrated a 1.0 to 2.0 log higher removal than uncoated anthracite at five of the nine sampling times (Table 4). Log differences between uncoated and coated GAC ranged from 1.3 to 2.1 for five of the twelve sampling times (Table 5).

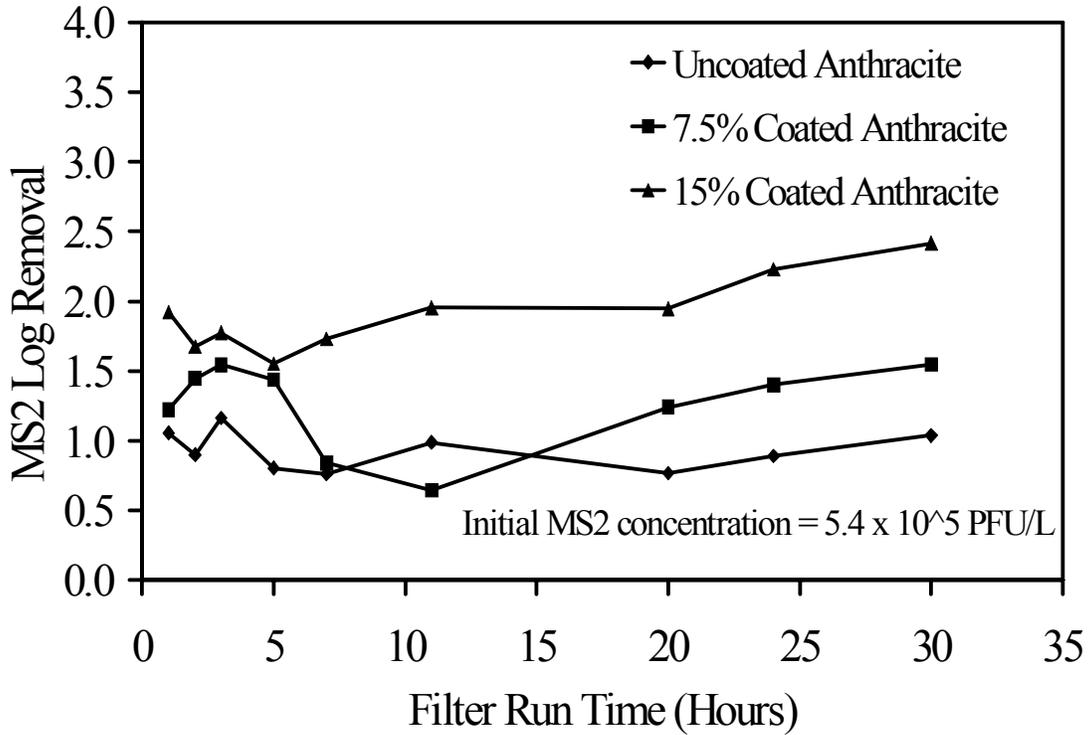


Figure 11 Effect of coating density on MS2 removal by anthracite at pH 7.3.

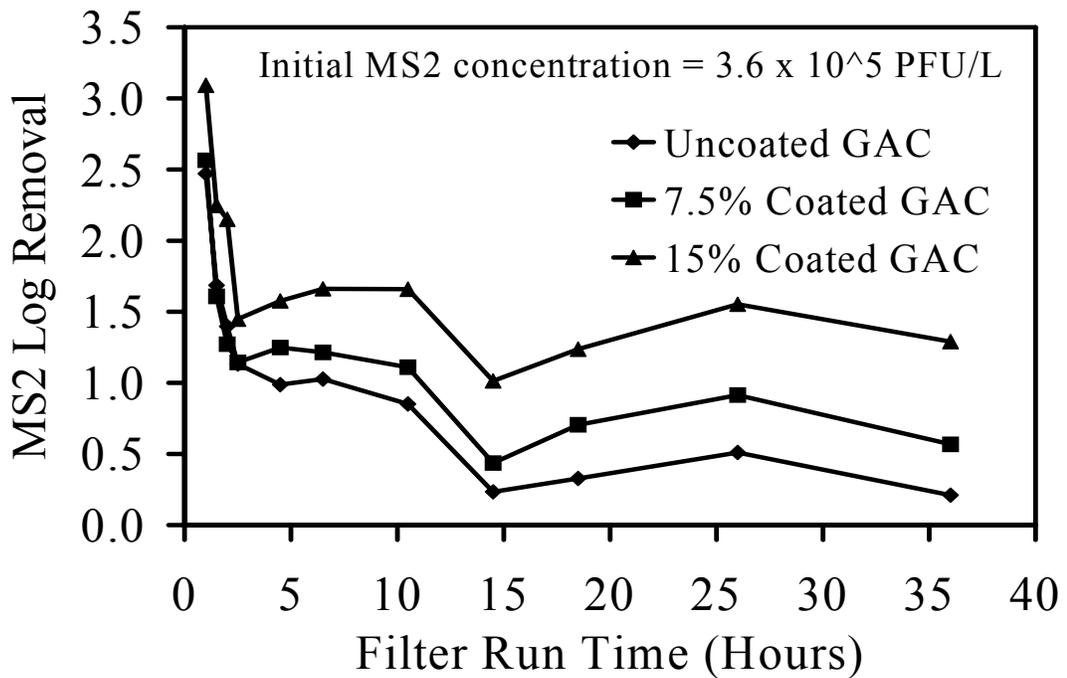


Figure 12 Effect of Coating Density on MS2 Removal by GAC at pH 7.3.

Table 4 Log Removal of MS2 by anthracite at pH 5.3 ($C_0 = 5.3 \times 10^4$ PFU/L).

Filter Run Time (Hours)	Uncoated Anthracite	7.5% Coated Anthracite	15% Coated Anthracite	Difference
1		> 5.4		-
2		> 5.3		-
3		> 5.5		-
5	3.5	> 5.5		> 2.0
7	3.9	> 5.7		> 1.8
11	3.8	> 5.5		> 1.7
20		> 5.9		-
24	5.0	> 6.0		> 1.0
30		> 6.1		-

Table 5 Log Removal of MS2 by GAC at pH 5.3 ($C_0 = 2.0 \times 10^5$ PFU/L).

Filter Run Time (Hours)	Uncoated GAC	7.5% Coated GAC	15% Coated GAC	Difference
1.0		> 5.6		-
1.5		> 5.7		-
2.0		> 5.5		-
2.5	3.1	> 4.4		> 1.3
4.5	2.7	> 4.3		> 1.6
6.5	3.4	> 5.5		> 2.1
10.5		> 5.1		-
14.5	2.6	> 4.7		> 2.1
18.5	3.0	> 4.7		> 1.7
26		> 3.7		-
36		> 3.9		-

The effect of pH can be studied by comparing average MS2 log removals summarized in Table 6. Uncoated anthracite and GAC removed an additional 3.2 log and 1.8 log of MS2 respectively when the pH was lowered from 7.3 to 5.3. The change of pH also resulted in at least an additional 3.7 log removal by coated anthracite and at least an additional 2.8 log removal by coated GAC. Hence, regardless of coating density and filter medium, MS2 log removal improved as the water became more acidic. This is expected for the same reason used in explaining the effect of pH on arsenic adsorption. A

Table 6 Summary of MS2 Average Log Removal.

Filter Media	pH	Coating Percentage		
		0%	7.5%	15%
Anthracite	5.3	4.1	> 5.6	
	7.3	0.9	1.3	1.9
GAC	5.3	3.0	> 4.7	
	7.3	1.2	1.4	1.9

positively charged surface enhanced the electrostatic attraction of MS2 onto anthracite and GAC.

With respect to the effect of filter media, anthracite and GAC performed very similarly at pH 7.3 regardless of coating percentages. Uncoated anthracite achieved an average of 1.1 log higher removal than uncoated GAC at pH 5.3. A comparison between coated anthracite and coated GAC could not be made because of insufficient initial MS2 concentrations to quantify MS2 removal on coated media at pH 5.3.

4.4 Aluminum Release

There is evidence that aluminum was released from coated anthracite. As coating density doubled, the average effluent aluminum concentration increased from 10 g/L to 16 g/L at pH 7.3 and from 435 g/L to 514 g/L at pH 5.3 (Figures 13 and 14). There seems to be no apparent correlation between effluent aluminum concentration and filter run time at either pH condition. The effluent aluminum concentration was 32 to 44 times higher at pH 5.3 than pH 7.3. For 15% coated anthracite, the average effluent aluminum concentration increased from 10 g/L to 514 g/L (Figure 15). The reduction of pH is associated with greater aluminum solubility, but may also release more particulate aluminum from the anthracite surface. At pH 7.3, the effluent aluminum concentration from coated anthracite was lower than the USEPA's National Secondary Drinking Water Regulations. At pH 5.3, release of aluminum was higher than the recommended concentration of 0.2 mg/L.

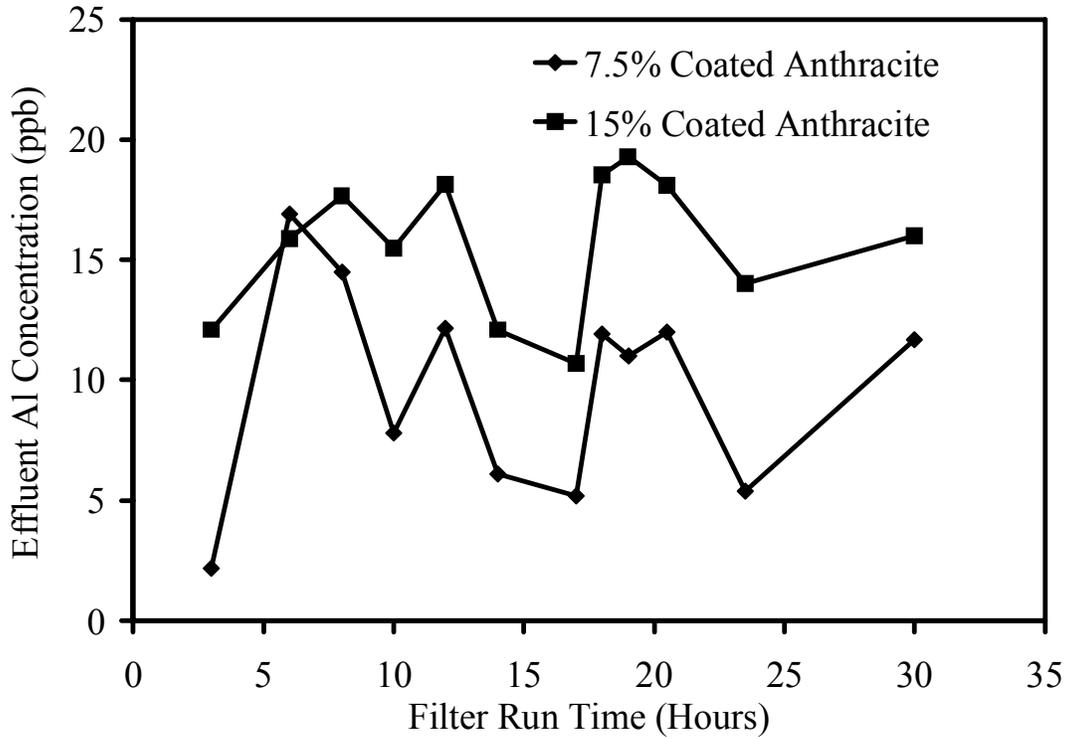


Figure 13 Effect of coating density on aluminum release by anthracite at pH 7.3.

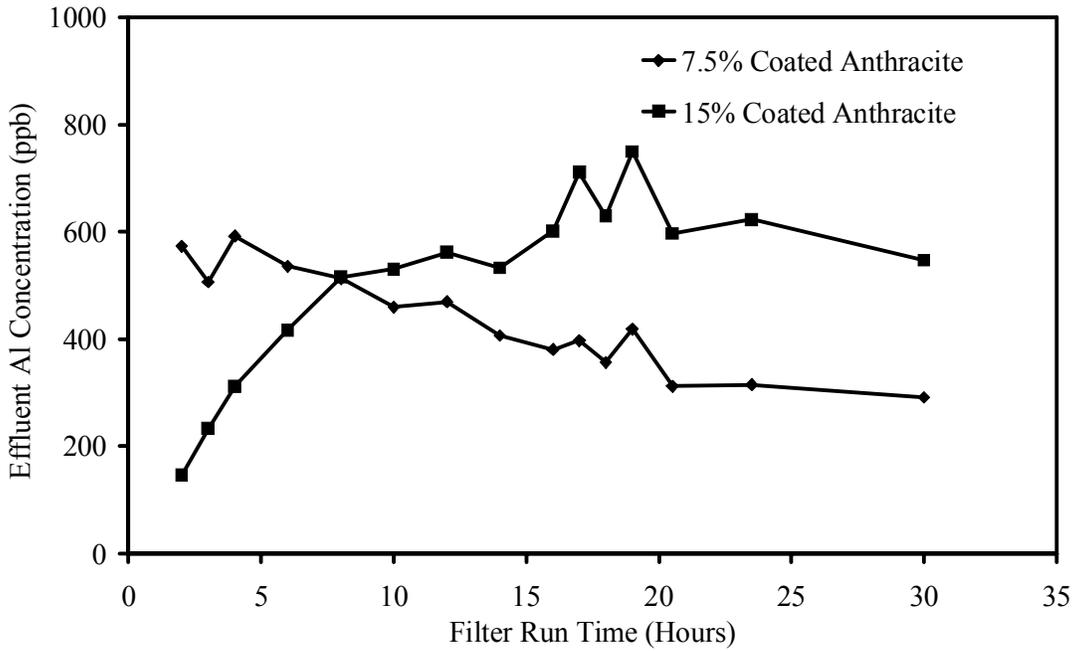


Figure 14 Effect of coating density on aluminum release by anthracite at pH 5.3.

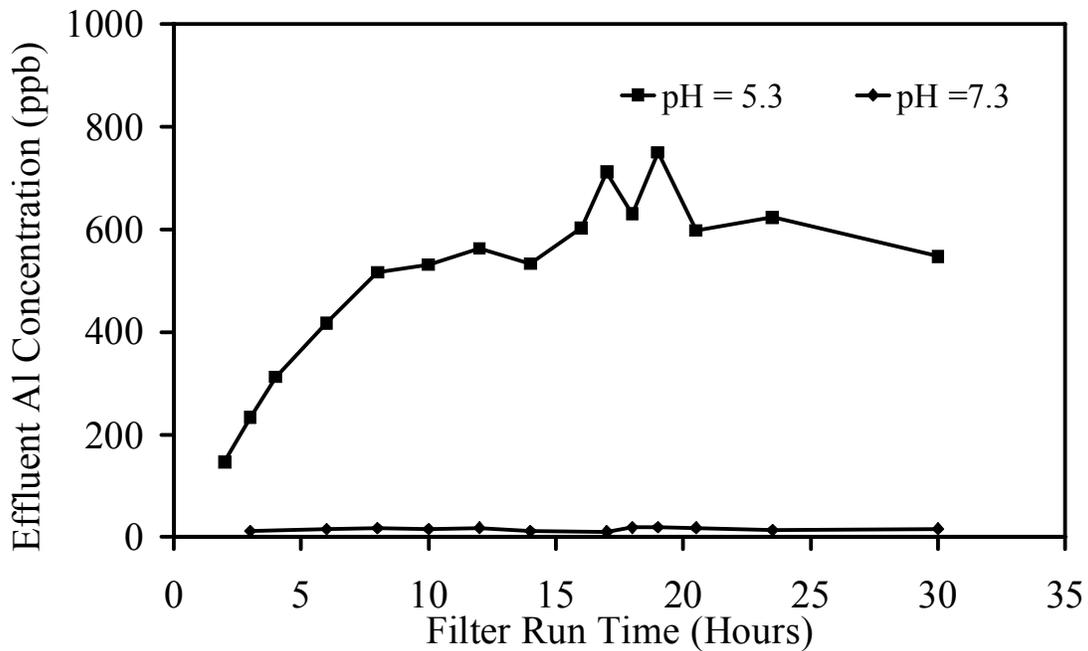


Figure 15 Effect of pH on aluminum release by 15% coated anthracite.

5 Conclusions

Overall, surface charge and surface area measurements were able to explain the effects of pH and coating density on contaminant removal, but failed to explain the differences in performance due to filter media. Lowering pH led to an increase in arsenic and MS2 removal by both anthracite and GAC. This effect is possibly due to the electrostatic attraction generated by the positively charged filter media surface at lower pH. The coated surface of the filter media possessed a higher isoelectric pH and surface area. Surface coverage by the nanoparticulate aluminum oxide coating was extended as a result of an increase in coating density. Increasing coating density resulted in higher removal of the two contaminants of this study.

With respect to arsenic removal, 15% coated anthracite, uncoated GAC, and coated GAC were able to maintain an effluent arsenic concentration below the US regulatory standard of 10 $\mu\text{g/L}$ throughout the entire filter run at pH 5.3. In terms of MS2 removal at pH 5.3, coated anthracite and GAC were able to provide an additional 1.5 log and 1.7 average log removal, respectively. The effect of pH was significant on aluminum

release. At pH 7.3, average effluent aluminium concentration stayed within 10 g/L to 16 g/L. At pH 5.3, an average of 435 g/L to 514 g/L of aluminum was found in the effluent water.

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