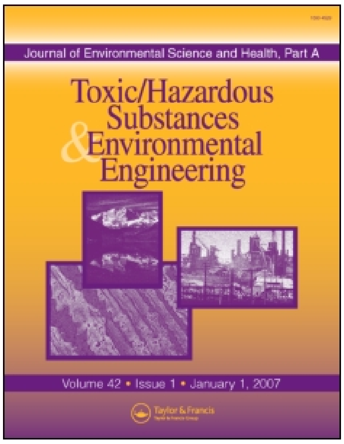
This article was downloaded by: *[National Taiwan University]*
On: *16 December 2008*
Access details: *Access Details: [subscription number 788846425]*
Publisher *Taylor & Francis*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of Environmental Science and Health, Part A
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597268

Regeneration and Reuse of Water Treatment Plant Sludge: Adsorbent for Cations

Chung-Hsin Wu [a]; Cheng-Fang Lin [b]; Wan-Ru Chen [b]
[a] Department of Environmental Engineering and Health, Yuanpei University of Science and Technology, Hsinchu, Taiwan, ROC [b] Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan, ROC

Online Publication Date: 01 January 2005

To cite this Article Wu, Chung-Hsin, Lin, Cheng-Fang and Chen, Wan-Ru(2005)'Regeneration and Reuse of Water Treatment Plant Sludge: Adsorbent for Cations',Journal of Environmental Science and Health, Part A,39:3,717 — 728

To link to this Article: DOI: 10.1081/ESE-120027737

URL: http://dx.doi.org/10.1081/ESE-120027737

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

JOURNAL OF ENVIRONMENTAL SCIENCE AND HEALTH
Part A—Toxic/Hazardous Substances & Environmental Engineering
Vol. A39, No. 3, pp. 717–728, 2004

Regeneration and Reuse of Water Treatment Plant Sludge: Adsorbent for Cations

Chung-Hsin Wu,[1,]* Cheng-Fang Lin,[2] and Wan-Ru Chen[2]

[1]Department of Environmental Engineering and Health, Yuanpei University of Science and Technology, Hsinchu, Taiwan, ROC
[2]Graduate Institute of Environmental Engineering, National Taiwan University, Taipei, Taiwan, ROC

ABSTRACT

This study applies sintering technology to convert water sludge to a useful and stable adsorption material. The properties of the sintered materials were characterized using SEM and BET. Additionally, adsorption experiments were conducted to elucidate interactions of Cr(III) and Hg(II) at the interface between water and sintered material. Elemental analysis of original water sludge indicates its main constituents to be SiO_2 (54%), Al_2O_3 (21%), and Fe_2O_3 (6.6%). The BET measurement indicated that the specific surface area of the sintered material is 4.6 m^2/g. Since the SiO_2 content exceeds 50%, the surface of the sintered material becomes negatively charged. Adsorption of Cr(III) and Hg(II) on sintered material shows that sorption depends on the systems' pH. The sorption densities are 1.40 mg Cr/g at equilibrium pH 4.6 and 0.43 mg Hg/g at equilibrium pH 6.0. Background electrolyte does not affect the sorption of Cr(III) but markedly affects the sorption of Hg(II). The affinity of Cr(III) for surface reacting sites seem to exceed that of Hg(II). Competitive adsorption experiments were performed to determine the magnitude of the variations in adsorption due to

---

*Correspondence: Chung-Hsin Wu, Department of Environmental Engineering and Health, Yuanpei University of Science and Technology, 306 Yuanpei St., Hsinchu 300, Taiwan, ROC; Fax: 886-3-5385353; E-mail: chwu@mail.yust.edu.tw.

DOI: 10.1081/ESE-120027737
1093-4529 (Print); 1532-4117 (Online)
www.dekker.com

competitive interactions among Cr(III) and Hg(II). The experimental results indicate that a higher competitive solute concentration results in a more significant competitive effect on Hg(II).

Key Words: Cr(III); Hg(II); Water treatment plant sludge; Sinter; Adsorption.

INTRODUCTION

Water treatment plant sludge left after water clarification contains the impurities filtered out of the water and the chemicals added for clarification. More than 2.4×10^7 tons (70% wt.) water treatment plant sludge is generated each year in Taiwan. Due to the shortage of landfill sites, disposal of waste has gained much concern in Taiwan in recent years. Although the heavy metals leaching potency of the water treatment plant sludge could meet the toxicity characteristic leaching procedure (TCLP) standard usually, its disposal directly to landfill in Taiwan could not meet the trend of resource recovery policy.

Recycling the water treatment plant sludge is usually an attempt to reduce its volume, make it harmless and stable, recover useful contents and facilitate its safe disposal without imposing burden to environment. Transforming waste into useful materials requires that its chemical characteristics be investigated and the cost of its reuse be reduced to increase resultant products' competitiveness in the marketplace. The water treatment plant sludge left after water clarification contains mainly inorganic and stable substances, such as Si, Ca, Fe, and Al, and much colloidal earth materials. The problem of disposal can be solved, the life of waste disposal facilities increased, and the demand for natural resources reduced by transforming the water treatment plant sludge into reusable substance.

The purity of the coagulants recovered from clarifier sludge may not be sufficient to justify their reuse in potable water operations.[1] Therefore, a new ion exchange process was further explored for selective removal, separation, and recovery of Fe(III) and Al(III) species from the clarifier sludge.[2] Trance metals present in the clarifier sludge are recovered and safely disposed in landfill. Sewage sludge was a valuable resource and that could be reused as soil conditioner.[3] Sewage sludge also could be stabilized by pulverized fuel ash and the product was recycled into a material for land reclamation, as a soil conditioner and as cover material for landfill.[4] The wastewater sludge reuse ways in South Australia included using in woodlots, brick-making, landscaping, and mine site rehabilitation.[5] Liaw et al.[6] employed granulation and sintering techniques to make the paper sludge into constructional bricks. Bricks containing 10% tannery sludge can be used safely and the properties of ceramic materials are acceptable.[7] Wastewater sludge and sludge ash can be used in the production of bricks or can be as a replacement to the bricks production.[8–12] Bricks made of 50% wt. harbour sediments at a temperature of 1050°C thermal treatment lead to an immobilization of most trace contaminants.[13] Alum sludge can be reused to remove heavy metal in wastewater and reduce the fresh alum dosage.[14] Different techniques have been applied to reuse sludge and also to solve the problem of insufficient landfill sites. However, there is no work to reuse sludge as adsorbent. Therefore, this study employs the sintering process to treat sludge and reuse it in wastewater treatment.

Adsorbents are increasingly substituted by natural by-products or stabilized solid materials to develop cost-effective composite adsorbents that can treat various contaminants. Water treatment plant sludge contains only few organic substances but much colloid, and is thus very suitable for sintering. According to Nowok et al.,[15] the high pressure and temperature during sintering alter the crystalline phase of the sludge, and the colloids to metal oxides. Sintering the water treatment plant sludge is a process of stabilization that reduces the probability that the water treatment plant sludge releases harmful substances when it is recycled. This work employs the sinter produced by sintering water treatment plant sludge at high temperature as an adsorbent, to elucidate the adsorption of cations on the surface of the sinter. The experiments include adsorption of Cr(III) and Hg(II) by water treatment plant sludge and sintered material. Furthermore, the competitive adsorption of Cr(III) and Hg(II) and the adsorption density of cation on the sintered material was also investigated. This study provides some insight into the interactions among Cr(III), Hg(II), and sintered material. The objective of this study is to transform the water treatment plant sludge into a resource and reuse it for treating wastewater containing toxic ions.

MATERIALS AND METHODS

Preparation and Purification of Adsorbent

The water treatment plant sludge used in this research was obtained from Taipei Chih-Tan Water Treatment Plant. The composition of the water treatment plant sludge is analyzed using inductively coupled plasma atomic emission spectroscopy (ICP-AES). The sludge was smashed and ground first. Then the ground water treatment plant sludge was placed in an oven and dried to a constant mass. Approximately 5 wt% water was used as a binder in the ground sludge powder, which was mixed evenly. Then 10.9 MPa of forming pressure was applied and the sludge was heated at 1000°C for 1.5 h.

The sintered material is ground and sieved through a #200 sieve to obtain the adsorbent used in this study. The excess salts on the surface must be removed with deionized water since various function groups on the surface of the sinter might affect its capacity to adsorb. Accordingly, the filtered sinter is mixed with deionized water (D. I. Water, Milli-Q) and, after the mixture, the subsided sludge is washed to remove the excess salts by reverse osmosis. It is then soaked with a large quantity of deionized water. The deionized water is occasionally renewed during the process. The washing is complete when the electrical conductivity of the water for washing the sintered powder equals that of the deionized water. The washed sinter is removed from the reverse osmosis. It is placed in an oven and dried at 103°C. The adsorbent used in this study is thus prepared.

The specific surface areas of the water treatment plant sludge and the sintered material, determined by the N_2 Brunauer-Emmett-Teller sorption experiments, are 30.5 and 4.6 m^2/g, respectively.

Adsorption Experiments

The chemicals used in this research are all reagent grade. The 1 mM Cr(III) stock solution is prepared with $CrCl_3$; the 0.2 mM Hg(II) stock solution is prepared with $HgCl_2$. The 1 N background electrolyte resolution is prepared with NaCl.

The experiment on the equilibrium adsorption of cations is conducted in a 100 mL plastic bottle. The concentration of the adsorbent during the test is 5 g/L, while the concentration of Cr(III) and Hg(II) is 40 and 2 μM, respectively. The pH values are controlled using 1 N NaOH and 1 N HCl. The concentration of the background electrolyte is controlled with NaCl at 0.1 N, 0.01 N, and 0.001 N. Solution containing cations and adsorbent are then equilibrated for 20 h at 25°C and shaked at 200 rpm. In the competitive adsorption experiments, Hg(II) (2 μM) was equilibrated with the sintered material (5 g/L), and the concentrations of competitive solutes (Cr(III)) were between 40 and 400 μM. A little HCl or NaOH was added to cover the pH range from 2 to 8 for the reactions. The pH values of all the samples that reach equilibrium are measured and the samples are then put into a centrifuge for 10 min at 3000 rpm. A 0.2 μm filter membrane (Gelman Sciences) is then used to filter the supernatant. The concentration of Cr(III) and Hg(II) is measured using AA (Atomic Adsorption, Perkin Elmer 5000).

RESULTS AND DISCUSSION

Composition of the Water Treatment Plant Sludge

The composition of the water treatment plant sludge is shown in Table 1. The water treatment plant sludge contains mainly SiO_2, representing approximately 54% of the total content of the water treatment plant sludge. The other substances in the water treatment plant sludge are Al_2O_3 and Fe_2O_3, in percentage order.

Table 1. Characterization of the water treatment plant sludge.

Component	Percentage (wt. %)
SiO_2	53.6
Al_2O_3	20.9
Fe_2O_3	6.6
MgO	1.9
CaO	0.3
PbO_2	0.2
CuO	<0.1
ZnO	<0.1
Cr_2O_3	<0.1
CdO	<0.1

The specific surface area of the sintered material ($4.6\,m^2/g$) is smaller than the water treatment plant sludge ($30.5\,m^2/g$), because the gaps between the particles are filled by the particles' neck growth between them that makes the sinter finer. This work aims to make the gaps between such particles finer and, consequently, prevent the dissolution of a harmful substance during the adsorption process.

Adsorption Envelope of Cr(III) and Hg(II) onto Water Treatment Plant Sludge

Figure 1 presents the adsorption envelope of Cr(III). The adsorption percentage increases with pH, because the number of active sites of positive charge on the surface of the oxide is higher at a lower pH, reducing the tendency of cations to adsorb onto the surface.

Figure 1 depicts the adsorption envelope of Hg(II). The adsorption percentage exceeds 90% when equilibrium $pH < 6.5$. Unlike that of the cations, the adsorption percentage of Hg(II) does not increase, but declines slightly as pH increases. Adhesion between Hg(II) and the organic substance in the water treatment plant sludge may exceed that caused by the electrical attraction between Hg(II) and the surface of the water treatment plant sludge. Therefore, the adsorption percentage does not decline due to fewer negatively charged sites on the surface of the oxide when the pH is low.

The adsorption density of Cr(III) and Hg(II) onto water treatment plant sludge at equilibrium $pH = 5$ is $2.62 \times 10^{-4}\,mmol/m^2$ and $1.31 \times 10^{-5}\,mmol/m^2$. This result shows that the affinity of Cr(III) on the surface of sludge is higher than Hg(II).

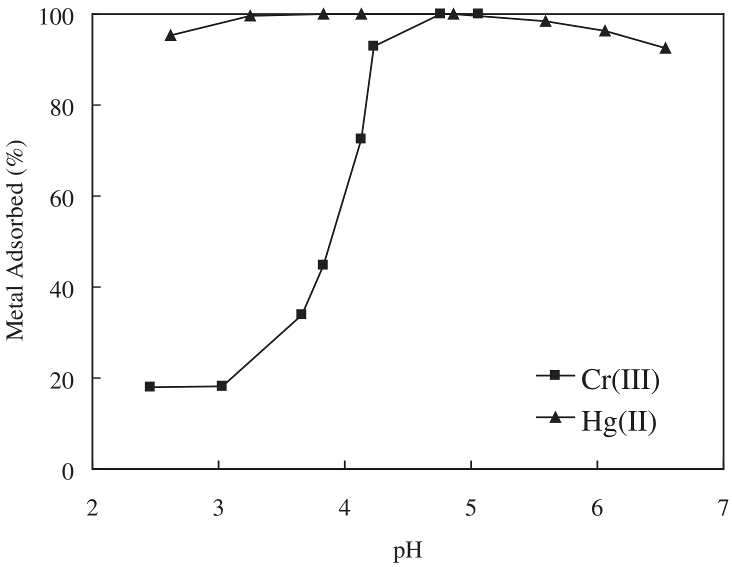


Figure 1. Adsorption of Cr(III) and Hg(II) by water treatment plant sludge as a function of pH ($[Cr(III)]_T = 40\,\mu M$, $[Hg(II)]_T = 2\,\mu M$, adsorbent = 5 g/L, and 25°C).

Adsorption of Cr(III) and Hg(II) onto the Sintered Material

The adsorption percentage of Cr(III) increases with the pH (Fig. 2a), revealing that the number of deprotonated sites on the surface of the sinter increases with the pH, facilitating the adsorption of the cations. As Fig. 2a shows, the background electrolyte (NaCl) does not clearly affect the adsorption of Cr(III), perhaps because the o-plane complex reaction of Cr(III) is not influenced by the β-plane complex reaction of the background electrolyte (Na^+ and Cl^-). Csoban and Joo[16] stated that Cr(III) adsorbs onto silica gel in the form of $Cr(OH)^{2+}$, which is an inner-sphere complex. Chang et al.[17] found that Cr(III) adsorbs on the surface of γ-Al_2O_3 as

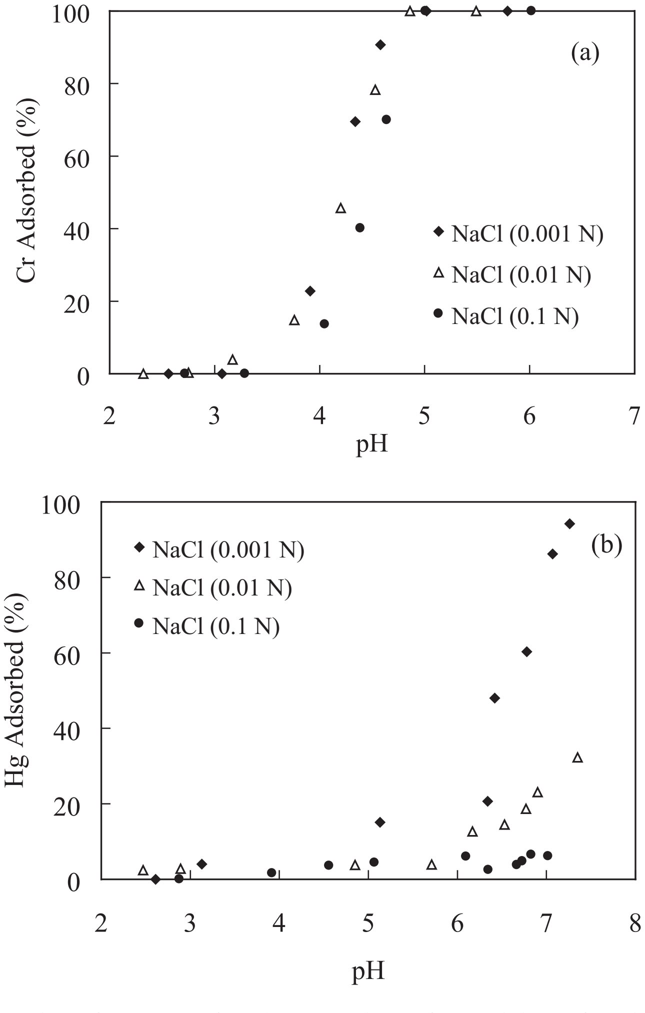


Figure 2. Adsorption of Cr(III) and Hg(II) onto sintered material as a function of pH under various background NaCl concentrations (a) $[Cr(III)]_T = 40\,\mu M$, adsorbent = 5 g/L, and 25°C; (b) $[Hg(II)]_T = 2\,\mu M$, adsorbent = 5 g/L, and 25°C.

co-existent Cr^{3+} and $Cr(OH)^{2+}$. Cr^{3+} forms an inner-sphere bidentate complex and $Cr(OH)^{2+}$ forms an inner-sphere monodentate complex on the surface of γ-Al_2O_3. The sinter includes large amounts of silica and Al_2O_3; therefore, its adsorption is similar to that elucidated in previous research, forming inner-sphere complexes on the surface.

The adsorption percentage of Hg(II) increases with the pH (Fig. 2b). As shown in Fig. 2b, the background electrolyte clearly influences the adsorption, implying that Hg(II) may form a β-plane complex that is similar to an ion pair on the surface of the sinter. Melamed and Villas Boas[18] claimed that the presence of the chloride anion increases the mobility of Hg(II) through the soil, since mercury chloride has a relatively low affinity at the oxide surface. In the absence of chloride, Hg(II) forms strong complexes with the surface and its adsorption behavior is consistent with the adsorption of other hydrolyzable cations.

The adsorption density of Cr(III) and Hg(II) on the sintered material at equilibrium $pH = 5$ is 1.74×10^{-3} and $1.31 \times 10^{-5}\,mmol/m^2$. In Cr(III)/adsorbent systems, the sintered material ($1.74 \times 10^{-3}\,mmol/m^2$) shows a greater adsorption density than the water treatment plant sludge ($2.62 \times 10^{-4}\,mmol/m^2$). In Hg(II)/adsorbent systems, the adsorption density of sintered material and the water treatment plant sludge is nearly the same ($1.31 \times 10^{-5}\,mmol/m^2$). The results indicated that the sintering process does not decline the activity sites of the surface. At equilibrium $pH = 5$, the adsorption density of Cr(III) on γ-Al_2O_3, amorphos silica gel, and acid Al_2O_3 is $7.50 \times 10^{-4}\,mmol/m^2$, $2.78 \times 10^{-6}\,mmol/m^2$, and $2.51 \times 10^{-5}\,mmol/m^2$, respectively.[16,17] The sintered material performs a better efficiency for Cr(III) removal than other oxides. The variances in the adsorption density for each oxide might be due to differences in laboratory conditions (e.g., adsorbate/adsorbent ratio) and adsorbate affinity for different oxide surface.

The Cr(III) adsorption isotherm is determined at equilibrium $pH = 4.6 \pm 0.2$. The adsorption capacity of Cr(III) is simulated by Freundlich and Langmuir isotherms. The simulation shows that the Cr(III)/sinter system is saturated and so cannot further adsorb ions. This observation reveals that initially, a high affinity exists between Cr(III) and the sinter, and the remaining Cr(III) is not adsorbed onto the surface of the sinter when the adsorption sites are slowly filled. Figure 3a shows that the Freundlich isotherm is not suitable for use in the simulation. Q_m (maximum capacity of adsorption) = 1.40 (mg/g) and K (Langmuir constant) = 1.62 (L/mg) are determined in the simulation that used the Langmuir isotherm, and the experimental results are consistent with the simulated curve.

The Hg(II) adsorption isotherm is determined at equilibrium $pH = 6.0 \pm 0.2$. The adsorption capacity of the Hg(II) is also simulated using Freundlich and Langmuir isotherms (Fig. 3b). Like Cr(III), the sinter is saturated and cannot adsorb more ions under the experimental conditions. A significant difference exists between the results of the simulation used by the Freundlich isotherm and the corresponding experiment. The simulation conducted using the Langmuir isotherm yields Q_m (maximum capacity of adsorption) = 0.43 (mg/g) and K (Langmuir constant) = 4.3×10^{-4} (L/mg).

Monser and Adhoum[19] treated wastewater with modified activated carbon and obtained an adsorption capacity of 6.84 mg Cr/g adsorbent. Zhang and Bishop[20] used reactivated carbon to adsorb mercury and their result matched that obtained

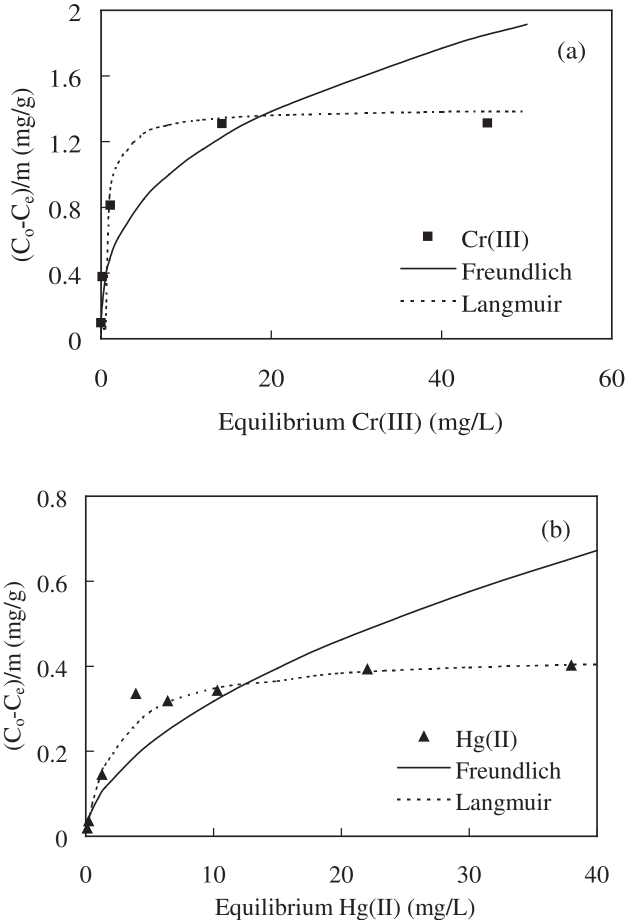


Figure 3. Cr(III) and Hg(II) adsorption isotherm by sintered material (a) Cr(III), adsorbent = 5 g/L, equilibrium pH = 4.6 ± 0.2, and 25°C; (b) Hg(II), adsorbent = 5 g/L, equilibrium pH = 6.0 ± 0.2, and 25°C.

with the Freundlich isotherm. The aforementioned studies show that the adsorption capacity and adsorption isotherms are different for different adsorbents. The capacity of the sinter to adsorb Cr, as determined in this study is not as high as that of the modified activated carbon. Its capacity to adsorb Hg is not as high as that of used tire rubber.[21] However, with reference to recycling, the adsorbent considered in this research can remove Cr and Hg without dissolving environmentally harmful heavy metals.

Competitive Adsorption of Cr(III) and Hg(II)

The mobility of cations in the environment is typically regulated by adsorption at the solid/water interface and by competition among various cation species for surface binding sites. The strength of these competitive interactions must be determined to predict the water treatment efficiency. Theoretically, multi-component mixture competition involves increasingly complex ion interactions at the water/oxide interface. Many complex systems exist, and the strength of these competitive interactions must be clarified to better predict the behavior of contaminants. This study seeks to examine the competitive adsorption of Cr(III) and Hg(II) at different concentration ratios.

Figures 4a–c presents the results of experiments to determine the competitive adsorption of Cr(III) and Hg(II) as a function of pH. Notably, when Cr(III) and

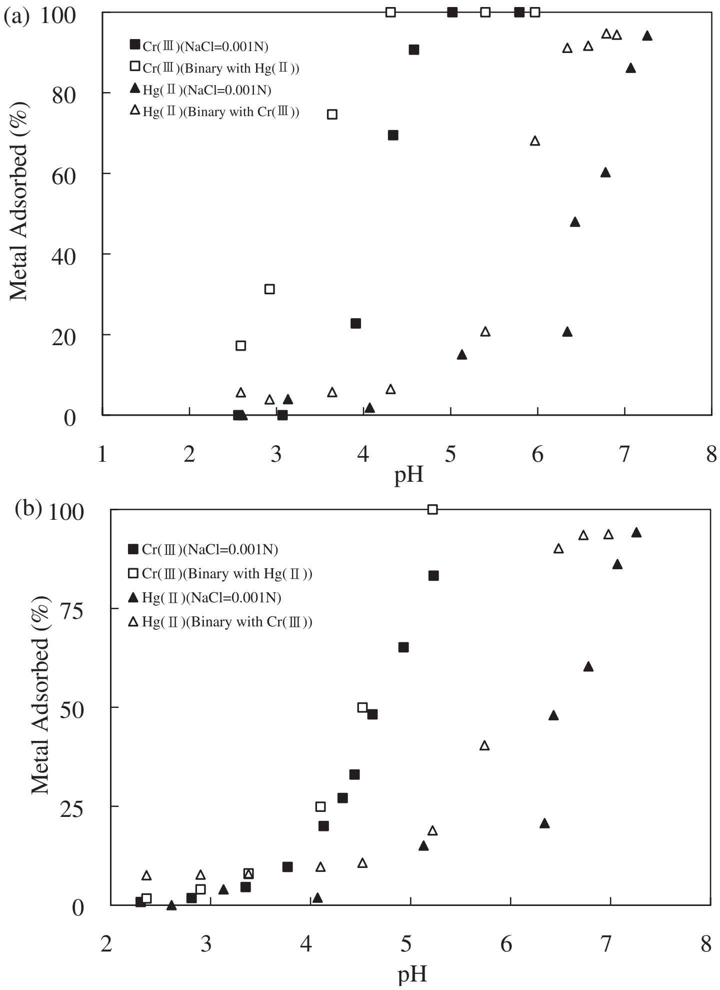


Figure 4. Competitive adsorption envelope of Cr(III) and Hg(II) onto sintered material (a) $[\mathrm{Cr(III)}]_T = 40\,\mu\mathrm{M}$, $[\mathrm{Hg(II)}]_T = 2\,\mu\mathrm{M}$, adsorbent = 5 g/L, and 25°C; (b) $[\mathrm{Cr(III)}]_T = 100\,\mu\mathrm{M}$, $[\mathrm{Hg(II)}]_T = 2\,\mu\mathrm{M}$, adsorbent = 5 g/L, and 25°C; (c) $[\mathrm{Cr(III)}]_T = 400\,\mu\mathrm{M}$, $[\mathrm{Hg(II)}]_T = 2\,\mu\mathrm{M}$, adsorbent = 5 g/L, and 25°C. *(continued)*

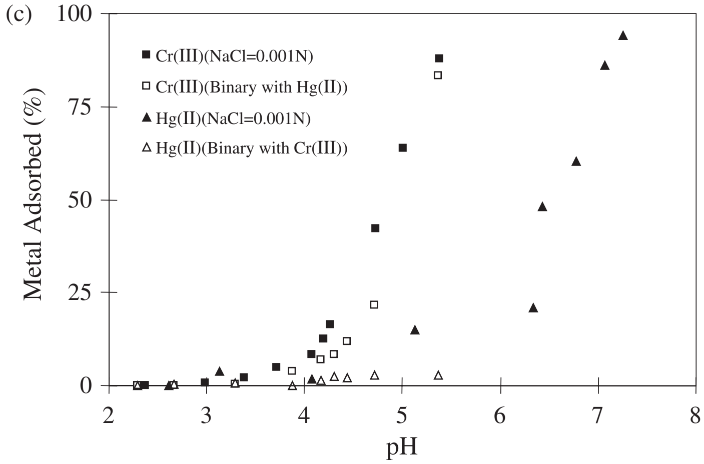


Figure 4. Continued.

Hg(II) were added alone, more Cr(III) than Hg(II) was adsorbed in the range of pH 2–8. When Cr(III) and Hg(II) ions were added to form a mixture, more Cr(III) than Hg(II) was adsorbed on the surface of sintered material over the range of pH values studied, but the percentage of Cr(III) and Hg(II) adsorbed in the binary system exceeded that in the single-adsorbate system (Fig. 4a), perhaps because the sites on the sintered material surface have a stronger affinity for Cr(III) than for Hg(II). The competition between two cations for a given surface site depends on the strength and type of binding between the cation and the surface. Hg(II) does not affect the adsorption of Cr(III), implying that the binding of Cr(III) (inner sphere complex) was stronger than that of Hg(II) (outer-sphere complex). The other reason for such results may) be that the maximum capacity of adsorption (Q_m) of Cr(III) (1.40 mg/g) exceeds that of Hg(II) (0.43 mg/g). However, the adsorption of Cr(III) and Hg(II) increased considerably in the binary-system, perhaps because the concentration of the competitive adsorbate is far lower than the concentration of the background electrolyte (0.001 N). Accordingly, the competition for adsorption sites is insignificant at low adsorbate concentration. Figures 4a–c also indicate that a higher competitive solute concentration results in a more significant competitive effect on Hg(II), implying that increasing the competitive adsorbate concentration enhances the opportunity for the competitive adsorbate to occupy the binding sites on the surface of the adsorbent. Hence, the adsorbent surface tended to be more positively charged than the original surface and resisted the adsorption of Hg(II) onto the sintered material.

CONCLUSION

The water treatment plant sludge left after water clarification contains various metal oxides. Recycling it by sintering can effectively prevent the release of harmful substances in the water treatment plant sludge to the environment. Sintering and reuse not only solves the problem of water treatment plant sludge disposal but also reduces the consumption of natural resources. The adsorption capacity of the sintered material for Cr(III) is 1.40 mg/g at equilibrium $\mathrm{pH} = 4.6 \pm 0.2$, and 0.43 mg/g for Hg(II) at equilibrium $\mathrm{pH} = 6.0 \pm 0.2$. Cr(III) forms an o-plane complex and is not influenced by the background electrolyte, while Hg(II) forms a β-plane complex and is affected by the background electrolyte. The pH ranges for Cr(III) and Hg(II) adsorption are $3 \sim 5$ and $5 \sim 7$, respectively. The adsorption of both Cr(III) and Hg(II) increases with the pH. Competitive adsorption experiments were conducted to determine the magnitude of concentration variations in adsorption due to competitive interactions between Cr(III) and Hg(II), introduced to a system in binary mixtures. The results indicate that a higher competitive solute concentration addition results in a more significant competitive effect on Hg(II). These observations provide valuable information concerning the treatment of wastewater using an unconventional adsorbent, water treatment plant sludge sinter, as a cost-effective substitute for the classical hydrous-oxide adsorbents, such as silica, alumina, and ferric oxides.

ACKNOWLEDGMENTS

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 90-2211-E002-038.

REFERENCES

1. Sengupta, A.K.; Bo, S. Selective alum recovery from clarifier sludge. Journal of the American Water Works Association **1992**, *84*, 96–103.
2. Petruzzelli, D.; Volpe, A.; Limoni, N.; Passino, R. Coagulants removal and recovery from water clarifier sludge. Water Research **2000**, *34*, 2177–2182.
3. Kuai, L.; Doulami, F.; Verstraete, W. Sludge treatment and reuse as soil conditioner for small rural communities. Bioresource Technology **2000**, *73*, 213–219.
4. Dirk, G. Pulverised fuel ash products solve the sewage sludge problems of the wastewater industry. Waste Management **1996**, *16*, 51–57.
5. Kayaalp, N.M. Regulatory framework in South Australia and reclaimed water reuse options and possibilities. Desalination **1996**, *106*, 317–322.
6. Liaw, C.T.; Chang, H.L.; Hsu, W.C.; Huang, C.R. A novel method to reuse paper sludge and co-generation ashes from paper mill. Journal of Hazardous Materials **1998**, *58*, 93–102.
7. Basegio, T.; Berutti, F.; Bernardes, A.; Bergmann, C.P. Environmental and technical aspects of the utilization of tannery sludge as a raw material for clay products. Journal of European Ceramic Society **2002**, *22*, 2251–2259.

8. Anderson, M.; Skerratt, R.G.; Thomas, J.P.; Clay, S.D. Case study involving using fluidized bed incinerator sludge ash as a partial clay substitute in brick manufacture. Water Science and Technology **1996**, *34*, 507–515.
9. Okuno, N.; Takahashi, S. Full scale application of manufacturing bricks from sewage. Water Science and Technology **1997**, *36*, 243–250.
10. Tay, J.H.; Show, K.Y. Resource recovery of sludge as a building and construction material—a future trend in sludge management. Water Science and Technology **1997**, *36*, 259–266.
11. Wiebusch, B.; Seyfried, C.F. Utilization of sewage sludge ashes in the brick and tile industry. Water Science and Technology **1997**, *36*, 251–258.
12. Wiebusch, B.; Ozaki, M.; Watanabe, H.; Seyfried, C.F. Assessment of leaching tests on construction material made of incinerator ash (sewage sludge): investigations in Japan and Germany. Water Science and Technology **1998**, *38*, 195–205.
13. Karius, V.; Hamer, K. pH and grain-size variation in leaching tests with bricks made of harbour sediments compared to commercial bricks. The Science of the total Environment **2001**, *278*, 73–85.
14. Chu, W. Lead metal removal by recycled alum sludge. Water Research **1999**, *33*, 3019–3025.
15. Nowok, J.W.; Benson, S.A.; Jones, M.L.; Kalmanovitch, D.P. Sintering behavior and strength development in various coal ashes. Fuel **1990**, *69*, 1020–1028.
16. Csoban, K.; Joo, P. Sorption of Cr(III) on silica and aluminium oxide: experiments and modeling. Colloids and Surfaces A: Physicochemical and Engineering Aspects **1999**, *151*, 97–112.
17. Chang, K.S.; Lin, C.F.; Lee, D.Y.; Lo, S.L.; Yasunaga, T. Kinetic of Cr(III) adsorption/desorption at the γ-Al_2O_3/water interface by the pressure-jump technique. Journal of Colloid and Interface Science **1994**, *165*, 169–176.
18. Melamed, R.; Villas Boas, R.C. Phosphate-background electrolyte interaction affecting the transport of mercury through a Brazilian oxisol. The Science of the total Environment **1998**, *213*, 151–156.
19. Monser, L.; Adhoum, N. Modified activated carbon for the removal of copper, zinc, chromium, and cyanide from wastewater. Separation and Clarification Technology **2002**, *26*, 137–146.
20. Zhang, J.; Bishop, P.L. Stabilization/solidification (S/S) of mercury-containing wastes using reactivated carbon and Portland cement. Journal of Hazardous Materials **2002**, *92*, 199–212.
21. Meng, X.; Hua, Z.; Dermatas, D.; Wang, W.; Kuo, H.Y. Immobilization of mercury(II) in contaminated soil with used tire rubber. Journal of Hazardous Materials **1998**, *57*, 231–241.

Received September 2, 2003

Downloaded By: [National Taiwan University] At: 03:21 16 December 2008

Request Permission or Order Reprints Instantly!

Interested in copying and sharing this article? In most cases, U.S. Copyright Law requires that you get permission from the article's rightsholder before using copyrighted content.

All information and materials found in this article, including but not limited to text, trademarks, patents, logos, graphics and images (the "Materials"), are the copyrighted works and other forms of intellectual property of Marcel Dekker, Inc., or its licensors. All rights not expressly granted are reserved.

Get permission to lawfully reproduce and distribute the Materials or order reprints quickly and painlessly. Simply click on the "Request Permission/ Order Reprints" link below and follow the instructions. Visit the U.S. Copyright Office for information on Fair Use limitations of U.S. copyright law. Please refer to The Association of American Publishers' (AAP) website for guidelines on Fair Use in the Classroom.

The Materials are for your personal use only and cannot be reformatted, reposted, resold or distributed by electronic means or otherwise without permission from Marcel Dekker, Inc. Marcel Dekker, Inc. grants you the limited right to display the Materials only on your personal computer or personal wireless device, and to copy and download single copies of such Materials provided that any copyright, trademark or other notice appearing on such Materials is also retained by, displayed, copied or downloaded as part of the Materials and is not removed or obscured, and provided you do not edit, modify, alter or enhance the Materials. Please refer to our Website User Agreement for more details.

Request Permission/Order Reprints

Reprints of this article can also be ordered at
http://www.dekker.com/servlet/product/DOI/101081ESE120027737