

# Trace Elements Leaching from Organic Soils Stabilized with High Carbon Fly Ash

Jacob J. Sauer<sup>1</sup>; Craig H. Benson, F.ASCE<sup>2</sup>; Ahmet H. Aydilek, M.ASCE<sup>3</sup>; and Tuncer B. Edil, F.ASCE<sup>4</sup>

**Abstract:** Leaching of four trace elements [cadmium (Cd), chromium (Cr), selenium (Se), and silver (Ag)] from soft organic soils stabilized with high carbon fly ashes (HCFAs) was assessed using water leach tests (WLTs) and column leach tests (CLTs) on soil alone, fly ash alone, and soil-fly ash mixtures. Concentrations from the WLTs on soil-fly ash mixtures were lower than concentrations from the WLTs on fly ash alone, and were controlled more by the fly ash than the soil. However, dilution calculations based on tests on soil alone and fly ash alone were unreliable. Thus, leaching assessments should be conducted directly on soil-fly ash mixtures. Leaching patterns from the CLTs followed first-flush and lagged-response patterns with comparable frequency, although first-flush patterns were more common with fly ash with higher calcium oxide content. Cd and Cr exhibited first-flush leaching more frequently, Ag a lagged-response pattern more frequently, and Se exhibited first-flush or lagged-response patterns with similar frequency. The hydrogen ion concentration (pH) had a strong effect on leaching concentrations, with lower concentrations of Ag and Cd and higher concentrations of Cr at a higher pH. Peak concentrations of Ag and Cd for flow-through conditions can conservatively be estimated as 50 times the WLT concentration, whereas a factor of 100 should be applied for Cr and Se for organic soil-HCFA mixtures. DOI: 10.1061/(ASCE)GT.1943-5606.0000653. © 2012 American Society of Civil Engineers.

**CE Database subject headings:** Soils; Fly ash; Trace elements; Leaching.

**Author keywords:** Organic soil; Fly ash; Coal combustion products; CCPs; Stabilization; Trace elements; Leaching; Sustainability.

## Introduction

Fly ash is a silt-size particulate collected by air pollution control systems at coal-fired electric power plants. Approximately 24% of fly ash is used in production of Portland cement (PC) or in PC concrete (Benson et al. 2010). However, some fly ashes contain significant amounts of unburned carbon and cannot be used as a concrete additive because of interactions with air entrainment agents. These high carbon fly ashes (HCFAs) generally are disposed in landfills (Hodges and Keating 1999). However, many HCFAs have cementitious properties that may be useful in other applications. For example, Edil et al. (2006) and Tastan et al. (2011) indicate that HCFAs can be effective in stabilizing soft organic soils, which can be difficult to stabilize with conventional cementing agents (Clare and Sherwood 1954, 1956; Hampton and Edil 1998; Tremblay et al. 2002).

In situ stabilization of soft soils using cementitious fly ash has become attractive because of factors such as construction

expediency, cost, and interest in sustainable construction (Ferguson 1993; Sridharan et al. 1997; Edil et al. 2006; Tastan et al. 2011). Stabilizing the soil in place reduces damage to the landscape associated with conventional construction methods, which involves removal and transport of large volumes of soft soil and replacement with crushed rock from quarries. Eliminating removal and replacement of soft soil also reduces the carbon and energy footprint associated with highway construction. However, the potential for environmental impacts, such as groundwater contamination because of leaching of trace elements, is a concern when fly ash is used in soil stabilization (Bin-Shafique et al. 2006; Li et al. 2007).

This study was conducted to evaluate leaching of four trace elements [silver (Ag), cadmium (Cd), chromium (Cr), and selenium (Se)] from three soft organic soils stabilized with high carbon fly ashes. All three soils are encountered as soft subgrades during highway construction in Wisconsin. Ag, Cd, Cr, and Se were selected because they are regulated by the Wisconsin Administrative Code when coal fly ash is used in confined geotechnical applications, such as subgrade stabilization with an overlying pavement. These elements also differ in solubility and mobility. Cr and Se typically are in oxyanion complexes that are soluble and mobile at neutral or alkaline hydrogen ion concentration (pH). Ag and Cd typically are cations that are less soluble and mobile, particularly at higher pH (Smith 2007).

Batch water leach tests (WLTs) and column leach tests (CLTs) were conducted on the soils and soil-fly ash mixtures. Results of these tests are used to evaluate leaching patterns, relationships between concentrations from batch tests used for regulatory applications and those from column tests that correspond to more realistic flow-through conditions, and peak concentrations that might be encountered in subgrade stabilization applications. Potential impacts to groundwater are also discussed.

<sup>1</sup>Project Engineer, Golder Associates, 44 Union Blvd., Ste 300, Lakewood, CO 80228. E-mail: jacob\_sauer@golder.com

<sup>2</sup>Wisconsin Distinguished Professor and Chair of Geological Engineering and Director, Recycled Materials Resource Center, Univ. of Wisconsin, Madison, WI 53706. E-mail: chbenson@wisc.edu

<sup>3</sup>Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of Maryland, College Park, MD 20742 (corresponding author). E-mail: aydilek@umd.edu

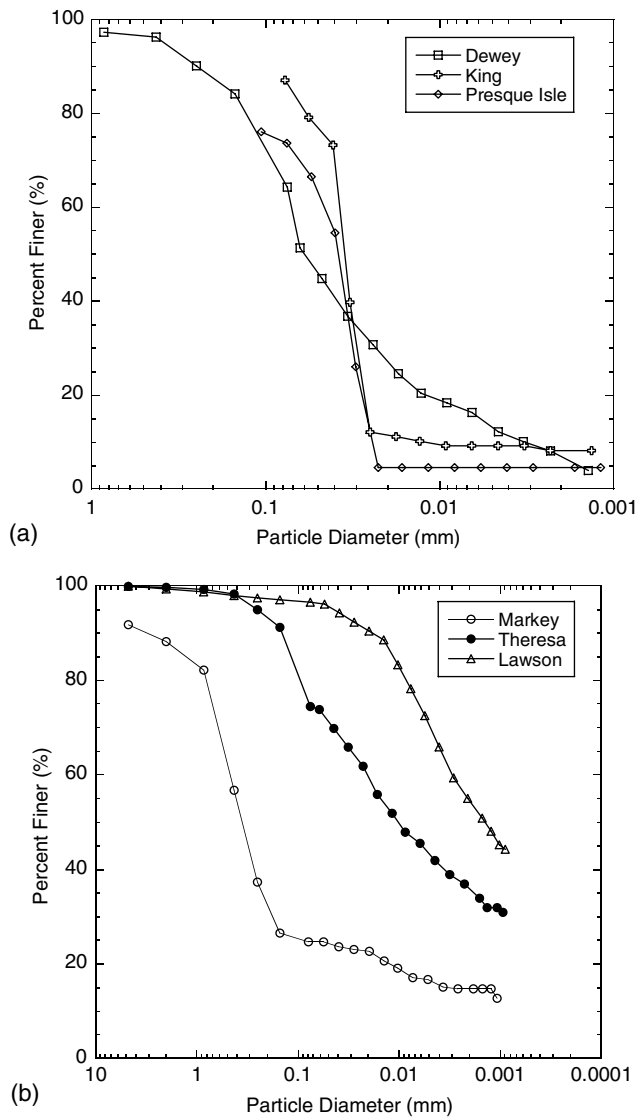
<sup>4</sup>Professor of Geological Engineering and Research Director, Recycled Materials Resource Center, Univ. of Wisconsin, Madison, WI 53706. E-mail: tbedil@wisc.edu

Note. This manuscript was submitted on February 16, 2011; approved on November 1, 2011; published online on November 3, 2011. Discussion period open until January 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 138, No. 8, August 1, 2012. ©ASCE, ISSN 1090-0241/2012/8-968-980/\$25.00.

## Materials

### Coal Fly Ash

Three HCFAs from power plants in Wisconsin and Minnesota were used in this study: Dewey, King, and Presque Isle. Dewey and King fly ashes are produced from combustion of subbituminous coal; Presque Isle fly ash is from a plant-burning bituminous coal. Petroleum coke is added to the coal during combustion at the plants producing Dewey and King fly ashes. All of the fly ashes consist primarily of nonplastic silt-size particles and contain 64–85% fines (passing 75- $\mu\text{m}$  sieve) (Fig. 1).



**Fig. 1.** Particle size distribution curves for (a) organic soils; (b) fly ashes

**Table 1.** Properties and Composition of Fly Ashes

Fly ash	Loss of ignition (%)	Hydrogen ion concentration	Natural water content (%)	Specific gravity	Lime (CaO) content (%)	Other oxides (SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> + Fe <sub>2</sub> O <sub>3</sub> ) (%)	MgO (%)	Fines content (finer than 75 $\mu\text{m}$ ) (%)	Fineness (larger than 45 $\mu\text{m}$ ) (%)
Dewey	42	10.7	1.5	2.53	9.2	17.6	2.4	64.2	57.0
King	12	11.4	0.1	2.68	25.8	45.0	5.3	85.0	26.5
Presque Isle	34	11.9	11	2.57	3.2	57.1	1.0	73.5	41.0

Physical and chemical properties of the fly ashes are summarized in Table 1. Chemical composition was determined using X-ray fluorescence spectrometry by ALS Chemex Laboratories (Henderson, Nevada). All three fly ashes are alkaline ( $\text{pH} \geq 10.7$ ) and are categorized as off-specification ashes, meaning that they do not meet the criteria for Class C or Class F in ASTM C618.

### Soils

Three organic soils representing typical soft organic subgrades in Wisconsin were used in the study: Lawson clay, Markey peat, and Theresa clay. Silica sand was also used as a control material. Each organic soil is very soft in its natural condition (unconfined compressive strength < 60 kPa) (Tastan et al. 2011). Samples of each soil were collected from shallow test pits (1.2-m deep) and stored in airtight buckets to preserve the natural water content. Physical properties of the three soils are summarized in Table 2; particle size distribution curves are presented in Fig. 1.

Lawson clay is more plastic and considerably finer than Theresa clay. Markey peat is a sandy organic soil that is nearly nonplastic and classifies as peat (Pt) in the USCS. Markey peat is coarser and has more organic matter (as measured by loss on ignition [LOI] Table 2) than the Lawson or Theresa clays. All three soils have near neutral pH (6.3–7.1).

## Methods

### Water Leach Tests

In Wisconsin, acceptable reuse applications for industrial byproducts are defined, in part, based on concentrations from WLTs conducted using the method in ASTM D3987. WLTs were performed following ASTM D3987 on fly ash alone, soil alone, and soil-fly ash mixtures with various fly ash contents using 70 g of solid material mixed with 1,400 mL of ASTM Type II deionized (DI) water in 2-L high-density polyethylene (HDPE) bottles [liquid-to-solid (L:S) ratio of 20:1 (mL/g)]. The bottles were rotated continuously at 29 rpm and room temperature (25°C) for 18 h, as required in D 3987. After rotation, the solution was allowed to settle for 5 min, the supernatant was sampled, and its pH was recorded. Supernatant samples were filtered through a 0.45- $\mu\text{m}$  membrane filter, acidified to  $\text{pH} < 2$  using ultrahigh-purity (UHP) nitric acid (HNO<sub>3</sub>), and stored in new 60-mL HDPE bottles. The sample bottles were washed with 2% UHP HNO<sub>3</sub> and rinsed with DI water prior to use. All samples were stored at 4°C prior to analysis. Blanks were also collected and treated using the same protocol.

Soil-fly ash mixtures used in the WLTs were prepared by mixing air-dried soil with a specified percent fly ash by weight. Fly ash percentages were higher than the typical ranges (10–20%) used in soil stabilization (American Coal Ash Association 1999; Edil et al. 2002; Bin-Shafique et al. 2006) because the organic matter and very soft nature of the subgrade soils required more ash to achieve suitable engineering properties (Tastan et al. 2011). Each soil was air-dried and crushed to pass a US No. 4 sieve (4.8 mm). A 2-kg

**Table 2.** Physical Properties of Soils

Soil	Loss of ignition (%)	Hydrogen ion concentration	Liquid limit	Plasticity index	Clay fraction (< 2 $\mu\text{m}$ ) (%)	Specific gravity	Fines content (< 75 $\mu\text{m}$ ) (%)	Natural water content (%)	Optimum water content (%)	Maximum dry unit weight ( $\text{kN/m}^3$ )	Unconfined compressive strength (kPa)	USCS Designation
Lawson	5	6.9	50	19	55	2.58	79	28	28	13.3	57	OL-OH
Markey	27	6.3	53	1	14	2.23	19	57	46	10.3	15	Pt
Theresa	6	7.1	31	8	37	2.57	47	20	21	15.2	36	SM-OL
Sand	0	7.5	Nonplastic	Nonplastic	0	2.65	0	—	—	—	—	SP

sample of soil and fly ash was blended on a tray, and DI water was added to the mixture using a spray bottle; therefore, the mixture had a water content 2% dry of standard Proctor optimum water content. These mixtures were sealed in plastic bags and allowed to cure in a moisture-controlled environment for 7 days prior to testing.

### Column Tests

CLTs were conducted on soils alone and soil-fly ash mixtures to assess leaching under flow-through conditions that resemble field conditions more closely. CLTs were also conducted on specimens

**Table 3.** Hydrogen Ion Concentration and Concentrations of Cadmium, Chromium, Selenium, and Silver from Water Leach Tests on Soils, Fly Ashes, and Soil-Fly Ash Mixtures

Soil	Fly ash	Fly ash content (%)	Leachate hydrogen ion concentration	Metal concentration ( $\mu\text{g/L}$ )			
				Cadmium	Chromium	Selenium	Silver
Lawson	Dewey	20	9.9	0.8	2.8	30.6	< 2.5
		30	10.0	< 0.2	1.4	< 10	< 2.5
		40	10.2	< 0.2	4.8	< 10	< 2.5
	King	20	11.3	< 0.2	1.8	< 10	< 2.5
		30	11.0	0.9	7.3	11.5	< 2.5
		40	11.2	< 0.2	5.3	< 10	< 2.5
	Presque Isle	20	9.2	1.0	1.2	38.7	< 2.5
		30	9.5	1.1	1.9	44.4	< 2.5
		40	9.4	< 0.2	1.2	< 10	< 2.5
Markey	Dewey	20	8.2	< 0.2	< 1.0	20.8	< 2.5
		30	8.6	< 0.2	< 1.0	26.5	< 2.5
		40	8.6	< 0.2	< 1.0	< 10	< 2.5
	King	20	9.6	< 0.2	1.1	< 10	< 2.5
		30	10.0	0.4	27.9	21.9	< 2.5
		40	10.5	< 0.2	3.9	< 10	< 2.5
	Presque Isle	20	8.5	< 0.2	< 1.0	18.4	< 2.5
		30	9.2	< 0.2	< 1.0	30.4	< 2.5
		40	8.9	< 0.2	< 1.0	12.0	< 2.5
Theresa	Dewey	20	9.4	< 0.2	< 1.0	< 10	< 2.5
		30	10.2	< 0.2	7.0	< 10	< 2.5
		40	9.7	< 0.2	1.5	< 10	< 2.5
	King	20	11.3	< 0.2	9.4	< 10	< 2.5
		30	11.6	0.3	50.4	23.7	< 2.5
		40	11.4	< 0.2	14.8	< 10	< 2.5
	Presque Isle	20	9.7	< 0.2	< 1.0	< 10	< 2.5
		30	10.1	< 0.2	4.1	12.4	2.7
		40	9.9	< 0.2	1.2	< 10	< 2.5
Lawson	None	0	8.0	< 0.2	< 1.0	< 10	< 2.5
Markey		0	8.2	< 0.2	< 1.0	< 10	< 2.5
Theresa		0	9.1	0.3	< 1.0	17.6	< 2.5
None	Dewey	100	10.7	0.4	12.8	22.8	6.6
	King	100	11.4	< 0.2	59.9	31.5	3.6
	Presque Isle	100	11.9	0.5	16.5	<b>165.0</b>	< 2.5
U.S. EPA maximum contaminant level				5.0	100.0	50.0	50
Wisconsin NR 538				25.0	5,000.0	250.0	250

Note: Concentrations exceeding maximum contaminant levels are in bold font. Wisconsin drinking water limits are the same as the U.S. EPA maximum contaminant levels for drinking water standards. Wisconsin limits were used for silver, because the U.S. EPA does not list a maximum contaminant level for silver. NR 538 is the maximum allowable concentrations for reuse of fly ash in confined fill applications in Wisconsin.

of clean sand mixed with 30% fly ash to simulate a fly ash mixture where sorption by soil solids is negligible.

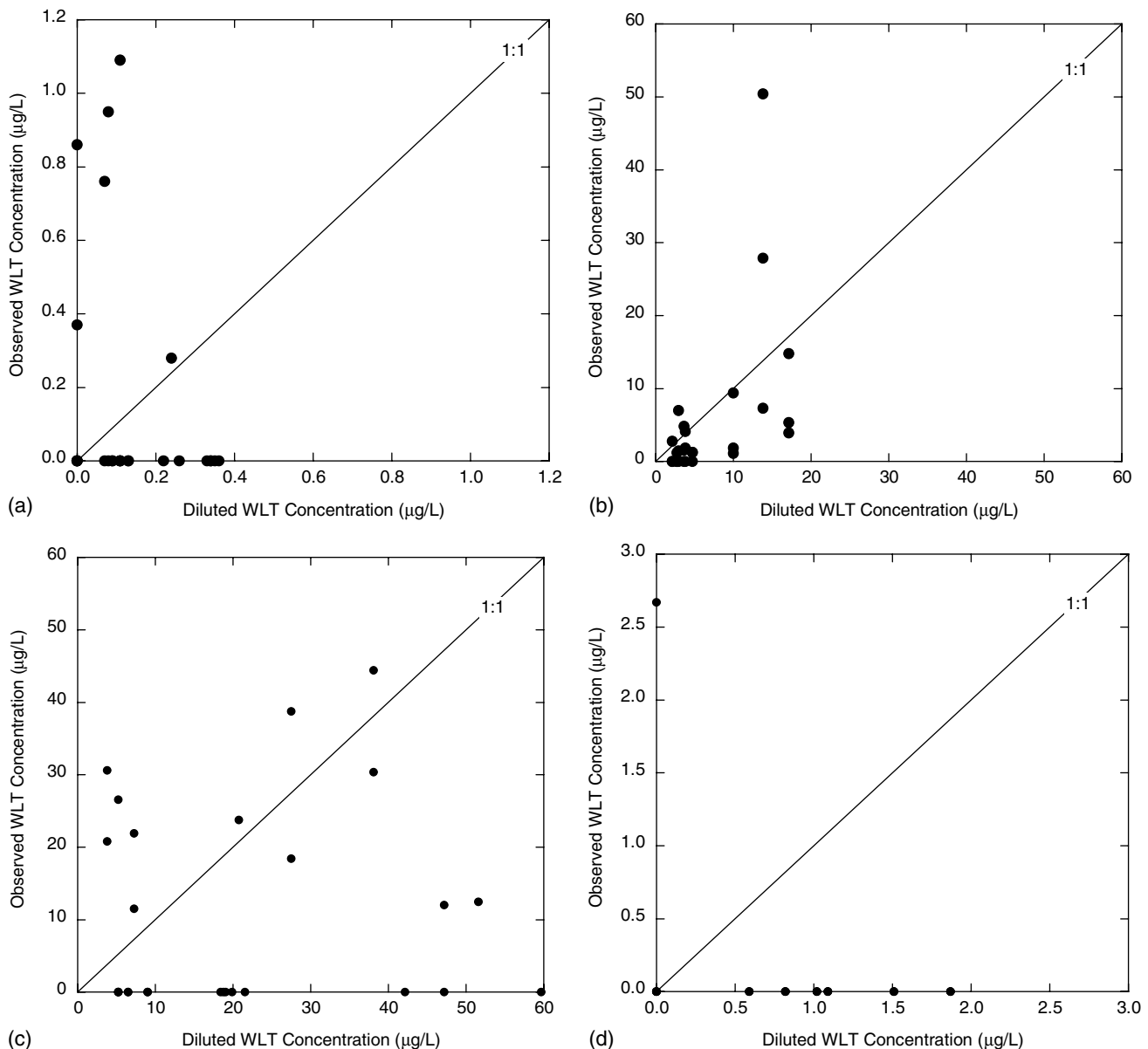
All soils were air-dried and crushed to pass the US No. 4 (4.8-mm) sieve. Fly ash was hand-mixed with the dry soil, and the blend was sprayed with DI water to achieve a water content 2% dry of standard Proctor optimum water content. Moistened soil-fly ash mixtures were compacted in a mold (102 mm diameter  $\times$  116 mm tall) using standard Proctor energy 1 h after mixing to simulate the delay between mixing and compaction that is common in the field (Ferguson 1993; Edil et al. 2002). After compaction, the specimens were extruded from the mold, sealed in plastic wrap, and cured for 7 days at 21°C and 100% humidity.

CLTs were conducted in general conformance with ASTM D4874; except a flexible wall permeameter was employed as described in Bin-Shafique et al. (2002). Flow was oriented upward, the effective confining pressure was 15 kPa, and the hydraulic gradient was maintained between 7 and 10. These gradients are larger than typically encountered in the field ( $\sim 1$ ), but were required to

conduct the tests in a reasonable time frame. Creek and Shackelford (1992) showed that leaching of trace elements from fly ash is independent of the hydraulic gradient. However, for some materials (e.g., bottom ash from solid waste incinerators), the release of trace elements can be affected by the gradient (e.g., Wehrer and Totsche 2008). The effect of gradient should be addressed when applying the findings from column tests to a field condition.

The influent was a 0.1-M LiBr solution prepared with ASTM Type II DI water, which was used to simulate a salt-laden percolate similar to that encountered in northern regions where salt is applied to roadways for deicing (Bin-Shafique et al. 2006). LiBr was used because both Li and Br are uncommon in subgrades and fly ashes, and Li has a lower preference for sorption compared with the trace elements of concern in this study (Cd, Se, Ag, and Cr). The influent was exposed to the atmosphere to permit equilibrium with atmospheric  $\text{CO}_2$  prior to testing.

Leachate from each column was collected in sealed Teflon bladders that were emptied after approximately 30–60 mL of flow had



**Fig. 2.** Comparison of water leach test leachate concentrations and diluted concentrations of (a) cadmium; (b) chromium; (c) selenium; (d) Ag

accumulated ( $\sim 0.1$  pore volumes). This leachate was filtered and acidified to  $\text{pH} < 2$  using UHP  $\text{HNO}_3$  and stored in HDPE sample bottles with no headspace at  $4^\circ\text{C}$ .

### Chemical Analysis

Analyses for Cd, Cr, Se, and Ag in solution were conducted by inductively coupled plasma optical emission spectroscopy (ICP-OES) in accordance with EPA Standard Method 200.7 using a Thermo Jarrell Ash ICAP 61E Trace Analyzer or a Perkin Elmer Optima 4300 DV ICP-OES with an AS 90 Plus autosampler. Blanks were run every 10–20 analyses, and the calibration was verified every 10 analyses. A reagent blank was tested every 20 samples and a spiked sample was analyzed every 10 samples. The limits of detection for the ICP analyses were as follows: Cd ( $0.2$  or  $0.7 \mu\text{g/L}$ ), Ag ( $0.8$  or  $2.5 \mu\text{g/L}$ ), Cr ( $1.0$  or  $1.7 \mu\text{g/L}$ ), and Se ( $4.0$  or  $10 \mu\text{g/L}$ ) (Thermo Jarrell Ash or Perkin Elmer).

## Results of Water Leach Tests

### Leachate Concentrations

Cd, Cr, Se, and Ag concentrations and leachate pH for all WLTs are shown in Table 3 along with U.S. EPA or Wisconsin maximum contaminant levels (MCLs) for drinking water (whichever is lower), and the maximum concentrations in Section NR538 of the Wisconsin Administrative Code for reuse of fly ash in confined geotechnical applications. All concentrations are below both of the limits, except for Se concentrations from Presque Isle fly, which exceed MCLs.

Leachate pHs for the soil-fly ash mixtures prepared with King ash are highest because of the higher lime content of King ash. Leachate pHs for mixtures prepared with the Dewey and Presque Isle ashes are comparable. Mixtures prepared with the Markey peat had the lowest leachate pHs of all mixtures, which may be because of buffering from the organic matter in the Markey peat. Leachate pHs for the tests on fly ash alone ranged from 10.7 to 11.9. The highest and lowest pHs are associated with Presque Isle and Dewey ashes, which have the highest and lowest trioxide ( $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ ) contents.

Concentrations of Cd and Ag for the soil-fly ash mixtures were very low, with Cd being below the detection limit for 78% of the mixtures and Ag being below the detection limit for 96% of the mixtures. Moreover, when Cd and Ag were detected, the concentrations were very low ( $< 1.1 \mu\text{g/L}$  for Cd,  $< 2.7 \mu\text{g/L}$  for Ag). The relatively low concentrations of Cd and Ag are attributed to their low solubility at an elevated pH (Kosson et al. 2009), as well as their high propensity for sorption onto the ash and soil solids.

Higher concentrations were obtained for Cr and Se, with the Se concentrations being the highest. Nevertheless, concentrations below the detection limit for Cr were obtained for 30% of the mixtures and for Se for 56% of the mixtures. The highest concentrations of Se generally were obtained from mixtures prepared with the Presque Isle ash, which had the highest Se concentrations in the WLTs conducted on fly ash alone.

Lower concentrations were obtained from the WLTs on the soils alone, and in most cases concentrations from WLTs on the soils were below detection limits. The exceptions are for Theresa soil, which had Cd ( $0.3 \mu\text{g/L}$ ) and Se ( $17.6 \mu\text{g/L}$ ) above detection limits. Leachate pHs for the soils ranged between 8.0 and 9.1.

### Dilution Calculations

Linear dilution calculations are sometimes applied to WLT data to account for the decrease in concentration anticipated by blending a

byproduct with soil. Bin-Shafique et al. (2006) showed that dilution calculations can be misleading for inorganic soils stabilized with low carbon ashes, and attributed the errors to the nonlinear variation of pH with fly ash content. A similar analysis was made for the soil-fly ash mixtures using the data in Table 3. Diluted concentrations were calculated as linear mass-weighted concentrations using concentrations from the WLTs on the soil alone and the fly ash alone.

Actual concentrations for soil-fly ash mixtures are compared with the diluted concentrations in Fig. 2. There is virtually no correspondence between the diluted and actual concentrations. There is also no systematic under- or overestimation of concentration from the dilution calculation. These findings, and those in Bin-Shafique et al. (2006), indicate that dilution calculations should not be used to determine leachate concentrations for soil-fly ash mixtures.

### Fly Ash Content, Hydrogen Ion Concentration, and Leachate Concentration

The relationship between leachate pH and fly ash content from the WLTs is shown in Fig. 3. Leachate pH is higher for the soil-fly ash mixtures than the soils alone, and lower than the pH of the ash alone, but is relatively insensitive to the fly ash content. Bin-Shafique et al. (2006) showed greater sensitivity of pH to the fly ash content for inorganic soils, but the authors used fly ash contents between 10 and 20%, whereas higher fly ash contents (20–40%) were used in this study to provide the additional cementing needed to stabilize organic soils (Tastan et al. 2011). The

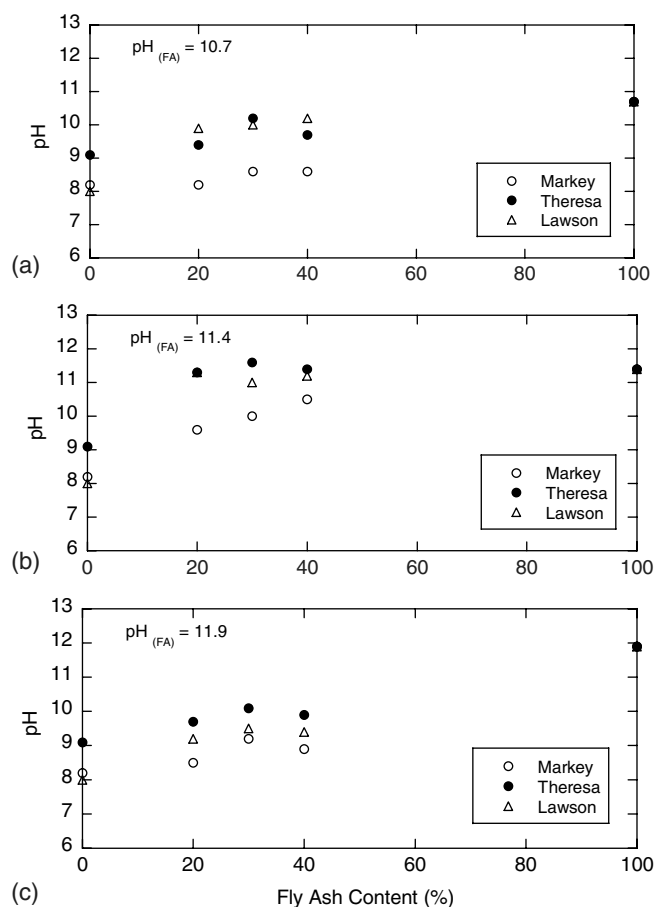


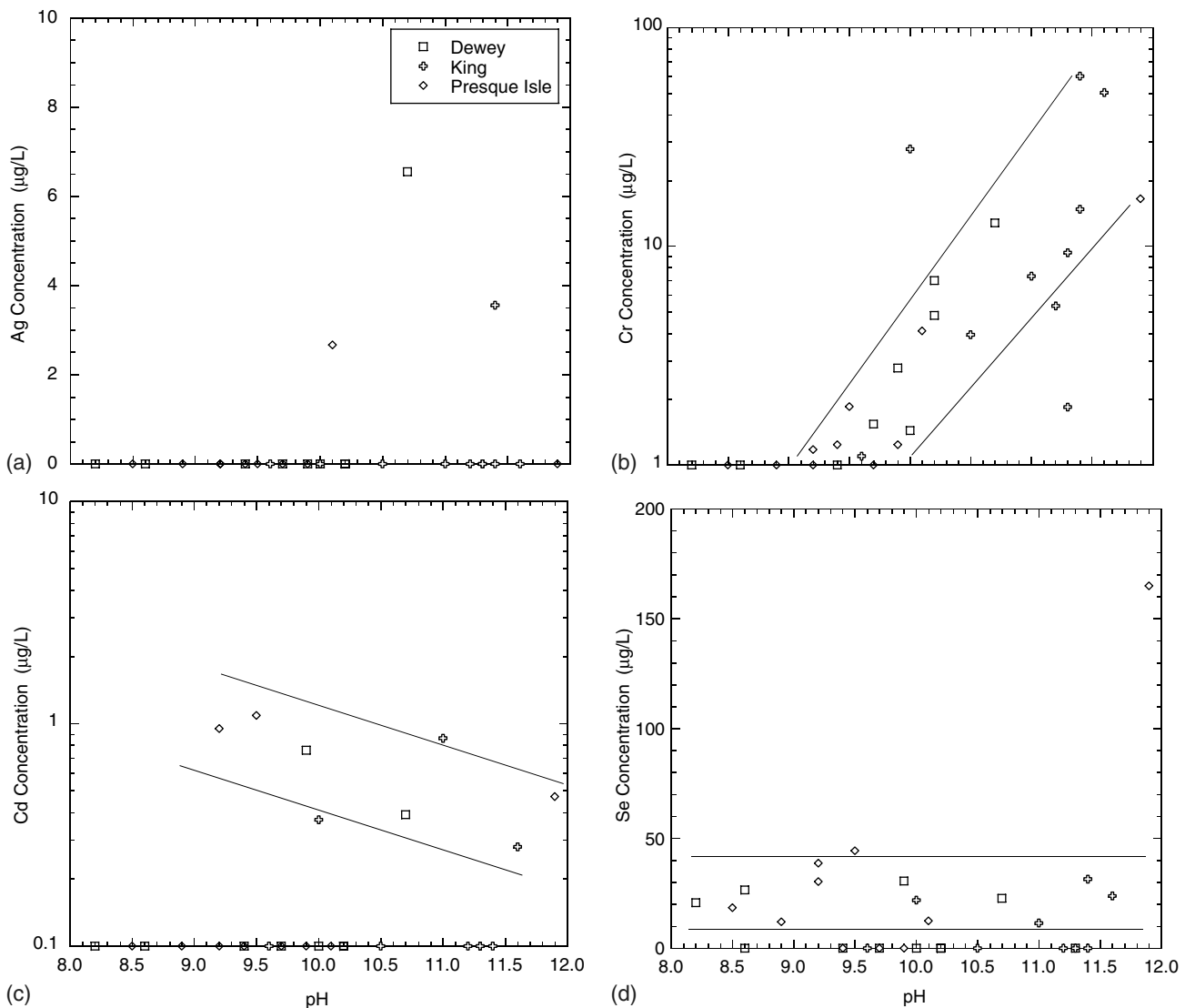
Fig. 3. Leachate hydrogen ion concentration from water leach tests on soil-fly ash mixtures containing (a) Dewey; (b) King; (c) Presque Isle fly ash

abundance of fly ash in the specimens tested in this study may have masked a relationship between pH and fly ash content.

pH of leachate from mixtures prepared with Markey peat was always lower than mixtures prepared with Theresa clay for any given fly ash type and fly ash content, with Lawson clay generally falling in between. Markey peat also had a lower paste pH than both Lawson and Theresa soils (pH 6.3 versus 6.9 and 7.1, Table 2). The lower paste pH and WLT leachate pH for the Markey peat may be because of organic acids in the Markey peat, which has much higher organic matter content compared with the other two organic soils.

Trace element concentrations are shown as a function of leachate pH in Fig. 4. Concentrations below the detection limits are plotted at the lower bound on each graph. Cr concentrations increase with increasing pH [Fig. 4(c)], and Cd concentrations diminish slightly with pH for samples with concentrations above detection limits. Se concentrations are essentially independent of pH, and nearly all Ag concentrations were below detection limits.

These trends are consistent with the M-O-H (M = element) speciation evident in Pourbaix (Eh-pH) diagrams for these elements. Ag typically is  $\text{Ag}^{2+}$  for all of the pHs observed in the WLTs on the soil-fly ash mixtures (pH 8–12, Fig. 4). Cd typically is  $\text{Cd}^{2+}$  or  $\text{CdOH}^+$  for  $\text{pH} < 9.5$ , and can be found as  $\text{Cd}(\text{OH})_2$  for a  $\text{pH} > 9.5$  or 10 (Geological Survey of Japan 2005). Thus, Ag and Cd sorb to the negatively charged mineral or fly ash solids for most pHs, although  $\text{Cd}(\text{OH})_2$  species may be present and mobile at a  $\text{pH} > 9.5$  [as illustrated by the points above the detection limit in Fig. 4(a)]. Cr and Se form oxyanions ( $\text{CrO}_4^{2-}$ ,  $\text{SeO}_3^{2-}$ ) at the pH present in the WLTs (pH 7–11) (Brookings 1988). Anionic Cr and Se species are less likely to sorb to soil or fly ash particles than cationic species. Cationic species of Cr (e.g.,  $\text{Cr}^{3+}$ ,  $\text{CrOH}^{2+}$ ) become less prevalent as the pH becomes alkaline, whereas Se remains in an anionic or neutral species for a broad range of pH (Geological Survey of Japan 2005). Consequently, the concentration of Cr increases with pH, whereas the concentration of Se is relatively insensitive to pH.  $\text{SiO}_2$  in the fly ash may also have dissolved at higher pH (Stumm and Morgan 1996), releasing Se and Cr encapsulated within the vitreous fly ash particles.



**Fig. 4.** Relationship between hydrogen ion concentration and concentrations of (a) silver; (b) cadmium; (c) chromium; (d) selenium from water leach tests

## Soil Properties and Leachate Concentrations

Organic matter content (as LOI) and plasticity index (PI) distinguish the soils and can be indicators of mobility. LOI is a measure of the organic content of the soil, which may alter mobility of trace elements by providing sorption sites or by providing dissolved organic carbon for complication of trace elements. The PI is a measure of clay content and clay type, and sorption of cationic species is expected to increase as PI increases (Bin-Shafique et al. 2006). However, neither LOI or the PI had a systematic effect on WLT concentrations (Figs. 5 and 6). This suggests that the WLT concentrations are controlled primarily by the ash, and to a lesser extent by the properties of their fine-textured soils.

## Results of Column Leach Tests

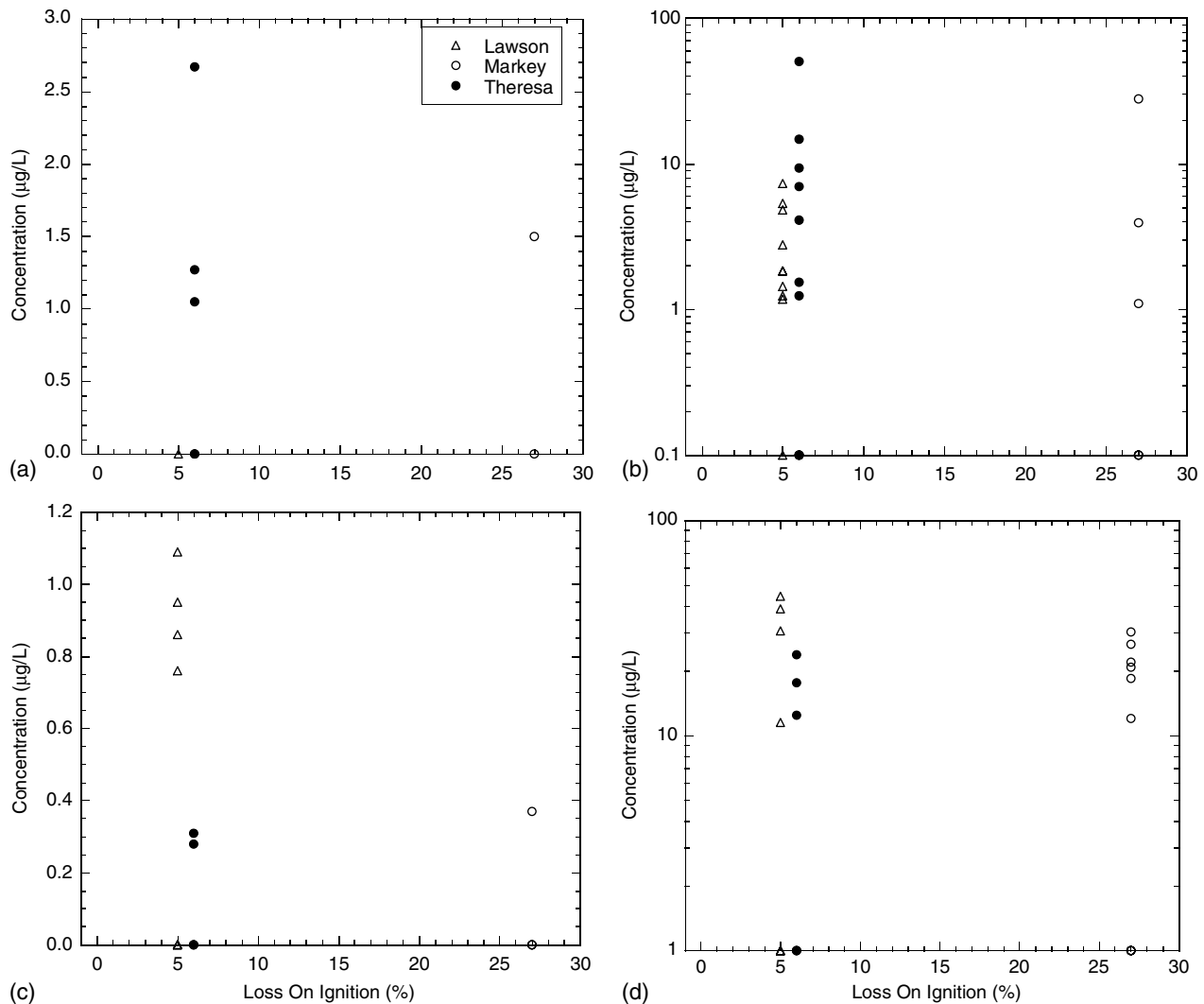
### Analysis of Leaching Patterns

CLTs were conducted on soil-fly ash mixtures and soils alone to assess leaching under flow-through conditions. Fly ash-sand mixtures were also tested to simulate mixtures with minimal sorption onto soil solids.

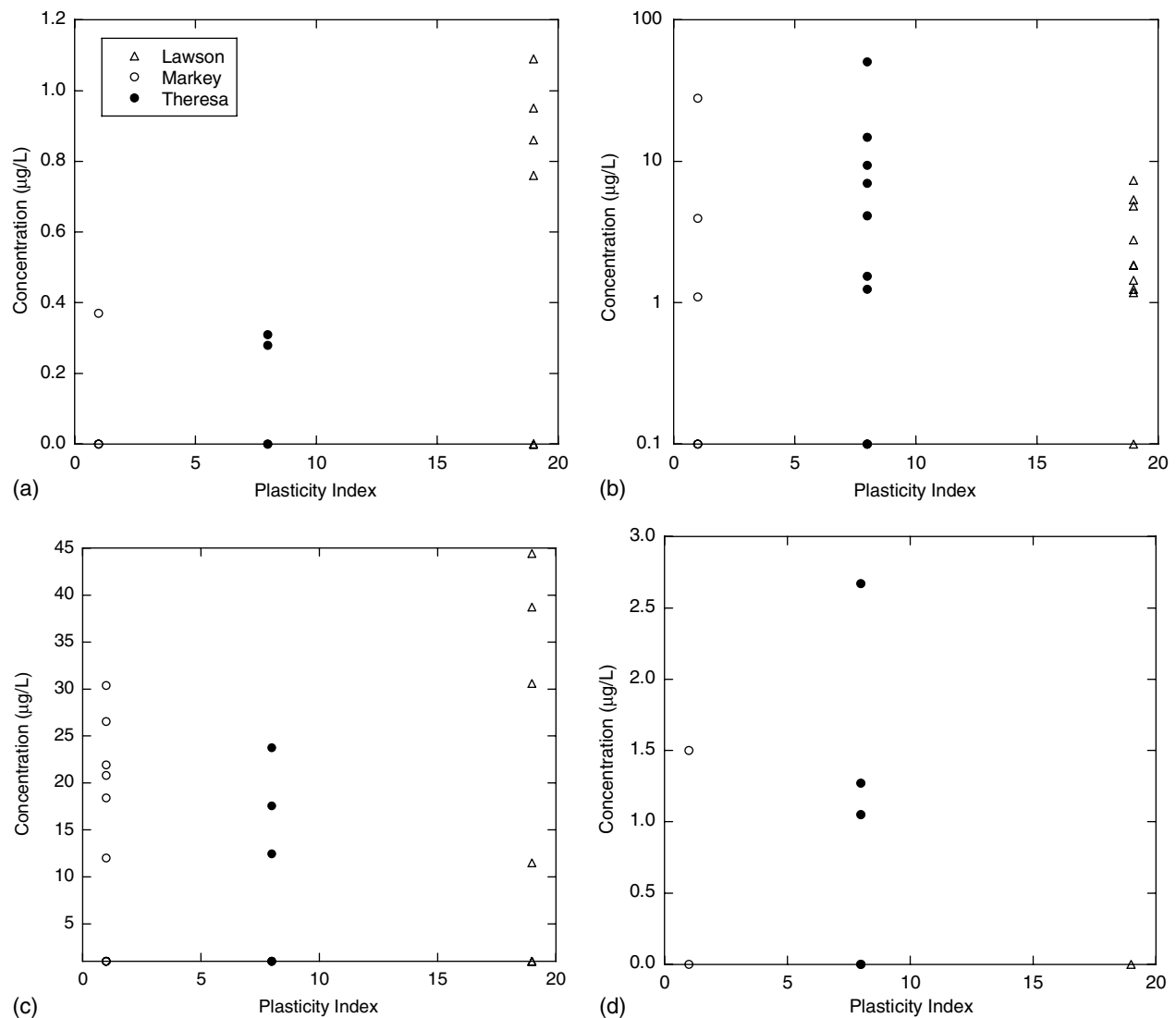
Two leaching patterns were observed during the study, first-flush and lagged-response, as illustrated by the examples shown in Fig. 7. First-flush leaching is characterized by high initial concentrations followed by monotonically decreasing concentrations with increasing pore volumes of flow (PVF) [Fig. 7(a)], whereas lagged response refers to an increasing concentration that reaches a peak and then decreases [Fig. 7(b)]. Because approximately 0.1 PVF was required to obtain a leachate sample for analysis, none of the samples precisely represent the initial first-flush effluent concentration (i.e., PVF = 0). Tests that had the highest concentration in the first sample collected were considered to follow the first-flush leaching pattern.

The CLT data are summarized in Table 4 in terms of peak concentration, PVF to reach peak concentration, and type of leaching pattern. Ag reached a peak concentration after 2.7 pore volumes of flow on average, and Se, Cd, and Cr tended to reach peak concentrations within the first two pore volumes of flow (average PVFs of 1.1, 1.2, and 1.6, respectively).

Of the 60 elution curves that were obtained, 16 exhibited first-flush leaching and 15 exhibited lagged-response leaching. The remaining elution curves did not follow either pattern, because too few data points (none in some cases) were above detection limits to define a leaching pattern (Table 4). Mixtures with inconclusive



**Fig. 5.** Relationship between loss on ignition of soil fraction and concentrations of (a) silver; (b) cadmium; (c) chromium; and (d) selenium from water leach tests



**Fig. 6.** Relationship between plasticity index of soil fraction and concentrations of (a) silver; (b) cadmium; (c) chromium; (d) selenium from water leach tests

leaching patterns are considered to pose minimal impact to groundwater because the detection limits used were below the MCLs.

Leaching patterns observed from the CLTs are summarized in Table 5, with respect to soil, fly ash, and element. Each soil had a comparable number of cases with first-flush and lagged-response leaching. Mixtures with Lawson clay had more cases (11) in which the elution pattern was inconclusive, which may reflect greater propensity for sorption by the higher PI Lawson clay. Soils mixed with Dewey fly ash and soils alone were equally likely to have first-flush or lagged-response leaching patterns. Mixtures containing King fly ash typically showed first-flush leaching, whereas none of the mixtures on Presque Isle fly ash exhibited a first-flush leaching pattern. Presque Isle has the lowest CaO content and King has the highest CaO content, which suggests that CaO content affects leaching behavior.

Evaluation of leaching patterns by element indicates that Cd and Cr typically follow a first-flush pattern (Table 5) when a pattern is discernible (three of four discernible cases for Cd, seven of eight for Cr). Ag mostly exhibited a lagged-response leaching pattern (six of seven discernible cases), and Se had a comparable number of first-flush and lagged-response patterns (Table 5). The pattern does not appear to be related to ionic form; both Cd and Cr primarily exhibit

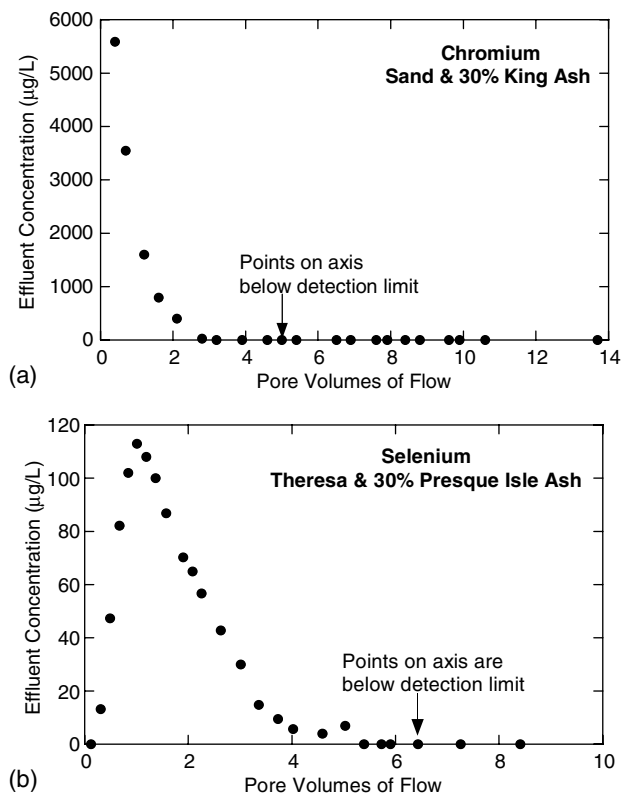
a first-flush pattern even though Cd was likely present in cationic species and Cr in anionic species, and Se exhibited a lagged-response pattern and was likely present in anionic species. Differences in the solubility or location of the oxides containing these elements probably had greater influence on the timing of their release.

The first-flush and lagged-response leaching patterns are similar to those reported by others. Creek and Shackelford (1992) indicate that first-flush patterns are typical of elements with higher charge density (including Cd and Cr), and Bin-Shafique et al. (2006) and Morar et al. (2008) report a first-flush pattern for leaching of Cd, Cr, Ag, and Se from soil-fly ash mixtures prepared with inorganic clays and sand. Edil et al. (1992) observed first-flush and lagged-response leaching patterns from CLTs conducted on fly ash alone and fly ash-sand mixtures; the authors concluded that leaching behavior is controlled by changes in solubility with changes in pH and alkalinity.

#### Soils versus Soil-Fly Ash Mixtures

Comparison of peak concentrations from the CLTs on soils and soil-fly ash mixtures (Table 4) shows that the likely ionic form (cationic versus anionic) affects whether peak concentrations are





**Fig. 7.** Typical patterns observed in elution curves from column leach tests: (a) first-flush; (b) lagged response

higher from the soil alone or the soil-fly ash mixture. Cd and Ag, which are expected to be in cationic form and to have low solubility at a higher pH, typically were eluted at a higher concentration from the soils alone (lower pH) than the soil-fly ash mixtures (higher pH). In contrast, Cr and Se, which are expected to be oxyanions and are soluble at an elevated pH, are eluted at higher concentrations from soil-fly ash mixtures than from soil alone in all but one case (Lawson clay mixed with Dewey ash).

This behavior can be attributed primarily to the increase in pH incurred when fly ash is added to the soil. The ash may have also provided additional sorption sites for Ag and Cd. The only exceptions are Cd and Ag leached from some of the soil-fly ash mixtures prepared with Presque Isle ash, which had lower pH than the mixtures prepared with other ashes (Table 3).

The mixtures with sand further illustrate the role of pH in the elution of trace elements likely to be in cationic and anionic forms. Leachate from the mixtures prepared with sand tended to have a pH that was two or more pH units higher than mixtures prepared with the organic soils (the mixtures with sand and Presque Isle ash were exceptions). As shown in Table 4, Cd was not detected in the leachate from the sand-fly mixtures, and Cr and Se were eluted at considerably higher concentrations. The Ag data are an exception. Ag concentrations in leachate from the sand-fly ash mixtures are higher than the soil-fly ash mixtures prepared with the Dewey and King fly ashes. This may reflect the lower sorptive capacity of the sand particles relative to the clay particles.

The elution curve in Fig. 8 illustrates this effect for Se elution from Theresa clay, a Theresa clay-King ash mixture, and a sand-King ash mixture. Se concentrations are consistently highest from the sand-King ash blend and lowest from Theresa clay alone. The fine organic soils have an important buffering effect, which reduces the pH and concentration of the most prevalent trace elements, Cr and Se.

## Comparison of Water Leach Test and Column Leach Test Concentrations

Fig. 9 compares the peak concentrations from the CLTs with the concentrations from the WLTs. The concentrations found in the leachate from the CLTs typically exceed the concentrations from the WLTs. The CLTs yield higher concentrations because of the lower L:S ratio in CLTs relative to WLTs ( $\approx 0.2$  versus 20), as well as a lower pH in the CLT.

Bin-Shafique et al. (2006) report that peak concentrations from CLTs on soil-fly ash mixtures can be estimated conservatively by multiplying WLTs by a scaling factor (50 for Cd and Ag, 10 for Cr and Se) for mixtures of inorganic soils and fly ashes. These scaling factors generally are conservative for Cd and Ag, as shown in Fig. 9(a) (one point for Cd is an exception), but are not conservative for Cr and Se. A scaling factor of 100:1 is more appropriate for Cr and Se for these mixtures of organic soil and HCFAs.

In general, the CLTs are the preferred method to assess leaching from soil-fly ash mixtures. The lower L:S ratio and laminar flow in a CLT more closely resemble field conditions compared with the aggressive agitation and high L:S ratio in WLT. Consequently, data from the CLTs are preferred over data from the WLTs when conducting environmental assessments.

## Practical Implications for Groundwater Quality

The CLT concentrations represent concentrations reaching groundwater only if the groundwater table is in direct contact with the base of a stabilized layer. In many roadways, the groundwater table is deeper, and processes such as sorption, diffusion, dispersion, and dilution between the base of the pavement and the groundwater table reduce concentrations.

Bin-Shafique et al. (2002) conducted a modeling study to simulate leaching of contaminants from pavement layers constructed with byproducts and transport to the groundwater table using a variably saturated model of flow and transport. The model was validated using data from field lysimeter studies. Their findings indicate that the maximum concentration decreases with increasing depth to the groundwater table. In particular, the maximum concentration 1 m below the byproduct layer typically is 20% of the peak concentration at the base of the byproduct layer and 10% of the peak concentration when the groundwater is 5 m below the byproduct layer.

Estimated concentrations at a groundwater table 1 and 5 m below the stabilized layer are shown in Table 6. These concentrations were computed by applying 10 and 20% factors to the peak CLT concentrations in Table 4. The concentrations at 1 and 5 m below the stabilized layer are typically below the MCLs. The exceptions are the Cr concentrations for mixtures of Lawson clay with the less alkaline Presque Isle fly ash (both depths), and Se concentrations for the King ash mixed with the Lawson and Theresa clays (1 m depth). For these cases, a more detailed analysis could be conducted to obtain a more precise assessment of potential impacts to groundwater at a point of compliance. Methods to conduct such analyses are described in Li et al. (2007).

## Summary and Conclusions

This study investigated leaching of Cd, Cr, Se, and Ag from soft organic soils stabilized with HCFAs using WLTs and CLTs. Tests were performed on three organic soils and three fly ashes. The soils represent typical organic clays and peats in Wisconsin. The three

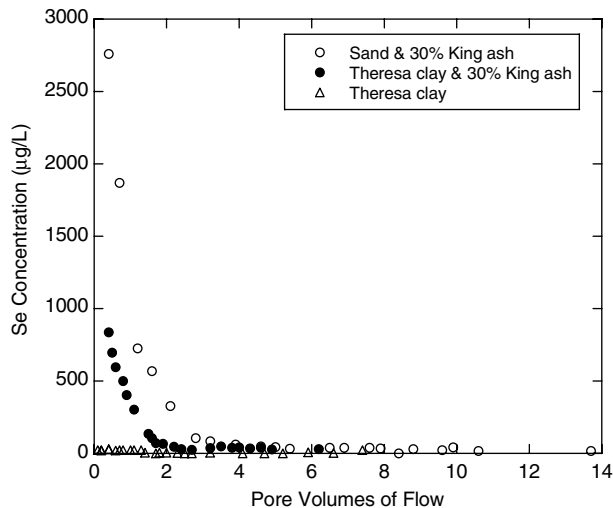
**Table 4.** Peak Effluent Concentrations of Cadmium, Chromium, Selenium, and Silver for Column Leach Tests, Hydrogen Ion Concentration at Peak Concentration, Number of Pore Volumes of Flow to Reach the Peak Concentration, and Leaching Pattern

Soil	Fly ash	Cadmium			Silver			Chromium			Selenium		
		Peak concentration ( $\mu\text{g/L}$ )	Pore volumes of flow to peak	Pattern	Peak concentration ( $\mu\text{g/L}$ )	Pore volumes of flow to peak	Pattern	Peak concentration ( $\mu\text{g/L}$ )	Pore volumes of flow to peak	Pattern	Peak concentration ( $\mu\text{g/L}$ )	Pore volumes of flow to peak	Pattern
Lawson	None	0.42	0.20	First-flush pattern	3.2	0.9	Lagged response	< 1.7	—	Inconclusive pattern	6.1	2.0	Inconclusive pattern
Dewey	King	< 0.40	—	Inconclusive pattern	2.4	0.1	Inconclusive pattern	3.1	0.10	Inconclusive pattern	6.1	0.3	Inconclusive pattern
Dewey	King	< 0.40	—	Inconclusive pattern	< 0.8	—	Inconclusive pattern	3.1	0.20	First-flush pattern	<b>734</b>	0.3	Lagged response pattern
Presque Isle	None	0.85	1.00	Inconclusive pattern	<b>61.7</b>	1.4	Lagged response pattern	<b>660</b>	4.10	Inconclusive pattern	<b>213</b>	4.1	Inconclusive pattern
Markey	None	4.00	0.23	First-flush pattern	1.7	3.2	Inconclusive pattern	2.9	5.24	Inconclusive pattern	<b>67.2</b>	4.0	Lagged response pattern
Dewey	King	0.66	1.40	Inconclusive pattern	8.6	1.2	Lagged response pattern	23.6	0.20	First-flush pattern	<b>162</b>	0.1	First-flush pattern
King	None	1.70	0.50	First-flush pattern	< 0.8	—	Inconclusive pattern	3.2	0.50	First-flush pattern	<b>135</b>	1.2	Lagged response pattern
Presque Isle	None	< 0.40	—	Inconclusive pattern	2.3	3.5	Inconclusive pattern	< 1.7	—	Inconclusive pattern	<b>140</b>	0.4	Lagged response pattern
Theresa	None	<b>29.20</b>	1.30	Lagged response pattern	17.7	0.1	First-flush pattern	3.1	7.40	Inconclusive pattern	<b>29.3</b>	0.4	First-flush pattern
Dewey	King	1.50	0.24	Inconclusive pattern	7.1	4.4	Lagged response pattern	123.0	0.24	First-flush pattern	<b>81.1</b>	0.53	Lagged response pattern
King	Presque Isle	0.41	4.30	Inconclusive pattern	6.1	1.7	Inconclusive pattern	<b>470.0</b>	0.40	First-flush pattern	<b>836</b>	0.4	First-flush pattern
Presque Isle	Dewey	< 0.40	—	Inconclusive pattern	24.0	6.4	Lagged response pattern	< 1.7	—	Inconclusive pattern	<b>113</b>	1	Lagged response pattern
Sand	None	< 0.40	—	Inconclusive pattern	22.6	6.5	Lagged response pattern	<b>295.0</b>	0.30	First-flush pattern	<b>133</b>	0.3	First-flush pattern
U.S. EPA maximum contaminant levels Wisconsin NR 538			5 $\mu\text{g/L}$			50 $\mu\text{g/L}$			100 $\mu\text{g/L}$			50 $\mu\text{g/L}$	
			25 $\mu\text{g/L}$			250 $\mu\text{g/L}$			500 $\mu\text{g/L}$			250 $\mu\text{g/L}$	

Note: Concentrations exceeding maximum contaminant levels are in bold font. Maximum contaminant levels are based on the U.S. EPA standards or Wisconsin standards if no maximum contaminant level is stipulated by the U.S. EPA.

**Table 5.** Number of Occurrences of First-Flush, Lagged-Response, and Inconclusive Leaching Patterns from Column Leach Tests Based on Soil, Fly Ash, and Element

Leaching pattern	Soil				Fly ash				Element			
	Lawson	Markey	Theresa	Sand	Dewey	King	Presque Isle	None	Cadmium	Chromium	Selenium	Silver
First-flush	2	5	5	4	5	7	0	4	3	7	5	1
Lagged-response	3	4	5	3	4	2	6	3	1	1	7	6
Inconclusive	11	7	6	5	7	7	10	5	11	7	3	8

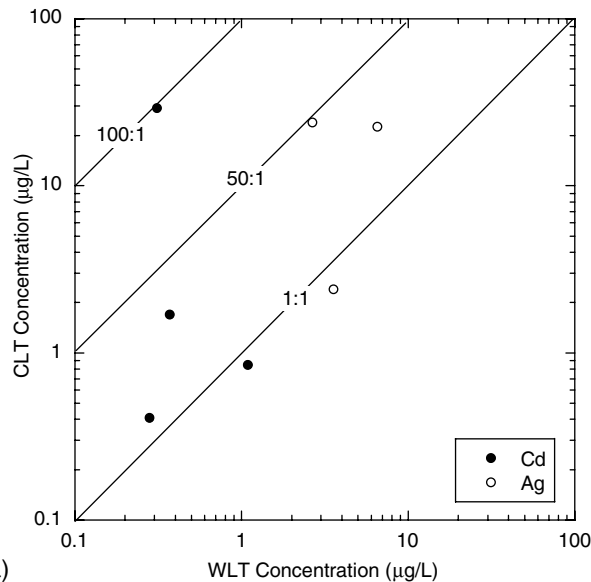


**Fig. 8.** Selenium elution curves from column leach tests on Theresa soil, Theresa soil mixed with 30% King fly ash, and sand mixed with 30% King fly ash

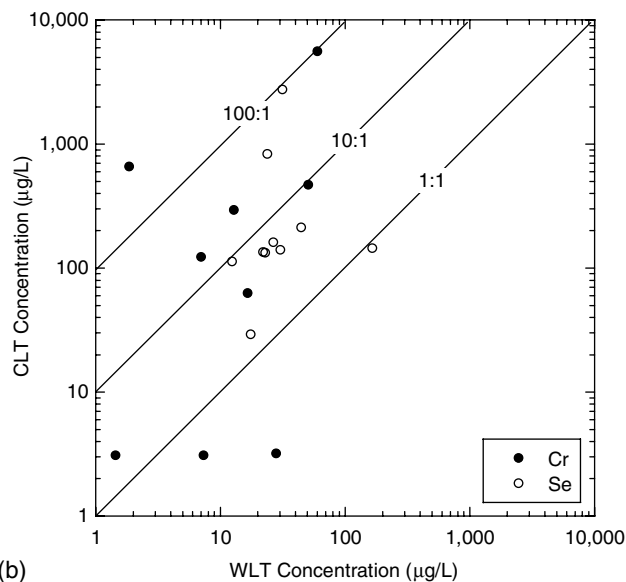
fly ashes are representative of high carbon fly ashes in Wisconsin, with carbon contents greater than 6%.

The following conclusions were obtained from the study:

- Concentrations of Ag, Cd, Cr, and Se from the WLTs on mixtures of organic soil and HCFAs tend to be very low (below MCLs). In most ( $\geq 78\%$ ) cases, Cd and Ag are below common detection limits. Cr and Se tend to have higher concentrations, but also are frequently ( $\geq 30\%$  cases) below common detection limits.
- Leaching tests should be conducted on soil-fly ash mixtures to assess concentrations to be eluted from mixtures. Concentrations computed from dilution calculations, based on concentrations from tests on soil and fly ash alone, are unreliable and should not be used.
- Leachate concentrations and pH from mixtures of organic soil and HCFAs are not sensitive to LOI or the PI of the organic soil or the fly ash content of the mixture. Leachate concentrations appear to be controlled more by the characteristics of the ash and to a lesser extent by the properties of the organic soil.
- First-flush and lagged-response leaching patterns are equally common for mixtures of organic soil and HCFAs, although first-flush patterns are more common for mixtures prepared with fly ashes with a higher CaO content. Cd and Cr exhibit first-flush patterns more frequently, Ag exhibits lagged-response patterns more frequently, and Se exhibits both patterns with comparable frequency. However, no pattern could be detected in at least 50% of the cases because concentrations were below MCLs and detection limits.



(a)



(b)

**Fig. 9.** Comparison of peak effluent concentrations of (a) cadmium and silver and (b) chromium and selenium from the column leach tests and the water leach tests concentration

- pH has a strong effect on leachate concentrations. Ag and Cd typically are cationic species that are less prevalent with an increasing pH, although Cd can form uncharged complexes above pH 9.5. Cr and Se typically are oxyanion species that are prevalent regardless of pH (Se) or increasingly prevalent with pH (Cr). Consequently, Ag and Cd can be eluted at higher concentrations from soil alone relative to more alkaline soil-fly ash mixtures, whereas Cr and Se are eluted at higher concentrations

**Table 6.** Peak Concentrations Observed from Column Leach Tests and Estimated Concentrations after 1 and 5 m of Migration from a Fly-Ash-Stabilized Soil Layer Based on Bin Shafique et al. (2002)

Soil	Fly Ash	Cadmium			Chromium			Selenium			Silver		
		Peak column leach test Conc. ( $\mu\text{g/L}$ )	Est. Conc. at 1 m ( $\mu\text{g/L}$ )	Est. Conc. at 5 m ( $\mu\text{g/L}$ )	Peak column leach test Conc. ( $\mu\text{g/L}$ )	Est. Conc. at 1 m ( $\mu\text{g/L}$ )	Est. Conc. at 5 m ( $\mu\text{g/L}$ )	Peak column leach test Conc. ( $\mu\text{g/L}$ )	Est. Conc. at 1 m ( $\mu\text{g/L}$ )	Est. Conc. at 5 m ( $\mu\text{g/L}$ )	Peak column leach test Conc. ( $\mu\text{g/L}$ )	Est. Conc. at 1 m ( $\mu\text{g/L}$ )	Est. Conc. at 5 m ( $\mu\text{g/L}$ )
Lawson	Dewey	< 0.40	—	—	3.1	0.6	0.3	6.1	1.2	0.60	2.4	0.5	0.2
	King	< 0.40	—	—	3.1	0.6	0.3	734.0	<b>146.8</b>	73.40	< 0.8	—	—
Markey	Presque Isle	0.85	0.2	0.1	660.0	<b>132.0</b>	<b>66.0</b>	213.0	42.6	21.30	61.7	12.3	6.2
	Dewey	0.66	0.1	0.1	23.6	4.7	2.4	162.0	32.4	16.20	8.6	1.7	0.9
Theresa	King	1.70	0.3	0.2	3.2	0.6	0.3	135.0	27.0	13.50	< 0.8	—	—
	Presque Isle	< 0.4	—	—	< 1.7	—	—	140.0	28.0	14.00	2.3	0.5	0.2
Maximum contaminant level	Dewey	1.50	0.3	0.2	123.0	24.6	12.3	81.1	16.2	8.11	7.1	1.4	0.7
	King	0.41	0.1	0.0	470.0	94.0	47.0	836.0	<b>167.2</b>	83.60	6.1	1.2	0.6
Maximum contaminant level	Presque Isle	< 0.40	—	—	< 1.7	—	—	113.0	22.6	11.30	24.0	4.8	2.4
	Soil												

Note: Concentrations exceeding maximum contaminant levels are in bold font. Wisconsin NR 538 limits are the same as the U.S. EPA maximum contaminant levels for drinking water standards. Wisconsin limits were used for silver, because U.S. EPA does not list a maximum contaminant level for silver.

from more alkaline soil-fly ash mixtures. The higher abundance of Cr and Se in fly ash also contributes to the higher concentrations observed in mixtures compared with soil alone.

- Concentrations from the CLTs typically are higher than concentrations in leachate from the WLTs. The peak CLT concentration for Ag and Cd can be conservatively estimated as 50 times the WLT concentration. For Cr and Se, the peak CLT concentration can be conservatively estimated as 100 times the WLT concentration. This scale factor for Cr and Se is 10 times higher than previously reported for inorganic soils stabilized with fly ash.
- Peak groundwater concentrations predicted by applying reduction factors from transport analyses that account for dilution and attenuation in the vadose zone generally were below the MCLs provided that the stabilized layer is at least 1 m above the groundwater table. Exceptions exist for Cr and Se, which may require additional analysis.

## Acknowledgments

The State of Wisconsin Solid Waste Research Program (SWRP), the Recycled Materials Resource Center (RMRC), and the U.S. National Science Foundation (Grant No. CMS-0343079) provided financial support for this study. Alliant Energy, Xcel Energy, and We Energies provided the fly ashes used in the study. The findings and opinions in this report are solely those of the authors. Endorsement by SWRP, RMRC, NSF or the fly ash suppliers is not implied and should not be assumed.

## References

- American Coal Ash Association. (1999). *Soil and pavement base stabilization with self-cementing coal fly ash*, American Coal Association, Alexandria, VA.
- Benson, C., Edil, T., Lee, J., and Bradshaw, S. (2010). "Quantifying the benefits of using coal combustion products in sustainable construction." *Rep. No. 1020552*, Electric Power Research Institute, Palo Alto, CA.
- Bin-Shafique, S., Benson, C., and Edil, T. (2002). "Leaching of heavy metals from fly ash stabilized soils used in highway pavements." *Geo Eng. Rep. No. 02-14*, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, Madison, WI.
- Bin-Shafique, S., Benson, C., Edil, T., and Hwang, K. (2006). "Leachate concentrations from water leach and column leach tests on fly-ash stabilized soil." *Environ. Eng. Sci.*, 23(1), 53–65.
- Brookings, D. G. (1988). *Eh-pH diagrams for geochemistry*, Springer-Verlag, Berlin.
- Clare, K., and Sherwood, P. (1954). "Effect of organic matter on setting of soil-cement mixtures." *J. Appl. Chem.*, 4(11), 625–630.
- Clare, K., and Sherwood, P. (1956). "Further studies on the effect of organic matter on setting of soil-cement mixtures." *J. Appl. Chem.*, 6(8), 317–324.
- Creek, D. N., and Shackelford, C. D. (1992). "Permeability and leaching characteristics of fly ash liner materials." *Transp. Res. Rec.*, 1345, 74–83.
- Edil, T. B., Acosta, H., and Benson, C. H. (2006). "Stabilizing soft fine-grained soils with fly ash." *J. Mater. Civ. Eng.*, 18(2), 283–294.
- Edil, T. B., Benson, C. H., Bin Shafique, S., Tanyu, B. F., Kim, W. H., and Senol, A. (2002). "Field evaluation of construction alternatives for roadway over soft subgrade." *Geo Eng. Rep. No. 02-04*, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, Madison, WI.
- Edil, T. B., Sandstrom, L. K., and Berthouex, P. M. (1992). "Interaction of inorganic leachate with compacted pozzolanic fly-ash." *J. Geotech. Eng.*, 118(9), 1410–1430.
- Ferguson, G. (1993). "Use of self-cementing fly ashes as a soil stabilization agent." *Fly ash for soil improvement, Geotechnical Special Publication No. 36*, ASCE, New York, 1–14.

- Geological Survey of Japan. (2005). "Atlas of Eh-pH diagrams." *Open File Rep. No. 419*, National Institute of Advance Industrial Science and Technology, Tokyo.
- Hampton, M. B., and Edil, T. B. (1998). "Strength gain of organic ground with cement-type binders." *Soil improvement for big digs, Geotechnical Special Publication No. 81*, A. Maher, and D. Yang, eds., ASCE, New York, 135–148.
- Hodges, W. K., and Keating, R. W. (1999). "Maryland power plant research program promotes the beneficial use of coal combustion products." *Proc., 30th Int. Symp. on Use and Management of Coal Combustion Products*, Center for Applied Energy Research, Univ. of Kentucky, Lexington, KY, 78.1–78.10.
- Kosson, D., Sanchez, F., Kariher, P., Turner, L., Delapp, R., and Seignette, P. (2009). "Characterization of coal combustion residues from electric utilities—leaching and characterization data." *Rep. EPA-600/R-09/151*, Office of Research and Development, U.S. EPA, Research Triangle Park, NC.
- Li, L., Benson, C., Edil, T., and Hatipoglu, B. (2007). "Groundwater impacts from coal ash in highways." *Water Resour. Manage.*, 159(4), 151–163.
- Morar, D., Aydilek, A. H., Seagren, E. A., and Demirkan, M. M. (2008). "Release of inorganic and organic contaminants from fly ash amended permeable reactive barriers." *Envir. Geotech. Rep. 08-01*, Dept. of Civil and Environmental Engineering, Univ. of Maryland-College Park, College Park, MD.
- Smith, K. (2007). "Strategies to predict metal mobility in surficial mining environments." *Understanding and responding to hazardous substances at mine sites in the western United States*, J. V. DeGraff, ed., The Geological Society of America, 25–46.
- Sridharan, A., Prashanth, J. P., and Sivapullaiah, P. V. (1997). "Effect of fly ash on the unconfined compressive strength of black cotton soil." *Ground Improv.*, 1(3), 169–175.
- Stumm, W., and Morgan, J. J. (1996). *Aquatic chemistry*, Wiley, New York.
- Tastan, E. O., Edil, T. B., Benson, C. H., and Aydilek, A. H. (2011). "Stabilization of organic soils with fly ash." *J. Geotech. Geoenviron. Eng.*, 137(9), 819–833.
- Tremblay, H., Duchesne, J., Locat, J., and Lerouil, S. (2002). "Influence of the nature of organic compounds on fine soil stabilization with cement." *Can. Geotech. J.*, 39(3), 535–546.
- Wehrer, M., and Totsche, K. U. (2008). "Effective rates of heavy metal release from alkaline wastes—Quantified by column outflow experiments and inverse simulations." *J. Contam. Hydrol.*, 101(1–4), 53–66.