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Sorption Behavior of Monosodium Titanate and Amorphous Peroxotitanate Materials
under Weakly Acidic Conditions

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Abstract

Inorganic, titanate-based sorbents are tested with respect to adsorption of a variety of sorbates under weakly acidic conditions (pH 3). Specifically, monosodium titanate (MST) and amorphous peroxotitanate (APT) sorption characteristics are initially probed through a screening process consisting of a pair of mixed metal solutions containing a total of 29 sorbates including alkali metals, alkaline earth metals, transition metals, metalloids and nonmetals. MST and APT sorption characteristics are further analyzed individually with chromium(III) and cadmium(II) using a batch method at ambient laboratory temperature, varying concentrations of the sorbents and sorbates and contact times. Maximum sorbate loadings are obtained from the respective adsorption isotherms.

Introduction

Since the discovery of naturally occurring zeolites, ion exchange sorbent materials have found widespread application in waste water treatment. Heavy metal ions are highly toxic even at low concentrations due to bioaccumulation and biomagnification necessitating the removal of such species to restore water to a potable quality. Much research has centered on adsorbents and ion exchangers for this application.^[1-8] Due to the inconsistent composition of naturally occurring zeolites and clays which typically varies as a function of its origin,^[9] synthetic sorbent materials have seen increasing attention for the sequestration of these hazardous ionic species. Nanoporous materials like synthetic zeolites^[10,11] and clays,^[10,12] as well as micro-^[13,14] and mesoporous^[15] materials have all found application in metal separations. Typically, sorption occurs by

ion exchange or electrostatic interaction between ions on the surface, within channels, or within pores.

Inorganic sorbents can typically be prepared in high yields by simple reactions. They are typically easier to prepare and less expensive than organic sorbents. While organic sorbents display greater selectivity due to tailored functionalized groups, they can undergo decomposition in the harsh chemical environments often found in industrial wastewaters. Inorganic sorbents do not typically display the same level of selectivity as organic based sorbents, however, they are attractive due to their stability over a wide range of pH conditions and temperatures. Increased selectivity is currently one of the primary goals of inorganic sorbent materials research. Incorporation of functional groups into inorganic sorbents is one promising avenue for enhancing selectivity.

Titanate-based materials such as MST, sodium nonatitanate, and the titanosilicate, ETS-10, have been studied as sorbent materials since their discovery.^[16-18] Sodium nonatitanate (SNT) and titanosilicates are both widely used now and are commercially available. MST has found use to remove strontium and actinides from strongly alkaline and high ionic strength nuclear waste solutions. A series of peroxotitanates were recently reported displaying significantly improved sorption characteristics for strontium and actinides compared to MST.^[19-21] These peroxotitanate materials, which have the empirical formula $H_vNa_wTi_2O_5 \cdot (xH_2O)[yH_zO_2]$ where $v + w = 2$ and z ranges from 0 to 2, are prepared by adding hydrogen peroxide either during the synthesis of MST or through a post synthesis treatment of MST. Both methods result in an amorphous yellow solid, which is indicative of a hydrated or protonated titanium-peroxo species.

Much of the titanate based sorbent research to date centers on sorption of radionuclides and in particular ^{90}Sr and transuranic elements.^[19-23] Sorption of heavy metals and other nonradioactive metals found in industrial waste streams receives less attention, however, a number of examples can be found. Sorption of barium, chromium, mercury and zinc onto MST,^[24-26] sorption of cadmium onto lithium, sodium, and potassium-titanates,^[27,28] and sorption of copper, zinc, and nickel onto lithium-titanate are reported.^[29] The research described herein will expand the body of work to include the sorption of a wide range of cationic species with MST and APT materials.

The present research will measure the affinity of MST and APT to sorb a variety of metals in weakly acid conditions including aluminum(III), barium(II), boron(III), cadmium(II), calcium(II), chromium(III), cobalt(II), copper(I), iron(III), lanthanum(III), lead(II), lithium(I), magnesium(II), manganese(II), molybdenum(VI), nickel(II), niobium(V), phosphorous(V), potassium(I), rhenium(VII), silicon(IV), sodium(I), strontium(II), sulfur(VI), tin(IV), titanium(IV), vanadium(V), zinc(II), and zirconium(IV). Following this preliminary screening, a more detailed sorption analysis was conducted with chromium(III) and cadmium(II).

Experimental

Materials. Screening sorption tests used two multiple-element solutions designated as Mix A and Mix B. These solutions were purchased from High-Purity Standards (Charleston, SC) and used without additional purification. Mix A contained the following elements, Al, B, Ba, Cd, Cr, Ca, Co, Cu, Fe, La, Pb, Li, Mg, Mn, Ni, P, K, Re, Na, Sr, V and Zn, each at a reported concentration of 1000 mg L⁻¹. Mix B contained the

following elements, Mo, Nb, Si, S, Sn, Ti and Zr, each at a reported concentration of 1000 mg L⁻¹. The solutions were diluted ten-fold with ultrapure H₂O (MilliQ Element) to reduce the element concentration to 100 mg L⁻¹. The pH of the diluted solutions was then adjusted to 3.0 ± 0.1 with ACS Reagent Grade 50 wt% NaOH solution. The pH adjustment of Mix A produced a brown precipitate. The pH adjustment of Mix B produced no visible evidence of a precipitate. Both of the diluted and pH-adjusted solutions were filtered through a disposable filter having a 0.45-micron nylon membrane. The filtered solutions were stored in tightly stoppered high-density polyethylene bottles until use. Based on the analysis of the filtered solutions, approximately 13% of the Al and Cr, 99% of the Fe, 33% of the P, 67% of the Pb and 60% of the V was removed from Mix A upon the pH-adjustment step (see Table I). Based on the elemental analysis, none of the seven elements in Mix B appeared to precipitate upon the pH-adjustment step (see Table II). Note, however, that the Mix B solution contained small amounts of Al (21.1 mg L⁻¹) and B (24.7 mg L⁻¹) and a much higher concentration of Si (273 mg L⁻¹) than expected.

MST was prepared as a 15 wt% suspension by the Optima Chemical Group Ltd. (Douglas, GA) designated as Lot #00-QAB-417. Prior to use the MST suspension was adjusted to pH 3.00 using reagent grade nitric acid (Fisher Scientific, Pittsburg, PA) diluted to 2 M with ultrapure water (MilliQ Element). Moisture analysis following pH adjustment determined the dry solids content at 15.06 ± 0.02 wt%.

APT was prepared as a 15 wt% suspension by the Optima Chemical Group Ltd. (Douglas, GA) designated as Lot #06-QAB-0139 using the post-synthesis method adapted from the laboratory procedure as follows.^[19] A 10 g suspension of MST (14.8

wt%; pH ~ 10.5) was stirred in a beaker as 0.1 to 2.0 M nitric acid was added drop-wise to adjust the pH to 7.0. This step was followed by drop-wise addition of a 30 wt% solution of hydrogen peroxide. Upon addition of hydrogen peroxide a reaction ensues resulting in oxygen evolution and a color change of the MST suspension from white to yellow. Hydrogen peroxide was added until the H₂O₂:Ti mole ratio was 3:1. The resulting solution was stirred for 24 hours. Any hydrogen peroxide remaining after this duration was removed by vacuum filtration followed by washing the wet APT solids with deionized, distilled water. Finally the APT suspension was adjusted to pH 3.00 ± 0.05 and approximately 15 wt% using nitric acid and deionized, distilled water. Moisture analysis following pH adjustment determined the dry solids content to be 15.54 ± 0.05 wt%.

Instrumentation. The dry solids content of aqueous suspensions of MST and APT was determined using a HG63-P moisture analyzer (Mettler Toledo, Columbus, OH). Each of the MST and APT suspensions was mixed for a minimum of 30 minutes using a magnetic stirrer prior to pipetting approximately 1.5-grams of the suspension onto the tared weighing dish of the moisture analyzer.

All pH measurements used an Accumet XL20 pH meter (Fisher Scientific, Pittsburg, PA). A Leeman Prodigy Inductively Coupled Plasma Emission Spectrometer (ICP-ES), purchased from Teledyne Leeman Labs (Hudson, NH) was used to determine concentrations of heavy metal ions for the mixed metal solutions and for chromium(III) and cadmium(II) before and after batch treatment with MST or APT suspension. The ICP-ES is equipped with a Large Programmable Array Detector (L-PAD) that provides

simultaneous wavelength coverage from 165-1100 nm and typical operates at 1.1 kW, with an Ar coolant flow rate of 18 L min⁻¹ and an Ar auxiliary flow rate of 0.5 L min⁻¹.

Zeta potential measurements used a Zeta Plus zeta potential analyzer (Brookhaven Instruments Corporation, Holtsville, NY). The potentiostat was operated in multicycle mode using 2 cycles per run with 40 runs per sample at 25 ± 0.1° C.

Results and Discussion

The initial screenings developed a preliminary understanding of the sorption performance of MST, which is considered the baseline material for this investigation, and APT with two solutions containing multiple ionic species. The 29 sorbates screened and the results of the sorption test are shown in Tables I and II. This preliminary study consisted of two batches, Mix A and Mix B. Mix A contains the species aluminum(III), barium(II), boron(III), cadmium(II), calcium(II), chromium(III), cobalt(II), copper(I), iron(III), lanthanum(III), lead(II), lithium(I), magnesium(II), manganese(II), nickel(II), phosphorous(V), potassium(I), rhenium(VII), sodium(I), strontium(II), vanadium(V), and zinc(II), while mix B contains the species aluminum(III), boron(III), lead(II), molybdenum(VI), niobium(V), silicon(IV), sulfur(VI), tin(IV), titanium(IV), and zirconium(IV).

Separate solutions of Mix A were contacted with 3.505 g of MST suspension (0.528 g MST) and 3.522 g of APT suspension (0.547 g APT), respectively for 8 days at ambient laboratory temperature. Similarly, and separate solutions of Mix B were contacted with 3.517 g of MST suspension (0.530 g MST) and 3.541 g of APT suspension (0.550 g APT), respectively. Following 8 days of contact, the mixtures were

filtered through a 0.1 μm filter (Millex W Millipore, PVDF membrane) to remove the MST or APT solids. The clear filtrates were analyzed by ICP-ES to determine the concentration of each of the elements.

Table I provides a summary of the concentrations of Mix A ions before and after contact with MST or APT as well as the percentage removed and decontamination factors (DF) of each of the components in solution. The decontamination factor (DF), which is a unitless value, is the ratio of the initial sorbate concentration to that measured after contact with the sorbent. Table I normalizes decontamination factor (NDF) for APT was obtained by dividing the respective DF values measured for APT by those measured for the MST material. Table II provides the same information upon contacting Mix B with MST and APT samples.

The results from the initial screening indicate both MST and APT perform best with high oxidation state metal cations as suggested by the high decontamination factors for chromium(III) (DF > 2060), vanadium(V) (DF > 297), molybdenum(VI) (DF > 365), niobium(V) (DF > 526, MST only), tin(IV) (DF > 270), and zirconium(IV) (DF = 56.8 MST, DF = 110 APT). Chromium(III) was adsorbed most strongly by MST and APT with an initial concentration of 86.7 mg L^{-1} and a post contact concentration of $<0.042 \text{ mg L}^{-1}$, the lower limit of detection following sample preparation for ICP-ES.

Not all high oxidation state metals are adsorbed strongly as indicated by rhenium(VII) (DF = 1.14 MST, DF = 1.18 APT), silicon(IV) (DF = 15.3 MST, DF = 3.23 APT), and sulfur(VI) (DF = 1.67 MST, DF = 1.53 APT). According to High-Purity Standards, these elements are present as the anionic complexes, ReO_4^- , $\text{Si}(\text{OH})_x(\text{F})_y^{2-}$ ($x + y = 6$), and SO_4^{2-} . However, according to Baes and Mesmer, vanadium(V) (DF > 297)

and molybdenum(VI) ($DF > 365$) are present as the anionic complexes $H_2V_{10}O_{28}^{4-}$, and $Mo_7O_{22}(OH)_2^{4-}$.^[30] Both of these complexes did display high affinity for sorption onto both MST and APT. Sorption of anionic species using metal oxides at low pHs is not unprecedented. Uheida et al. reports the sorption of cobalt(II), palladium(II), platinum(II), and rhodium(III) complexes by magnetite (Fe_3O_4) and maghemite (γFe_2O_3) under acidic conditions.^[31,32] Zeta potential measurements indicate that both MST and APT materials have positive surface charges at pH 3. The surface charge of MST switches from positive to negative surface charge between pH 4 and 5, whereas the surface charge of APT switches between pH 3 and 4. Given these findings, the authors conclude that those elements present as anionic complexes in Mix A and Mix B are sorbed due to the positive surface charge of the sorbent particles.

Sorption of titanium(IV) using both MST and APT was tested using Mix B. MST performed well removing 98.9% of the Ti ($DF = 87.6$). Note, however, that the titanium concentration increased in the test with APT. This result suggests that 1.17 mg (0.033%) of the APT dissolved upon contact with Mix B solution resulting in an increase in titanium concentration. Note that dissolution of Ti did not appear to occur with Mix A as the Ti concentration remained below the lower limit of detection after contacting Mix A with APT. Experiments in which both MST and APT were allowed to contact a pH 3 solution of nitric acid indicated no measurable dissolution of either sorbent. Thus, we attribute the apparent dissolution of a small amount of APT in the test with the Mix B solution to a component in Mix B that is not present in Mix A.

Two cationic species were selected to perform a more detailed analysis of the sorption behavior of MST and APT. A series of solutions containing 100 mg L^{-1} or 500

mg L⁻¹ of chromium(III) or cadmium(II) were prepared to which varying amounts of MST or APT suspension were added ranging from 0.065 to 5.55 g, equivalent to between 0.01 to 0.86 g of solid MST or APT. The amounts of MST or APT added result in a range of phase ratios from 1 g L⁻¹ to 100 g L⁻¹. Contact time ranged from 24 hours to 168 hours (7 days) during which the centrifuge tubes were tumbled to provide good contact between the solids and the solutions. Following the prescribed contact time, the mixtures were centrifuged and the clear supernates filtered through a 0.1 µm filter (Millex W Millipore, PVDF membrane). Aliquots of each of the filtrates were analyzed by ICP-ES to obtain Cr and Cd concentrations.

Sorption of chromium(III) onto MST and APT was compared using an initial chromium concentration, [Cr]_{ini}, of 500 mg L⁻¹ and a contact time of 24 hours. Chromium loading is calculated for each solution of chromium containing 0.01 to 0.86 g (solid weight) of MST or APT and plotted versus the final chromium concentration, [Cr]_{fin} (see Fig. 1). The maximum loading for chromium was determined to be >17.7 mg g⁻¹ for MST and >16.4 mg g⁻¹ for APT. Highest loadings occurred at the highest phase ratio of solution to MST or APT solid. No clear peak maxima are observed for this set of experimental conditions which indicates that higher loadings may be achieved at higher phase ratios.

Figure 1 also indicates that chromium has a slightly higher affinity to APT than it has for MST at lower phase ratios. The difference in affinities gradually decreases as the phase ratio increases. At high phase ratios chromium's affinity for loading onto MST and APT becomes nearly equivalent on a weight basis.

Chromium loading was also probed as a function of initial sorbate concentration. Initial chromium concentrations, $[\text{Cr}]_{\text{ini}}$, of 100 mg L^{-1} and 500 mg L^{-1} were contacted with varying amounts of APT for 7 days. The loading results for these conditions are shown in Figure 2. Loadings for both chromium stock solutions were similar. Slightly higher maximum loadings were observed for $[\text{Cr}]_{\text{ini}} = 500 \text{ mg L}^{-1}$ ($>30.5 \text{ mg/g}$) than for $[\text{Cr}]_{\text{ini}} = 100 \text{ mg L}^{-1}$ ($>23.2 \text{ mg g}^{-1}$) with larger differences observed for low phase ratios and smaller differences observed for higher phase ratios.

$[\text{Cr}]_{\text{fin}}$ are approximately one order of magnitude higher for $[\text{Cr}]_{\text{ini}} = 500 \text{ mg L}^{-1}$ than for $[\text{Cr}]_{\text{ini}} = 100 \text{ mg L}^{-1}$ while the initial concentration is only five times higher. The total amount of chromium absorbed is slightly greater for $[\text{Cr}]_{\text{ini}} = 500 \text{ mg L}^{-1}$ than for $[\text{Cr}]_{\text{ini}} = 100 \text{ mg L}^{-1}$, resulting in a lower percentage of chromium adsorbed. This may indicate that sorption has reached equilibrium after 7 days for $[\text{Cr}]_{\text{ini}} = 100 \text{ mg L}^{-1}$, but not for $[\text{Cr}]_{\text{ini}} = 500 \text{ mg L}^{-1}$. Additional time based measurements are needed for a more detailed kinetic analysis and to ascertain the contact time needed to reach equilibrium for both initial chromium concentrations.

Figure 3 compares the adsorption of chromium(III) and cadmium(II) onto MST after 7 days of contact with solutions containing 100 mg L^{-1} of the appropriate sorbate. MST exhibited a higher affinity for chromium than for cadmium, which is consistent with the results from the initial screening tests containing multiple sorbates. The maximum loading for chromium appears to occur at a higher phase ratio than the measured range under the present set of experimental conditions. A maximum loading for cadmium was observed which was calculated to be 8.7 mg g^{-1} . For a comparison, loading of cadmium onto MST has been previously reported. $[\text{Cd}]_{\text{ini}}$ ranging from $1.12 \mu\text{g L}^{-1}$ to 1.12 g L^{-1}

were tested resulting in loadings ranging from $0.112 \mu\text{g g}^{-1}$ to 106 mg g^{-1} which was fit to a Freundlich isotherm.^[27] Cadmium loadings measured in this work agreed well with those previously reported.

A comparison of sorption of cadmium and chromium onto MST was made plotting the final sorbate concentration versus the amount of solid MST added in grams per liter of solution, Figure 4. This comparison also includes a plot of the maximum contaminant level (MCL) for drinking water as determined by the Environmental Protection Agency (EPA).^[33] MCLs are enforceable standards set and regulated by the EPA. The MCLs for chromium and cadmium are 0.10 mg L^{-1} and 0.005 mg L^{-1} respectively.^[33] This comparison can indicate the relative effectiveness for sorption of cadmium and chromium onto MST. All solutions initially contained 100 mg L^{-1} of chromium or 100 mg L^{-1} of cadmium and were contacted with varying amounts of MST ranging from 1 g L^{-1} to 100 g L^{-1} for 7 days. It was determined that 20 g L^{-1} of MST decreased [Cr] to 0.065 mg L^{-1} (removal of 99.97% of chromium), below the MCL of 0.10 mg L^{-1} . Using the same phase ratio, the final cadmium concentration was determined to be 0.962 mg L^{-1} . Although sorption of cadmium was good, 99.03% removal, the MCL for cadmium (0.005 mg L^{-1}) was not obtained. Additional sorption tests at lower $[\text{sorbate}]_{\text{ini}}$ could determine if MST or APT would be most effective as a primary or secondary treatment for water remediation.

Conclusions

A series of sorption tests were conducted for multiple sorbates to probe the nature and performance of the sorbents monosodium titanate and amorphous peroxy titanate. A

preliminary screening showed high oxidation state ions, +3 or higher, were adsorbed strongly by both MST and APT. Sorption of chromium(III) was highly efficient, displaying the highest decontamination factor (> 2060). Results indicated that sorbates present as anionic complexes were adsorbed less efficiently than cationic sorbates. Sorption of anionic sorbates is postulated to occur through electrostatic interaction with the positively charged titanate surface.

MST and APT sorption performance was evaluated in more detail using the sorbates cadmium(II) and chromium(III). Maximum loadings for chromium(III), $[Cr]_{ini} = 500 \text{ mg L}^{-1}$, onto APT was determined to be $>16.4 \text{ mg g}^{-1}$ with 24 hours of contact time and $>30.5 \text{ mg g}^{-1}$ with 7 days of contact time. MST and APT sorption performance was similar, however, APT performed slightly better at low solvent:sorbate phase ratios. Maximum loading for cadmium occurred between 0.05 g and 0.10 g for $[Cd]_{ini} = 100 \text{ mg L}^{-1}$ with a contact time of 7 days resulting in $[Cd]_{fin} = 0.065 \text{ mg L}^{-1}$ (99.97 % removal) (Fig 3). This is below the maximum contaminant level for chromium (0.10 mg L^{-1}). These sorption experiments show MST and APT can be used as sorbents for materials outside of the radiological arena, potentially as part of a primary or secondary treatment.

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Table I. The concentrations of sorbates for mix A are listed before and after contact with MST or APT for eight days followed by the percentage of sorbates removed from solution and the resulting decontamination factor, defined as the ratio between the initial sorbate concentration and the concentration after contact with the sorbent. Finally, the normalized decontamination factor for APT versus MST is shown comparing MST and APT sorption performance.

Mix A	Initial Conc. (mg/L)	Mix A + MST (mg/L)	Mix A + APT (mg/L)	Mix A + MST % removed	Mix A + APT % removed	Mix A + MST DF	Mix A + APT DF	Mix A NDF ¹
Al³⁺	87.4	9.80	9.14	88.8%	89.5%	8.92	9.56	1.07
B³⁺	109	92.3	87.2	15.3%	20.0%	1.18	1.25	1.06
Ba²⁺	101	36.6	41.9	63.8%	58.5%	2.76	2.41	0.87
Ca²⁺	103	80.5	85.6	21.8%	16.9%	1.28	1.20	0.94
Cd²⁺	105	30.9	58.8	70.6%	44.0%	3.40	1.79	0.53
Co²⁺	104	78.8	70.4	24.2%	32.3%	1.32	1.48	1.12
Cr³⁺	86.7	< 0.042	< 0.042	> 99.95%	> 99.95%	> 2060	> 2060	-
Cu⁺	109	36.8	27.3	66.2%	75.0%	2.96	3.99	1.35
Fe³⁺	0.402	< 0.068	< 0.068	> 83.1%	> 83.1%	> 5.91	> 5.91	-
K⁺	105	89.0	83.3	15.2%	20.7%	1.18	1.26	1.07
La³⁺	103	1.51	1.14	98.5%	98.9%	68.2	90.4	1.32
Li⁺	103	90.2	82.8	12.4%	19.6%	1.14	1.24	1.09
Mg²⁺	102	93.6	81.7	8.2%	19.9%	1.09	1.25	1.15
Mn²⁺	95.4	68.5	40.2	28.2%	57.9%	1.39	2.37	1.70
Ni²⁺	104	79.3	72.6	23.8%	30.2%	1.31	1.43	1.09
P⁵⁺	68.8	18.7	13.6	72.8%	80.2%	3.68	5.06	1.38
Pb²⁺	38.1	1.04	0.758	97.3%	98.0%	36.6	50.3	1.37
Re⁷⁺	104	91.6	87.8	11.9%	15.6%	1.14	1.18	1.04
Sr²⁺	105	63.2	69.4	39.8%	33.9%	1.66	1.51	0.91
V⁵⁺	39.8	< 0.134	< 0.134	> 99.7%	> 99.7%	> 297	> 297	-
Zn²⁺	105	60.6	60.8	42.3%	42.1%	1.73	1.73	1.00

¹NDF is indeterminate for ionic species with MST and APT post contact concentration below the detection threshold.

Table II. The concentrations of cations for mix B are listed before and after contact with MST or APT followed by the percentage of cations removed from solution and the resulting decontamination factor, and normalized decontamination factor for APT versus MST.

Mix B	Initial Conc. (mg/L)	Mix B + MST (mg/L)	Mix B + APT (mg/L)	Mix B + MST % removed	Mix B + APT % removed	Mix B + MST DF	Mix B + APT DF	Mix B NDF ¹
Al³⁺	21.1	1.56	1.28	92.6%	93.9%	13.5	16.5	1.22
B³⁺	24.7	5.37	4.78	78.3%	80.6%	4.60	5.17	1.12
Mo⁶⁺	101	< 0.277	< 0.277	> 99.7%	> 99.7%	> 365	> 365	-
Nb⁵⁺	103	< 0.196	6.03	> 99.8%	94.1%	> 526	17.1	< 0.0325
Pb²⁺	9.32	< 0.205	< 0.205	> 97.8%	> 97.8%	> 45.5	> 45.5	-
S⁶⁺	103	61.5	67.3	40.3%	34.7%	1.67	1.53	0.91
Si⁴⁺	273	17.8	84.5	93.5%	69.0%	15.34	3.23	0.21
Sn⁴⁺	97.8	< 0.362	< 0.362	> 99.6%	> 99.6%	> 270	> 270	-
Ti⁴⁺	113	1.29	230	98.9%	-	87.6	-	-
Zr⁴⁺	109	1.92	0.995	98.2%	99.1%	56.8	110	1.93

¹NDF is indeterminate for ionic species with MST and APT post contact concentration below the detection threshold.

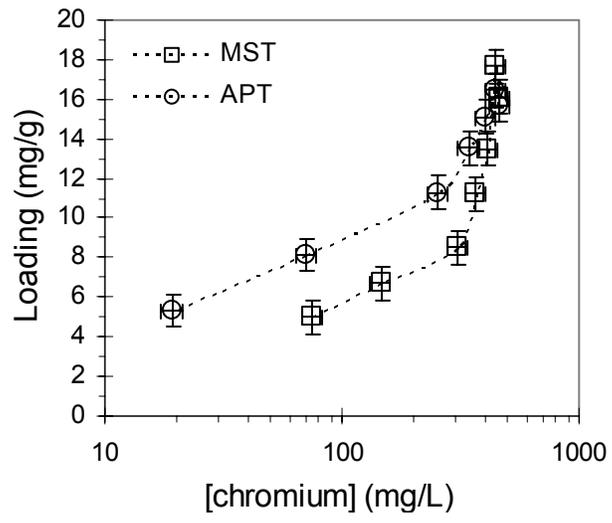


Figure 1.

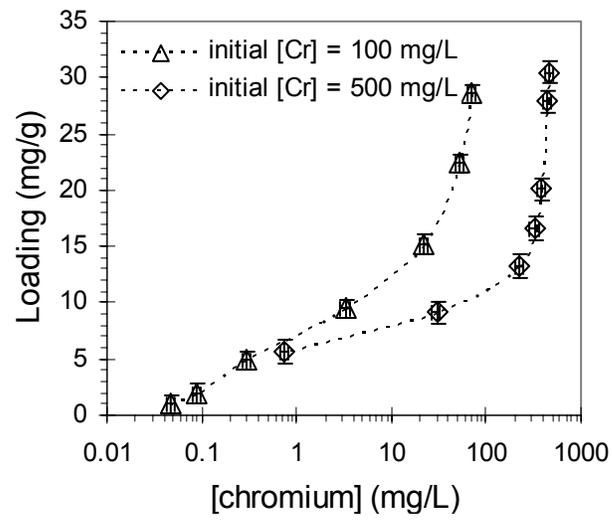


Figure 2.

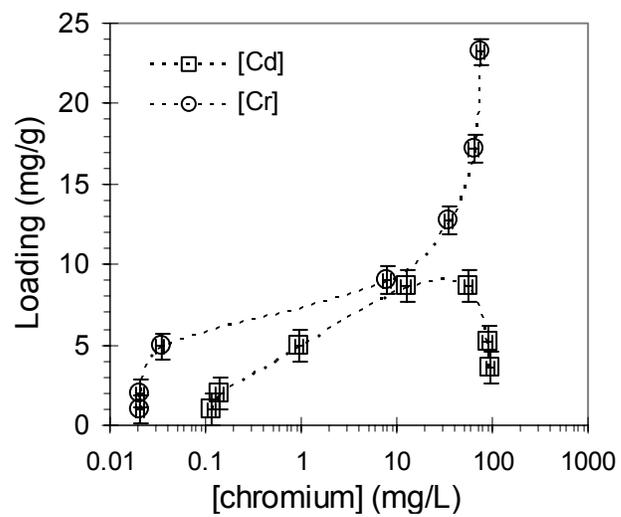


Figure 3.

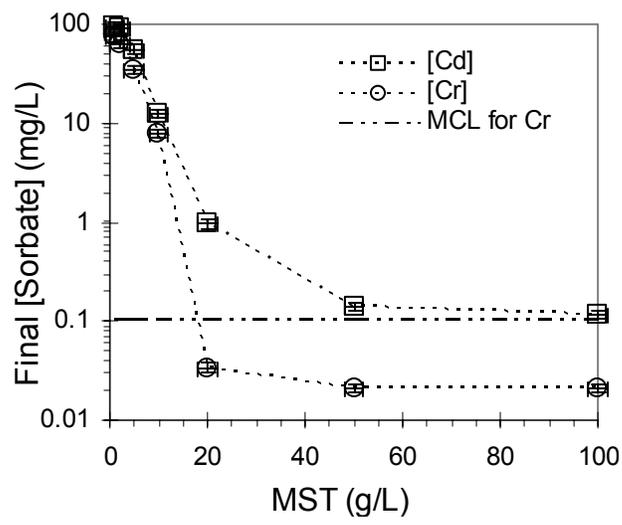


Figure 4.

Table I. The concentrations of sorbates for mix A are listed before and after contact with MST or APT for eight days followed by the percentage of sorbates removed from solution and the resulting decontamination factor, defined as the ratio between the initial sorbate concentration and the concentration after contact with the sorbent. Finally, the normalized decontamination factor for APT versus MST is shown comparing MST and APT sorption performance.

Table II. The concentrations of cations for mix B are listed before and after contact with MST or APT followed by the percentage of cations removed from solution and the resulting decontamination factor, and normalized decontamination factor for APT versus MST.

Figure 1. Chromium loading onto MST and APT with an $[Cr]_{ini} = 500 \text{ mg L}^{-1}$, a contact time of 24 hours, and sorbent phase ratios ranging from 1 g L^{-1} to 100 g L^{-1} . Chromium loading is the amount of sorbate sorbed in milligrams per gram of MST or APT sorbent plotted versus the final sorbate concentration.

Figure 2. Chromium loading onto APT with $[Cr]_{ini} = 100 \text{ mg L}^{-1}$ and 500 mg L^{-1} , a contact time of 7 days and sorbent phase ratios ranging from 1 g L^{-1} to 100 g L^{-1} . Chromium loading is the amount of sorbate adsorbed in milligrams per gram of APT sorbent plotted versus the final sorbate concentration.

Figure 3. Cadmium and chromium loading onto MST with $[Cr]_{ini} = [Cd]_{ini} = 100 \text{ mg L}^{-1}$, a contact time of 7 days, and sorbent phase ratios ranging from 1 g L^{-1} to 100 g L^{-1} . Cadmium and chromium loading, which is the amount of sorbate adsorbed in milligrams per gram of MST sorbent, is plotted versus the final sorbate concentration.

Figure 4. Final sorbate concentration of cadmium and chromium is plotted versus the amount of solid MST added in grams per liter. The maximum contaminant level (MCL) for chromium is also plotted, a standard set and regulated by the EPA for drinking water. Initial cadmium and chromium concentration was 100 mg L^{-1} and the contact time was 7 days.