LEACHING OF TRACE ELEMENTS FROM ROADWAY MATERIALS STABILIZED WITH FLY ASH

by

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ABSTRACT
LEACHING OF TRACE ELEMENTS FROM ROADWAY MATERIALS STABILIZED WITH FLY ASH

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This study evaluated the leaching of trace elements from roadway materials physically stabilized with fly ash from coal combustion. Five field sites with stabilized materials and three sites with control materials used as base course or subgrade were constructed with pan lysimeters to collect leachate discharging from the bottom of the roadway layers. Pore volumes of flow from the layers was calculated from the volume of leachate collected, pH and Eh of the leachate was measured, and samples were collected for chemical analysis. Laboratory column leach tests (CLTs) and water leach tests (WLTs) were also conducted on specimens of some fly ash and base course/subgrade materials collected in the field. The type, concentration, and pattern of elemental leaching from field and laboratory specimens were determined, and concentrations were compared to those from control materials and relevant groundwater maximum contaminant levels (MCLs). The laboratory tests were compared for their utility in predicting field leaching behavior. The elements As, Cd, Cr, Mo, Ni, Pb, Se, and V exceeded MCLs and were elevated relative to control concentrations, with B, Mo, and V concentrations the most elevated from the controls, and exceeding the MCL for the longest time. Both CLTs and WLTs were similar in their utility for estimating peak field concentrations, especially when peak field concentrations were >500 µg/L.

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SECTION 1

1. INTRODUCTION

Cementitious fly ash is mixed with soils or granular materials in roadway construction to increase strength and stiffness (Edil *et al*. 2002; Bin-Shafique *et al*. 2004; Li *et al*. 2007; Hatipoglu *et al*. 2008; Li *et al*. 2009), as well as to reduce the swelling of expansive soils (Cokca, 2001; Buhler and Cerato 2007). Use of fly ash as a stabilizer in road construction has also been found to reduce construction costs and energy use (Kumar and Patil 2006; US EPA 2008) depending on the scale of the project and the local availability of fly ash and other construction materials (Kumar and Patil 2006).

Fly ash is a coal combustion product (CCP) captured from hot flu gases. Most fly ashes contain trace elements that were present in the coal, including As, B, Ba, Be, Cd, Cr, Co, Cu, Pb, Mn, Ni, Se, Sr, Tl, V, and Zn (NRC, 2006; US EPA 2008). A primary limitation to greater use of fly ash in road construction is concern about environmental impacts to soil and groundwater from trace elements leaching from the ash. This report describes field and laboratory experiments conducted. Particularly of interest were the type, concentration, and pattern of elemental leaching. The paper also evaluates the utility of laboratory water leach tests and column leach tests to predict field leaching of elements from fly ash stabilized materials. A discussion and summary of current state policies in the United States concerning use of fly ash in road construction is presented in Appendix D.

SECTION 2

2. FIELD SITES

Data from five field sites employing fly-ash-stabilized base course or subgrade were evaluated in this study. Additionally, some roadway materials and fly ash from the field sites were used for laboratory leaching tests for comparison with the field data. The field sites were Wisconsin State Highway 60 (STH60) in Lodi, WI; US Highway 12 (US12) in Fort Atkinson, WI; the Scenic Edge subdivision (Scenic Edge) in Cross Plains; WI, 7th Avenue in Waseca, MN; and the Minnesota Department of Transportation MnROAD highway testing laboratory (MnROAD) in Albertville, MN. During construction of the stabilized roadway sections, at least one pan lysimeter was installed directly beneath the stabilized materials to collect leachate discharging from the bottom of the layer. Control lysimeters were also installed beneath unstabilized materials at STH60, US12, and MnROAD.

2.1. State Highway 60 Site

During reconstruction of STH60 between Lodi and Prairie du Sac, WI in August 2000, a 0.1-km section located 8.2-km west of Lodi, WI (Fig. 2.1) was reconstructed using fly ash to stabilize the subgrade soil. STH60 is a two lane highway carrying approximately 3500 vehicles per day (WISDOT 2003). The upper 300 mm of the subgrade was mixed with 18% fly ash by weight using a road reclaimer and then compacted using tamping foot, steel drum, and rubber tire compactors.

The stabilized subgrade was overlain with 140-mm of recycled paving material (RPM) subbase followed by 115-mm of crushed limestone base course and 125 mm of hot mix asphalt (HMA). Details of stabilized materials for all sites can be found in Table 2.1. The construction of STH60 is described in Edil *et al.* (2002) and Bin Shafique *et al.*

(2004). A profile of the roadway layers for all field sites is included in Figures 2.2 and 2.3.

Two pan lysimeters were installed during construction directly beneath the stabilized subgrade to collect leachate discharged from the stabilized layer. One is located beneath the centerline, and the other is located near the shoulder (half is beneath the HMA and half beneath the shoulder) (Fig. 2.4). Two identical lysimeters were installed beneath a control section composed of a 840-mm crushed dolostone sub-base in place of the fly ash stabilized subgrade, with identical overlying layers. A cross-section of typical lysimeter construction is shown in Figure 2.5. Construction methods for all lysimeters are described in Section 3.3, and lysimeter details are included in Table 2.1. Leachate from STH60 has been monitored since September 2000.

2.2. US Highway 12 Site

A 15.1-km section of US US12 between Fort Atkinson and Cambridge, WI was reconstructed between April 2004 and January 2005 (Fig. 2.1). US12 is one of the primary truck routes in Dane and Jefferson Counties in Wisconsin, and carries approximately 7400 vehicles per day (WISDOT 2006). A 0.6-km section of this project employed fly ash to stabilize the soft subgrade.

The upper 300-mm of subgrade was mixed with 12% fly ash by weight using a road reclaimer and then compacted using tamping foot and vibratory steel drum compactors. The stabilized subgrade was cured for 7-d and then overlain with 254 mm of base course (mixed recycled paving material (RPM) and gravel) and 203 mm of Portland cement concrete riding surface.

Two pan lysimeters were installed during construction beneath the stabilized subgrade to collect leachate discharged from the stabilized layer. One is located at the eastern end of the stabilized subsection and the other at the western end. A third identical control lysimeter was installed beneath unstabilized subgrade soils near the western stabilized soil lysimeter. Additional information on the US12 lysimeters can be found in Li *et al*. (2009). Leachate from US12 has been monitored since November 2005.

2.3. Scenic Edge Site

During the 2000 construction of a 200-m section of a residential street in the Scenic Edge subdivision in Cross Plains, WI (Fig. 2.1), the existing subgrade soil was stabilized with fly ash. Subgrade was mixed with 12% fly ash by weight to a depth of 300 mm. The mixture was compacted using tamping foot, steel drum, and rubber tire compactors. The stabilized subgrade was overlain with a 175-mm thick crushed stone base course, and 100 mm of hot-mix asphalt (HMA). Details of the Scenic Edge site construction can be found in Bin Shafique *et al.* (2004). One pan lysimeter was installed beneath the stabilized subgrade during construction. Leachate from Scenic Edge has been monitored since February 2006.

2.4. Waseca Site

During Summer 2004 road construction, fly ash was used to stabilize RPM base course near the intersection of 7th St. and 7th Ave. in Waseca, Minnesota, located 125 km south of Minneapolis (Fig. 2.3). The RPM was reclaimed on-site by pulverizing the existing asphalt pavement and base course materials using a road reclaimer. The *in situ* water content of the RPM was approximately 4% dry of standard Proctor optimum water content based on standard compaction effort (ASTM D 698).

The RPM was spread to form a 225 mm base course and then fly ash (10% by dry weight) was spread and mixed using a road reclaimer with water added during mixing using a water truck. The mixture was compacted by tamping foot and vibratory steel drum compactors, and then cured for 7 d and overlain with 75 mm of HMA.

One lysimeter was installed below the stabilized base course. Photographs showing the road and lysimeter construction are in Appendix A-1. Leachate from Waseca was monitored from September 2004 to September 2008.

2.5. MnROAD Site

The Minnesota Department of Transportation (MNDOT) MnROAD Facility is a full scale highway testing laboratory located in east-central Minnesota adjacent to Interstate 94 between Albertville and Monticello, Minnesota (Fig. 2.1). The facility contains a low traffic volume road loop that simulates traffic on rural roads as well as a high volume freeway section that carries live traffic from Interstate 94 when active. Test sections at MnROAD contain sensors that measure load response and environmental data (MNDOT 2009).

Three test sections were constructed in 2007 on the low volume loop at MnROAD to evaluate fly-ash-stabilized RPM as base course. One test section contains stabilized RPM base course, a control section contains unstabilized RPM, and a second control section contains crushed stone (Class 5, as classified by MNDOT) as the base course. The RPM was reclaimed from to a depth of 305 mm from a HMA wearing course and MNDOT Class 4 aggregate base course at the MnROAD facility. The RPM was stockpiled before use.

The base courses were initially constructed in early August 2007. Each is 203 mm thick and was compacted with a steel-drum vibratory roller. The stabilized RPM base course was mixed with 14% fly ash, compacted and then covered with plastic sheets and allowed to cure for one week. The RPM and crushed stone aggregate base courses had to be reconstructed due to heavy rainfall. Both were excavated, air dried, and recompacted. The RPM and crushed stone aggregate sections were compacted in early October 2007, and all three sections were then paved with a 102 mm HMA wearing course was paved.

One pan lysimeter was installed in each of the three sections during construction directly beneath the base course layer to collect leachate discharged from the layers above. The lysimeters are located beneath the HMA wearing course and base course, off set to one side, approximately 600-mm from the shoulder along the closest side of the lysimeter. Photographs of lysimeter construction at MnROAD are included in Appendix A-2. Leachate from MnROAD has been monitored since October 2007.

SECTION 3

3. METHODS AND MATERIALS

3.1. FLY ASH

Fly ash is classified based on chemical composition by ASTM C 618 as either Class C or Class F. Fly ash that does not meet the requirements of Class C or F is often referred to as “off-specification”. The composition within a class can vary significantly The majority of the fly ash that is recycled in the United States is Class C or F (US EPA, 2008).

Fly ash is in a highly oxidized state and chemically reacts and cements in the presence of water and lime (CaO and CaOH). Lime may already be present in the ash, constituting a self-cementitious fly ash, or lime may be added to produce cementitious ash. The field sites in this study employed three cementitious fly ashes for stabilization of base course or subgrade: Columbia, Riverside 7, and Riverside 8. Chemical and physical properties of the fly ashes are presented as Table 3.1. Columbia fly ash is from Alliant Energy’s Columbia Power Station in Portage, WI, whereas the Riverside 7 and Riverside 8 fly ashes are from Xcel Energy’s Riverside Power Plant in Minneapolis, MN. Columbia ash was used at the STH60, Scenic Edge, and US12 sites. The Riverside ashes were used at the MnROAD and Waseca sites. Columbia fly ash and both Riverside fly ashes were captured using electrostatic precipitators.

Columbia ash contains 98% fines, and classifies as Class C in ASTM C 618 and AASHTO M 295 (Table 3.1). Riverside 7 classifies as Class C in ASTM C 618 and AASHTO M 295, whereas Riverside 8 is an off-specification ash due to its high carbon content (>5%) (Table 3.1). Elemental composition of the Columbia and Riverside 8 ashes is presented in Table 3.2. The major components of the fly ashes (in descending order) are Ca, Al, V, Mg, Fe, Na, P, K, Ba, and Sn. All other elements comprised less than 0.1% of the fly ash mass (Table 3.2).

3.2. BASES AND SUBGRADES

Particle size distributions of the soils and RPMs that were stabilized with fly ash are presented in Figure 3.1. The subgrades at STH60 and Scenic Edge both classify as low plasticity clay (CL) in the USCS system and A-6 in AASHTO. At US12 the subgrade ranges in properties across the site from low plasticity clay (CL) in the USCS system and A-7-6 in AASHTO (east lysimeter) to clayey sand (SC) in the USCS system and A-6 in AASHTO (west and control lysimeters) (Fig. 3.1). The RPMs used at MnROAD and Waseca both classify as well graded silty gravel (GW-GM) in the USCS system and A-1-a in AASHTO. The stone sub-base at STH60 and the stone base course at MnROAD both classify as poorly graded sand (SP) in the USCS system and A-1-b in AASHTO (Fig. 3.1).

3.3. FIELD LEACHATE MONITORING

Pan lysimeters were employed in this study to monitor leachate transmitted from the overlying pavement layers. A profile of a typical pan lysimeter is shown in Fig. 2.5. A depression was excavated to the size of the desired lysimeter and the depression bottom was graded for drainage to a single point. A 120-L HDPE leachate collection tank was installed along the road shoulder, buried approx. 2 m deep. The tanks were connected to the lysimeter through a trench using PVC pipe with adequate drainage gradient from the pan to the tank, and were connected vertically to the surface for leachate collection. The depression was lined with 1.5 mm thick LDPE geomembrane which was connected and heat-sealed to the PVC drainage pipe. A drainage layer consisting of geonet between two layers of geotextile was installed in the lysimeter. The stabilized layers were then compacted above the lysimeter. Photographs of lysimeter construction at Waseca and MnROAD are located in Appendix A.

Leachate in the 120-L tanks was pumped and sampled periodically. Volume of leachate discharged from the layer was recorded and pore volumes of flow (PVF) was calculated from the porosity of the stabilized layer. Volumetric fluxes from the layers were compared to local precipitation data. A daily precipitation rate was averaged for each month of the study (mm/day), and flux from the layer (mm/day) was calculated from the volume of leachate collected, the time between tank pumping events, and the area of the lysimeter. Long-term average fluxes were calculated from the total volume collected, lysimeter area, and total days of lysimeter operation.

Aqueous samples were collected for chemical analysis during pumping events. All samples were collected in HDPE sample bottles with zero head space. Within 24 hr of sampling, pH and oxidation-reduction potential (Eh) were measured in the laboratory. The equipment used to test pH and Eh varied over the course of the study. The leachate was then filtered with a 0.2-μm micropore filter and preserved to pH<2 using trace-metal-grade HNO_3.

3.4. LABORATORY LEACH TESTS

3.4.1. Column Leach Tests (CLTs)

Column leach tests (CLT) were conducted on materials obtained from three of the field sites. These were the stabilized subgrade from STH60, the stabilized RPM from Waseca, and the three base course materials from MnROAD. The column testing conditions are summarized in Table 3.3. The CLTs were used to evaluate leaching under saturated steady-flow conditions.

Specimens were prepared from each material by compaction to field dry unit weight and water content. Material was mixed to field water content using deionized water in a spray bottle, and compacted by mallet and tamp in three lifts. Columns were either compacted in molds, and extruded and tested in flexible wall permeameters (STH60 and Waseca), or compacted directly in rigid wall permeameters (MnROAD) (Table 3.3). After compaction, the stabilized specimens were cured for one week at constant temperature and 100% humidity.

All specimens were permeated from bottom to top with 0.1 M LiBr solution using gravity with constant-head (STH60 and Waseca) or peristaltic pumps with constnt flow rate (MnROAD). This solution was chosen to simulate percolate in regions where salt is used to manage ice and snow (Bin-Shafique *et al.* 2006). Neither lithium nor bromide have drinking water maximum contaminant levels (MCLs), and therefore would not be chemicals of interest in the leachate analysis. Effluent was collected in sealed Teflon bags to minimize chemical interaction with the atmosphere. Volume of leachate was measured by weighing the bag, PVF was calculated using weight-volume computations based on layer compaction and material properties. A sample was collected for chemical analysis and filtered with 0.2-μm mircopore filters and preserved with trace-metal-grade nitric acid to $pH < 2$. The Teflon bags were rinsed with deionized water between sampling events.

3.4.2. Water Leach Tests (WLTs)

Water leach tests (WLTs) were conducted on the stabilized subgrade from STH60 and the three materials from MnROAD according to ASTM D3987-85. The unstabilized materials were passed through a US No. 4 sieve and dried as in Bin-Shafique *et al.* (2006). The stabilized materials were compacted to average field dry unit weight and water content, and then were cured for 7 d at constant temperature and 100% humidity. After curing, the stabilized materials were crushed by hand until the gradation appeared similar to the unstabilized RPM.

WLTs were conducted on all the materials using a 20:1 liquid:solid (L:S) ratio (by mass) with deionized water as the eluent as described in the ASTM D3987-85. The MnROAD materials were also tested with deionized water at 3:1, 5:1, and 10:1 L:S ratios. Only the 20:1 ratio is described in the standard.

Leaching was conducted in 2-L HDPE bottles rotated for eighteen hours. Afterwards the solids were allowed to settle 5 min., and then a sample was collected from the supernatant using a wide mouth syringe. The sample was filtered with 0.2-µm micropore filters, and preserved to < pH of 2 using trace-metal-grade HNO_3. Pictures of the MnROAD WLTs are in Appendix A-2.

3.5. LEACHATE ANALYSIS

3.5.1. Chemical Indicator Parameters

The pH and oxidation-reduction potential (Eh) of all field and laboratory leachate samples were measured in the laboratory within 24 hours of sampling. The water quality instruments used for leachate testing varied between sites and over the years of testing.

3.5.2. Major and Minor Elements

Numerous methods for chemical analysis have been used over the course of this project due to the availability of equipment and changing requirements for certain analytes. The methods used were atomic adsorption (AA), inductively coupled plasma (ICP), and cold vapor atomic fluorescence spectrometry (CVAFS). These methods with the dates of use, chemicals analyzed for, and minimum detection limits are summarized in Table 3.4.

All chemical analyses of field and laboratory leachates prior to Fall 2005 were performed by atomic adsorption (AA) according to EPA Standard Methods 213.2, 218.2, 270.2, and 272.2. Due to the complexity of the AA method, only four elements were considered; cadmium (Cd), chromium (Cr), selenium (Se), and silver (Ag). The only active site during this period was STH60.

After Fall 2005, AA analysis was discontinued and chemical analyses of field and laboratory leachates were conducted by inductively coupled plasma - mass spectrometry (ICP-MS) according to USEPA Method 200.8. Seventeen elements were analyzed by ICP-MS for the STH60, Scenic Edge, and US12 sites. These analytes along with minimum detection limits (MDLs) are presented in Table 3.4. A suite of calibration standards containing the seventeen elements was prepared spanning a range of concentrations appropriate for trace elements and based on expected concentrations of each element. The analytes tested using ICP-MS are presented with MDLs in Table 3.4.

After June 2007, field and laboratory leachates for the STH60, US12, Scenic Edge, and MnROAD sites were analyzed by inductively coupled plasma - optical emission spectrometry (ICP-OES) using a Varian Vista-MPX CCD Simultaneous ICP-OES instrument. All Waseca site leachate was analyzed using ICP-MS including samples from prior to June 2007. The number of chemical analytes increased in June 2007 to 23 for the STH60, US12, Scenic Edge sites. All leachates from the MnROAD, and Waseca sites were analyzed for these 23 elements. The analytes tested for using ICP-OES are presented with MDLs in Table 3.4.

Beginning in 2008 leachate from field lysimeters at the STH60, US12, Scenic edge, and MnROAD sites was periodically sampled and analyzed for mercury (Hg) using USEPA Method 1631, Revision E: Mercury in Water by Oxidation, Purge and Trap, and Cold Vapor Atomic Fluorescence Spectrometry (CVASF). All sampling equipment that contacted the leachate samples was acid cleaned, dried, and double bagged in cleaned and sealed bags. Samples were collected using two people following the procedure in USEPA Method 1669. In this method, one person only touched the sample bottle and the inner of the two bags containing the bottle. Handling of the outer of the two bags containing the sample bottle and all other equipment and was conducted by the other person. A field blank and duplicate sample were collected for every 10 to 15 lysimeters sampled. Samples were collected in LDPE bottles with zero head space. All Samples were maintained at 4° C, and were preserved and analyzed according to USEPA Method 1631.

Minimum detection limits (MDLs) for AA, ICP-MS, ICP-OES, and CVAFS were determined for each instrument and set of calibration solutions according to US Code of Federal Regulations Title 40, Appendix B to Part 136. The method and analytes tested for during each time period are presented with MDLs in Table 3.4.

SECTION 4

4. RESULTS AND DISCUSSION

4.1. FIELD LEACHING BEHAVIOR

4.1.1. Precipitation Patterns and Lysimeter Drainage

The flux of leachate from the bottom of the stabilized and control layers was compared to the local precipitation rate for each site. Short-term leachate fluxes and precipitation rates from stabilized subgrade are shown in Figs. 4.1 and stabilized RPM in Fig. 4.2. Peak fluxes from the layers tend to occur in the spring months when heavy rains and snow melt occur, and again in late summer and early fall (Figs. 4.1 and 4.2). The peak flux occurs one to two months after the peak monthly precipitation. The minimum flux tends to occur in the winter when precipitation and pore water are often frozen, and in July or August when evaporation tends to exceed precipitation in the upper Midwest (Figs. 4.1 and 4.2). Occasionally the flux from the stabilized layers approaches 15% of precipitation for a period of several months (Fig. 4.2.b). However, as shown subsequently, the long-term average is never more than 7.8% of precipitation for stabilized RPM or 2.4% for stabilized subgrade (Fig. 4.3). Short-term fluxes were calculated from the volume of leachate collected during each pumping event, the surface area of the lysimeter pan, and the time between pumping events. The daily precipitation corresponds to the average precipitation per day occurring during each month (Figs. 4.1 and 4.2) (NOAA 2009).

Long-term fluxes from the pavement layers and precipitation rates averaged over the entire time of the study are shown in Fig. 4.3. Long-term flux of leachate discharged from the fly-ash-stabilized layers was less than 8% of the local precipitation, and often only 1-3% of precipitation. Greater discharge of leachate (relative to precipitation) occurs in the fly-ash-stabilized RPM base courses (2.1 to 7.8% of precipitation) compared to the stabilized soil subgrades (1.8 to 2.4% of precipitation). The control base courses also had greater flux relative to precipitation than the control subgrades. Flux from the MnROAD RPM control base course was 6.1% of precipitation and flux from the stone aggregate control base course was 14% of precipitation. The STH60 stone subgrade control layer had a leachate flux that was 2.9% of precipitation, and the US12 soil subgrade control had 1.6% of precipitation (Fig. 4.3).

The regional average percentage of precipitation recharging the groundwater is estimated to range from 19% to 24% for the Minnesota sites and from 20% to 21% for the Wisconsin sites (USGS 2007). The asphalt or Portland cement concrete wearing courses on the roadways likely have lower hydraulic conductivity than adjacent road shoulder and native soils. Therefore recharge rates in the areas adjacent to a stabilized roadway may be significantly higher than the percentage of precipitation that leaches from the stabilized layers, which may affect the transport of leachate in the subsurface.

According to the US National Weather Service (May 2009), the annual precipitation in the region that includes Waseca and MnROAD ranges from approximately 500 mm to 900 mm, with an average of 750 mm. The annual precipitation in the region that includes STH60, US12, and Scenic Edge ranges from approximately 500 mm to 1200 mm, with an average of 930 mm (US NWS 2009). Based on the leachate volumes that were collected, total annual flux from a stabilized base course in eastern-central Minnesota should range from 11 to 70 mm/year, and total annual flux from a stabilized fine-grained soil subgrade in south-central Wisconsin should range from 9 to 30 mm/year.

Long-term fluxes from the layers were calculated from the total volume of leachate collected, the surface area of the lysimeter pan, and the total time of leachate collection, and are shown in Fig. 4.3 with long-term average precipitation rates for each site during the testing periods (NOAA 2009). The long-term average precipitation was calculated as the total precipitation during the study divided by the total time of the study. Leachate volume from each pair of lysimeters at the STH60 site (Fig. 2.2) from each pumping event were compared using a paired t-test to determine if statistically significant differences existed between fluxes measured beneath the pavement and beneath the shoulder. A two-tailed P-value of 0.05 was obtained by the t-test, indicating that the fluxes were not statistically different, although the outcome was marginal. Therefore each lysimeter pair at STH60 is treated as one data set.

4.1.2. Chemical Indicator Parameters

The pH and Eh of the leachates collected in the lysimeters are presented in Fig. 4.4. The pH in the field leachate ranged from 6 to 9, with most of the data near neutral (Fig. 4.4a) for both stabilized and control materials. Only the east stabilized lysimeter at the US12 site regularly had pH greater than 8, and no lysimeters had pH regularly less than 6. Ganglof *et al.* (1997) also found near neutral pH in leachate collected from fly ash amended sandy soil using ceramic-cup pore-water lysimeters in an agricultural field.

The leachate Eh generally ranged from +300 to -150 mV, with most data predominantly oxidizing (Eh > 0) and occasional samples in a reducing state (Eh < 0) (Fig. 4.4b). Only the east lysimeter at the US12 site had Eh less than -150 mV on a regular basis (Fig. 4.4b). The US12 east lysimeter regularly had leachate that was grey in color and had a strong odor, possibly indicating anaerobic conditions. All other field leachates were generally clear to yellow and had no noticeable odor. The differences in color and odor are likely associated with the differences in pH and Eh between leachate from US12 east and the other field leachates.

4.1.3. Elements Released and Magnitude of Concentrations

Of the twenty-four trace elements considered in the analysis (Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, Sr, Ti, Tl, V, and Zn), all except Be were present in detectable quantities in leachate from the fly-ash-stabilized layers. The elements detected in the leachate are presented in Table 4.1 with the peak concentration and average peak concentration (average of the three highest concentrations). The following elements are presented in order of descending peak concentration observed in leachate from the fly-ash-stabilized materials (Table 4.1): Mo (maximum peak concentration of 18,176 μg/L); Sr, Al, Fe, B, and Mn (maximum peak concentration between 10,000 and 1,000 μg/L); Sn, Ba, V, Se, Zn, As, Cu, Tl, and Ni (maximum peak concentration between 1,000 and 100 μg/L); and Pb, Cr, Sb, Ti, Co, Cd, and Ag (maximum peak concentration between 100 and 10 μg/L). Peak concentrations of both Hg and Be were less than 1 μg/L.

The relationship between peak aqueous concentration in the leachate and solid-phase concentration in the fly ash is shown in Fig. 4.5. Linear regression of the base 10 logarithms of the peak aqueous concentration and the solid-phase concentration in the fly ash for all sites and elements indicates a statistically significant, but weak correlation between peak aqueous concentration and solid phase concentration ($R^2 = 0.30$, F-test p value = 2.8×10^{-12}). Fly ash particles contain multiple solid forms (crystalline, glass, and oxide crusts) with different solubilities. Elements such as Cd and Ni may be concentrated in the least soluble crystal phase, and other elements may be preferentially occluded in the glass phase, which is more soluble than the crystalline phase, but less soluble that than metal oxides in the outer crust of the particles (Huett *et al.* 1980)

4.1.4. Elution Patterns

Concentrations of each element recorded in each lysimeter are reported as a function of PVF in Appendix B. Not all elements were tested during the early years of some sites (Table 3.4). Therefore initial leaching patterns could not be observed in these cases. Among elements that were tested during the entire operation of each site and that were detected at the site, 61% of elements had the peak concentration occur during the first two PVF (Table 4.2). The elements most commonly with early peak concentrations are Cd, Co, Cr, Ni, and Se. As an example, the leaching pattern of Cd and Cr is shown in Fig. 4.6. All other elements except Be, Hg, and Ti were observed to have peak concentration occur during the first two PVF for at least one site (Table 4.2).

4.2. POTENTIAL ENVIRONMENTAL IMPACTS

4.2.1. Field Concentrations Compared to Control Sections

An analysis was conducted to determine if element concentrations in leachate from stabilized materials were elevated relative to concentrations in leachate from adjacent control sections. The average peak concentration and the geometric mean of all observed concentrations for each site and element were compared. The determination of concentration elevation was conducted using Equation 4-1,

$$(C^*_c + 2\sigma) \geq (C^*_s - 2\sigma) \text{ OR } (C^*_c + 2\sigma) \leq (C^*_s - 2\sigma) \qquad \textbf{Eq. 4-1}$$

where C^*_s is the average peak or geometric mean concentration from stabilized materials, C^*_c is the average peak or geometric mean concentration from control materials, and σ is the standard deviation. If $(C^*_c + 2\sigma) \leq (C^*_s - 2\sigma)$ was true, then the concentration from stabilized material was considered significantly elevated relative to concentration from control material. The standard deviation, σ, was obtained as the product of the average peak or geometric mean concentration and the coefficient of variation (COV). The COV for each element was determined from 7 replicate tests on the ICP-OES at 20 μg/L.

For the three sites with control lysimeters (STH60, US12, and MnROAD), 19 of the 24 elements were elevated in concentration relative to the control. The following six elements had elevated concentrations at all 3 sites (in order of descending magnitude of concentration elevation): Mo, B, Cu, Cr, Cd, and Zn (Table 4.3). Eleven elements were elevated at two of the three sites (Sr, Al, Ba, Ti, Co, Fe, Sn, As, V, Ni, and Mn). Both Pb and Ag were elevated at one of the sites. Concentrations of five elements in stabilized leachate (Hg, Be, Se, Tl, and Sb) were not elevated relative to control leachate concentrations at any of the sites with control sections (Table 4.3). Adriano *et al.* (2002) found elevated As, B, Be, Ba, Mo, and Se in pore water in fly ash amended soil, but found all these elements were below detection limits in groundwater collected from a depth of 3.6-m below the amended soil.

4.2.2. Elements Exceeding Regulatory Maximum Contaminant Levels

Concentrations of all elements observed in lysimeter leachates were compared to the maximum contaminant levels (MCLs) for groundwater or drinking water promulgated by the States of Minnesota and Wisconsin (Minnesota - MN MDH IC 141-0791, Wisconsin - WI NR 140.10). The US government also has MCLs for groundwater (US CFR Title 40 Chapter 141.62), but the State MCLs are equal to or lower than those promulgated by the US government (Table 4.4).

Concentrations of the following eleven elements in lysimeter leachate from fly-ash stabilized materials exceeded MCLs at least once: As, B, Cd, Cr, Mo, Ni, Pb, Sb, Se, Tl, and V. The other thirteen elements never exceeded an applicable MCL in leachate from stabilized materials. Concentrations observed in the lysimeters are only representative of leachate as it exits the bottom of the stabilized or control layer, and do not represent concentrations as leachate drains downward from the pavement through the unsaturated zone and then merges with local groundwater flow.

Concentrations of As and Tl exceeded the MCL most frequently. Leachate from all five stabilized materials and all four control materials had average peak concentrations of As and Tl exceeding MCLs. The geometric mean concentration of Tl also exceeded the MCL at all stabilized and control sites, and As had geometric mean concentration exceed the MCL at two stabilized sites and two control sites (Table 4.5). Concentrations of all elements in field leachate from stabilized and control materials during the course of the study are shown with MCLs in Appendix B.

Average peak concentrations of B, Pb, Sb, and V exceeded the MCL in four of the five stabilized sections, and in none (B), two (V), three (Pb), or all four (Sb) of the control materials. The average peak concentrations of Cd, Mo, Ni, and Se exceeded the MCL in one (Ni), two (Cd and Mo) or three (Se) of the stabilized sections, and in none (Se and Ni) or one (Cd and Mo) of the control sections. (Table 4.5).

Geometric mean concentrations of V exceeded the MCL at three stabilized sites and two control sites. Both Pb and Sb had geometric mean concentration exceed the MCL at one stabilized site and two control sites. Geometric mean concentrations of Cd, Cr, Mo and Ni exceeded the MCL in one of the five stabilized sections, and in none of the control sections.

Geometric mean concentrations of elements that have MCLs are presented with the relevant MCL in Figures 4.7 and 4.8.

4.2.2.1. Concentrations Exceeding MCL and Elevated at All Sites

Concentrations of B, Mo, Cr, and Cd in leachate from fly-ash-stabilized materials exceeded MCLs and were elevated relative to the adjacent control sections at all sites with control sections (Figs. 4.9 to 4.12) (Table 4.3). At sites where B and Mo exceeded the MCL, concentrations of both elements exceed the MCL for many PVF (the stabilized RPM at MnROAD is an exception) (Figs. 4.9 and 4.10). Concentrations of Cd and Cr only exceeded MCLs in the first sample collected (total PVF < 0.25), and then remain well below the MCL in all subsequent leachate (Figs. 4.11 and 4.12).

4.2.2.2. Concentrations Exceeding MCL and Elevated at Some Sites

Concentrations of V, Ni, As, and Pb exceeded MCLs and were elevated in leachate from stabilized materials relative to control materials at only one or two of the three sites (Figs. 4.13 to 4.16) (Table 4.3). Vanadium (V) persists at concentrations above the MCL when the MCL is exceeded (Fig 4.13). Nickel (Ni) only exceeded the MCL and was elevated relative to the control at the US12 site which has higher pH and more reducing conditions than the other sites.

Both As and Pb have concentrations that remain very close to the MCL for many PVF, and were observed to periodically exceed the MCL. The concentrations of As and Pb from stabilized materials were only slightly elevated relative to the concentrations from the control materials (Figs. 4.15 and 4.16) (Table 4.3).

4.2.2.3. Elements in Exceedance of MCL but Not Elevated Compared to Controls

Concentrations of Se, Tl, and Sb in leachate from the fly ash stabilized materials exceeded MCLs, but were not elevated relative to the controls (Figs. 4.17 to 4.19). Both Tl and Sb concentrations tended to be below detection limits with occasional concentrations above the MCL. Concentrations of Se were consistently below the MCL except for the US12 (West) site and the earliest sample taken from the stabilized section at the MnROAD site.

4.2.3. Effects of pH and Eh on Element Mobility

Chemical speciation of elements in the roadway pore water can affect mobility and concentrations. Elements that exist as anions, oxy-anions, or non-ionic soluble molecules at the range of pH and Eh in the field leachate are less likely to be sorbed to solids, and therefore will have greater mobility than elements that form cations (which are likely to sorb on mineral surfaces) or elements that precipitate out as a solid (Jury and Horton 2004). For the elements that exceeded MCLs, the most probable speciation was estimated by pH-Eh speciation diagrams produced by the Geologic Survey of Japan (2005). All probable species over the range of pH and Eh observed in the field leachates were included (Table 4.6). Speciation was not determined in the laboratory.

Six of the eleven elements that exceeded MCLs are likely to form anions, oxy-anions, or non-ionic soluble molecules at the observed pH-Eh conditions (As, B, Mo, Sb, Se, and V). Five of the elements primarily form cations (Cd, Cr, Ni, Pb, and Tl) (Geologic Survey of Japan 2005) (Table 4.6).

Of the three elements with concentrations exceeding MCLs in early PVF and then having concentrations fall below the MCL (Cd, Cr, and Se), two (Cd and Cr) primarily form cations at field pH-Eh conditions. Se is likely to be present as an anion or oxy-anion. Five of the eight elements with concentrations that persistently exceed MCLs for at least several PVF (As, B, Mo, Sb, and V) form anions, oxy-anions, or non-ionic soluble molecules at field pH-Eh conditions (Table 4.6). The other three elements with concentrations that persistently exceed the MCL (Ni, Pb, and Tl) primarily form cations at the observed field pH-Eh conditions.

4.3. LABORATORY TESTS

Two laboratory leaching methods were employed on specimens of fly-ash-stabilized and control materials prepared in the laboratory using materials obtained from the field sites: column leach tests (CLTs) and water leach tests (WLTs). Specimens were prepared using field conditions whenever possible. Chemical properties of the laboratory leachates were compared to those of the field lysimeter leachates to determine the effectiveness of the tests in predicting field leachate qualities. CLTs were conducted on stabilized materials from STH60, Waseca, and MnROAD, as well as the MnROAD control materials. WLTs were conducted on stabilized materials from STH60 and MnROAD as well as the MnROAD control materials.

4.3.1. Chemical Indicator Parameters

The pH of the CLT and field leachates are presented in Fig. 4.20. The pH of leachate from the fly-ash-stabilized CLTs is higher than from the same materials in the field (3 to 4 pH units higher for MnROAD,1 to 2 pH units for STH60) (Fig. 4.20). All field leachate from stabilized materials (except at the US12 site) had pH near neutral (Fig. 4.4a). The CLT leachate from the control materials also tended to be near neutral. In contrast, the pH of leachate from stabilized CLTs (from MnROAD) remained elevated relative to the field pH for over 45 pore volumes of flow, which is longer than the life-cycle flow for most of the field lysimeters.

The lower pH in the field compared to WLTs and CLTs on stabilized material may be due to unsaturated conditions in the field. Microbial respiration in the field can enhance soil pore gas CO_2 (Zwick *et al.*, 1984). Diffusion of CO_2 from the atmosphere or microbial respiration into pore water may form weak carbonic acid and may reduce the pH. In contrast, the CLTs are saturated and therefore have no opportunity for CO_2 to reduce the pH. The pH of WLT leachate from MnROAD materials was also 3 to 4 pH units higher than field leachate. Bin-Shafique *et al.* (2006) also found similar pH in leachate from CLT and WLT on stabilized soils and sand. The WLT data is in Appendix C.

The Eh of the CLT and field leachates are presented in Fig. 4.21. Leachate from stabilized RPM at the MnROAD field site consistently had positive oxidation-reduction potential (Eh), of approximately +150 mV, indicating oxidizing conditions (Fig. 4.21). The stabilized RPM CLT leachate had lower Eh than the field, ranging generally from -5 mV to +40 mV. Leachate from control CLTs had similar Eh to the field leachates from stabilized and control materials.

The differences in leachate Eh between field and CLT concentrations are likely associated with the differences in pH between field and CLT concentrations. For MnROAD field and CLT leachates (the only site with CLT, pH, and EH results), leachate Eh and pH are linearly related (and statistically signinificant) ($R^2 = 0.80$, F-test $p = 5.7 \times 10^{-20}$) (Fig. 4.22). Altering the CLT method used in this study to obtain pH near neutral in CLT leachate may cause the Eh of CLT leachate to more closely match the observed field Eh.

4.3.2. Column Leach Tests

4.3.2.1. Prediction of Field Leaching Concentrations

Average peak concentrations of 23 elements (calculated from the mean of the three highest concentrations) in leachate from the field lysimeters and CLTs on the same materials are compared in Fig. 4.22. The data are for the MnROAD, Waseca, and STH60 sites (the only sites with CLTs performed. Average peak concentrations from the CLTs are within one order of magnitude of the average peak field concentration for 77% of elements (Fig. 4.23). Graphs of all field concentrations as a function of PVF are included in Appendix B and all CLT concentrations as a function of PVF are included in Appendix C.

Of the eight elements in field leachate with concentrations elevated relative to the control section and exceeding MCLs (As, B, Cd, Cr, Mo, Ni, Pb, and V), four also exceeded the MCL and were elevated in the CLT leachate relative to the controls (B, Cr, Mo, and V) (Fig. 4.24) (Tables 4.7 and 4.8). Concentrations of these four elements were among the most elevated relative to the control concentrations in both the field and lab. In addition, concentrations of B, Mo, and V may remain higher than MCL for many pore volumes of flow in both the field and CLTs. Field and laboratory concentrations of all elements for the entire monitoring period are presented in Appendices B and C.

The CLT provided measurable concentrations of all 23 elements analyzed, and was most successful at estimating the average peak field concentrations for the three elements most likely to leach at concentrations above MCL for long periods of time (B, Mo, and V) (Figs. 4.9, 4.10, and 4.13). The CLT concentrations of Bo, Mo, and V were greater (1.2, 1.1, and 3.5 times, respectively) than the average peak field concentrations.(Table 4.3).

Concentrations of As, Cd, Ni, and Pb exceeded the MCL and were elevated relative to control concentrations in the field, but not in CLTs. Concentrations of these elements were either only slightly elevated in the field but not in the CLT (As, Cd, and Pb), or were elevated in both the field and CLT (Ni) but only exceeded the MCL at US12 where pH and Eh conditions were different than the other sites and CLTs were not conducted (Fig. 4.25). Of these elements, only As had a peak field concentration greater than 20 µg/L.

Average peak field concentrations of As, Cd, and Ni may be significantly underestimated by the CLT procedure used in this study. The CLT concentrations of As, Cd, and Ni tend to be below or near the detection limit and well below the MCL. In contrast, peak field concentrations for these elements may exceed the MCL. For example, the average peak field concentration of As was 26 times the average peak from the CLT, Cd was 15 times the peak from the CLT, and peak Ni concentration was 2.5 times greater in the field. Detection limits for Pb differed significantly for the field and CLT leachates. All field Pb concentrations were below the detection limit (above the MCL) and most CLT concentrations were below a lower detection limit (below the MCL). Because of these differences the ability of CLTs to predict field leaching of Pb can not be adequately assessed from this study.

All three elements that exceeded MCLs in the field but were not elevated relative to control materials (Sb, Se, and Tl) also exceeded the MCL in CLTs. However, Sb and Se concentrations were elevated relative to controls concentrations from the CLTs. These differences are possibly due to differences in pH and Eh between the field and CLT leachates.

4.3.2.2. Comparison of Leaching Patterns

Under saturated constant-flow conditions in the CLTs, concentrations of thirteen of the 24 elements displayed a first-flush elution pattern, with the peak concentration occurring during the first or second PVF (Ag, B, Be, Cd, Cr, Cu, Mo, Mn, Sb, Se, Sr, V, and Zn). All of these elements also had first-flush elution pattern for at least one field site. Examples of observable first-flush behavior in CLT concentrations are presented in Figure 4.26.

Concentrations of the thirteen elements with a first-flush elution pattern peaked at an average of 1.5 PVF, with the latest peak at 6 PVF for Zn. The remaining 11 elements either had very low initial CLT concentrations (As, Co, Hg, Ni, Pb, Sn, Ti, and Tl) and long-term concentrations just above or below the MDL, or had distinctly different leaching patterns (Al, Ba, and Fe). Elements that exceeded the MCL in field leachates and did not have a first-flush pattern in the CLTs were As, Ni, Pb, and Tl.

Flow through the MnROAD CLT columns was halted after approximately 46 pore volumes of flow. The columns were left saturated with no flow for 54 days, and then restarted. Concentrations of 11 elements increased when flow was restarted (As, B, Be, Cd, Cu, Mo, Sb, Se, Sr, V, and Zn). This spike in concentrations suggests that under the constant flow conditions in the CLT equilibrium conditions do not exist between the liquid and solid phases. Following the spike, concentrations decreased to those observed just before the flow was stopped (Figs. 4.26.b, 4.26.d, and 4.26.f).

Three elements had the concentration rise back to original peak (Sb), or higher (1.5 to 2.9 times) after the columns were restarted (As and Cd), although As and Cd had very low initial CLT concentrations. Low initial concentrations with subsequent fluctuations at or above initial concentrations were observed for As in the field. For the other seven elements the initial peak concentration was significantly higher then the secondary peak concentration caused by the stoppage and restarting (1.5 to 14 times higher than the secondary peak).

4.3.3. Water Leach Tests

Peak concentrations from the field lysimeters at STH60 and MnROAD are compared with concentrations from WLTs on the same materials in Figure 4.27a. WLTs were not performed on the materials from the other sites. Four liquid-to-solid mass ratios were tested (3:1, 5:1, 10:1, and 20:1). Figure 4.27a shows that concentrations from the 3:1 WLT most closely estimated the peak field concentrations. For elements that were detectable in the 3:1 WLT, the concentrations were within one order of magnitude of the peak field concentration for 91% of tests (Fig. 4.27b). All further discussion of the WLTs will refer to the 3:1 WLT.

Of twenty elements that were detected in field leachate at the MnROAD site, eight elements (Ag, Cd, Co, Fe, Mn, Se, Sn, and Tl) were not detected in 3:1 WLTs on the MnROAD materials (Fig. 4.28). Of these elements, three (Cd, Se, and Tl) had concentrations that exceeded the MCL in field leachate from stabilized materials, but only Cd was found to be elevated relative to the control sections.

The WLT was most useful in predicting field concentrations of elements when the peak field concentration was greater than 200 μg/L. Seven of the eight elements that were not detected in WLT leachate had peak field concentrations of 170 μg/L or less. All elements with peak field concentrations of 500 μg/L or greater were detected in the WLT (Fig. 4.27b).

4.3.4. Comparison of CLT and WLT Prediction Of Field Leaching

Detection limits for the WLT samples were generally higher than those for the CLT samples (Table 3.4). Figure 4.28a compares peak concentrations from the CLT and WLT concentrations to field peak concentrations, with two sets of detection limits for the two laboratory tests. When the CLT has lower detection limits than the WLT, the CLT detects all elements, and is better at predicting the field concentrations of elements that have lower (<500 μg/L) peak field concentrations. If the higher WLT detection limits are applied to the CLT data, the WLT and CLT become very similar in their ability to predict peak field concentrations of elements that exceeded MCLs in the field (Fig. 4.28b). The WLT may have been more successful at predicting elements with lower peak field values if the WLT samples were analyzed with lower detection limits similar to those for the CLT leachates (Table 3.4)

When the higher WLT detection limits are applied to both the WLT and CLT, 45% of elements detected in the field, 36% of elements that exceeded MCLs in the field (Cd, Sb, Se, and Tl), and 13% of elements that exceeded MCL and were elevated relative to the control in the field (Cd) were not detected in the WLT leachate. When the higher WLT detection limits are applied, 25% of elements detected in the field, 27% of elements that exceeded MCLs in the field (Cd, Ni, and Pb), and 38% of elements that exceeded MCL and were elevated relative to the control in the field (Cd, Ni, and Pb) were not detected in the CLT leachate.

SECTION 5

5. CONCLUSIONS

5.1. Conclusions from Field Lysimeters

- Peak concentration of elements observed in leachate from the fly-ash-stabilized materials are, in descending order, Mo (maximum peak concentration of 18,176 µg/L); Sr, Al, Fe, B, and Mn (maximum peak concentration between 10,000 and 1,000 µg/L); Sn, Ba, V, Se, Zn, As, Cu, Tl, and Ni (maximum peak concentration between 1,000 and 100 µg/L); and Pb, Cr, Sb, Ti, Co, Cd, and Ag (maximum peak concentration between 100 and 10 µg/L). Peak concentrations of both Hg and Be were less than 1 µg/L.
- Among elements that were tested during the entire operation of each site and that were detected at the site, 61% of elements had the peak concentration occur during the first two PVF. Cd, Co, Cr, Ni, and Se are the most common elements with early peak concentrations.
- Elements that exceeded MCLs in field leachate from stabilized materials were As, B, Cd, Cr, Mo, Ni, Pb, Sb, Se, Tl, and V. Of these 11 elements, As, B, Cd, Cr, Mo, Ni, Pb, and V had concentrations of were elevated relative to concentrations from control materials at the same site.
    - B, Mo, and V concentrations in leachate from the fly-ash-stabilized materials were elevated relative to concentrations from control sections, and were above the MCL at most sites. B, Mo, and V concentrations exceeded the MCL for at least 6 PVF and 9 years at the STH60 site.
    - Ni concentrations only exceeded the MCL, and were elevated relative to concentrations from control sections, at the US12 site. Leachate at this site had

    higher pH and more reducing conditions than the other sites. These conditions are not common, but illustrate how pH and Eh influence leaching behavior.

    - Concentrations of As and Pb in field leachate remained near the MCL and periodically exceed the MCL, over many PVF. Concentrations of As and Pb were elevated only slightly relative to control concentrations.
    - At sites where Cd and Cr exceeded the MCL, the MCL was only exceeded during the first sampling event (PVF at Peak ≤ 0.25). Concentrations were below the MCL in all subsequent PVF.

- All sites except for US12 East had pH near 7 and predominantly oxidizing conditions (Eh of approximately +150 to +300 mV). US12 East had higher pH (up to 9) and reducing conditions (Eh of approximately -370 to +250 mV). The US12 East leachate was grey in color, and a strong odor. All other field leachates were generally clear to yellow and had no noticeable odor. Differences in pH and Eh between sites may influence solubility and leaching of trace elements.
- Long-term average flux discharged from the stabilized roadway layers is 1% to 3% of precipitation for stabilized subgrade and 2% to 8% of precipitation for stabilized RPM base course. Flux discharged from the stabilized roadway materials is less than average regional recharge rates (approximately 20% of precipitation). The difference between flux discharged from the stabilized materials and recharge in areas adjacent to the road will affect the fate in the subsurface of elements in the leachate, and may reduce the impact to groundwater.
- Peak volumetric fluxes from the layers occur in the spring months when heavy rains and snow melt occur, and in the late summer and early fall. Minimum fluxes occur in the winter, and in July or August. Occasionally the flux from the stabilized materials approaches 15% of

precipitation for a period of several months, but the long-term average is never more than 7.8% of precipitation.

- There is a statistically significant, but weak correlation between peak concentration in the field leachate and the solid-phase concentration in the fly ash ($R^2 = 0.30$).

5.2. Conclusions from Laboratory Leaching Tests

- When using laboratory tests to predict field leaching concentrations, an analytical method with minimum detection limits equal to or less than the lowest MCL should be used. Without sufficiently low MDLs in the laboratory tests, elements that are not detected in the laboratory tests may be present in field leachate, and may exceed the MCL in the field. 45% of elements detected in the field, 36% of elements that exceeded MCLs in the field (Cd, Sb, Se, and Tl), and 13% of elements that exceeded MCL and were elevated relative to the control in the field (Cd) were not detected in the WLT leachate. When the higher WLT MDLs were applied to the CLT data, 25% of elements detected in the field, 27% of elements that exceeded MCLs in the field (Cd, Ni, and Pb), and 38% of elements that exceeded MCL and were elevated relative to the control in the field (Cd, Ni, and Pb) were not detected in the CLT leachate The method detection limits should be determined before testing of samples begins.
- The pH of leachate from CLT and WLT on stabilized materials (generally 10 to 11) is higher than from the same materials in the field (6 to 8). Eh of leachate from CLT and WLT on stabilized materials is lower (-5 to +40 mV) than from the same materials in the field (mostly between +150 to +300 mV), where leachate is generally oxidizing. The differences in pH and Eh between stabilized materials in the field and in a CLT may be caused by the difference in saturation (saturated flow in CLTs and unsaturated flow in the field). This may

affect element speciation, solubility, and mobility, and therefore affect the prediction of field concentrations using the CLT and WLT methods described in this study.

- Average peak concentrations from the CLT were within one order of magnitude of the average peak field concentration in 77% of cases. Both the CLT and field leachates had concentrations that were above the MCL, elevated relative to the control, and 1.1 to 3.5 times higher than the field average peak) for the elements consistently elevated relative to the control concentrations and MCLs (B, Mo, and V), as well as for Cr (CLT average peak 8.6 times higher than the field average peak).
- As, Cd, Ni, and Pb had concentrations exceeding the MCL in the field, but not in the CLTs. Concentrations of these elements were either slightly elevated in the field but not in the CLT (As, Cd, and Pb), or elevated in both the field and CLT (Ni).
- Sb, Se, and Tl concentrations exceeded MCLs in the field but were not elevated relative to concentrations from control materials. Concentrations of these elements also exceeded the MCL in CLTs. However, Sb and Se were elevated relative to controls in the CLT.
- First-flush leaching patterns were more commonly observed in CLTs compared to field leaching patterns, First-flush leaching patterns were observed in CLTs for 13 elements, all of which had first-flush leaching pattern in leachate from at least on field site with stabilized materials. B, Cd, Cr, Mo, Sb, Se, and V exceeded MCLs in field leachate and had first-flush leaching patterns in CLTs. As, Ni, Pb, and Tl exceeded the MCL in the field and did not have a first-flush CLT patterns.
- Stopping and restarting the CLTs caused concentrations of 11 of the elements to spike (As, B, Be, Cd, Cu, Mo, Sb, Se, Sr, V, and Zn), suggesting that local equilibrium between liquid and solid phases may not exist in CLT tests with steady saturated flow. Following the spike, concentrations decreased to those observed just before the flow was stopped.

- Of the four liquid-to-solid (L:S) ratios used in the WLTs, the 3:1 L:S ratio provided concentrations closest to field peak concentrations. Of twenty elements that were detected in field leachate at the MnROAD site, eight of these were not detected WLTs conducted with 3:1 L:S ratio on the materials. Seven of the eight elements that were not detected in WLT leachate had peak field concentrations of 170 µg/L or less. All elements with peak field concentrations of 500 µg/L or greater were detected in the WLT. If the WLT leachates were analyzed with lower detection limits, the WLT with 3:1 L:S ratio may have detected more or all of the elements detected in the field.
- When CLT and WLT concentrations are compared using the same detection limits, concentrations from both tests are similar in the ability to predict peak field concentrations within one order of magnitude.

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FIGURES

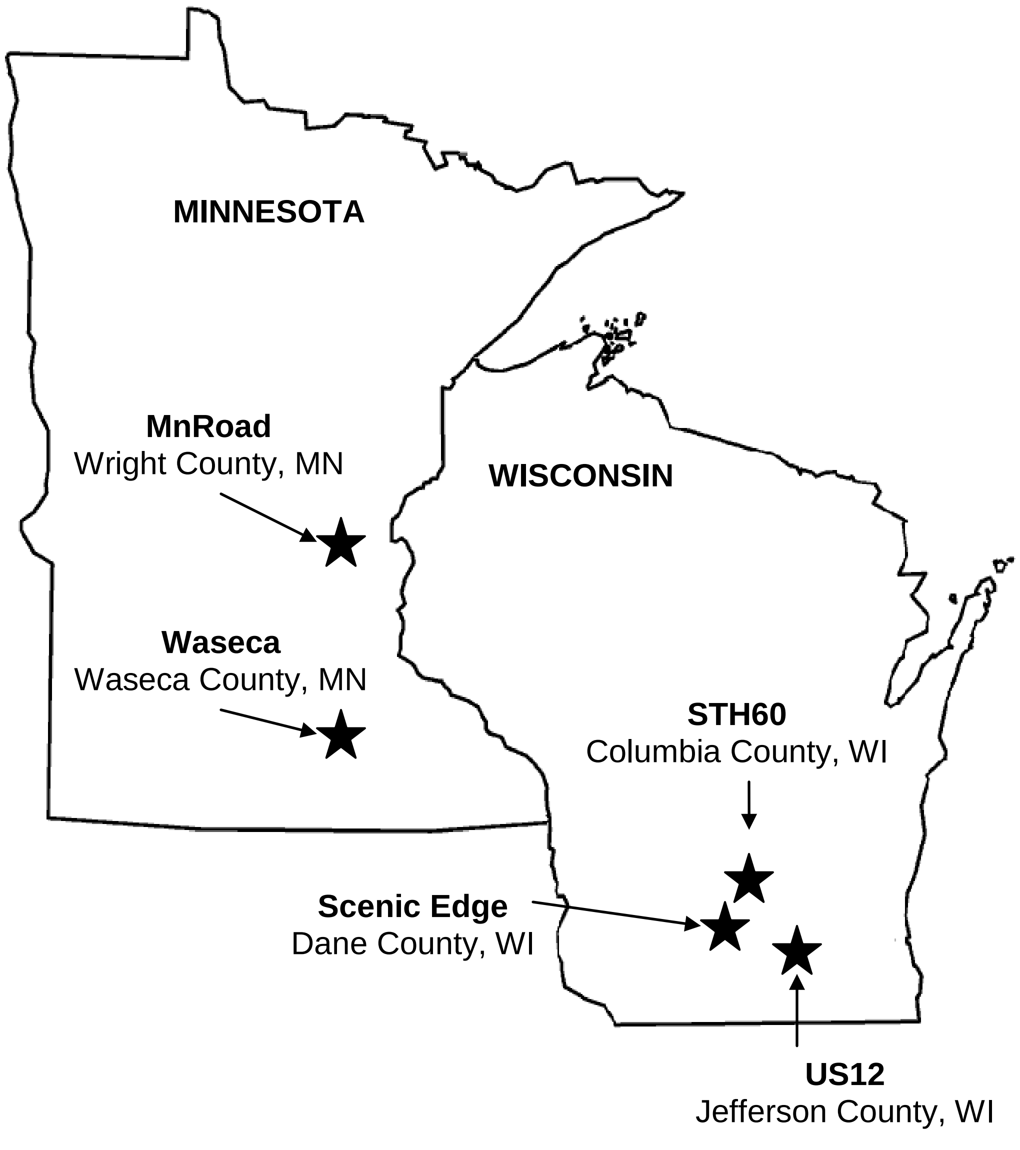
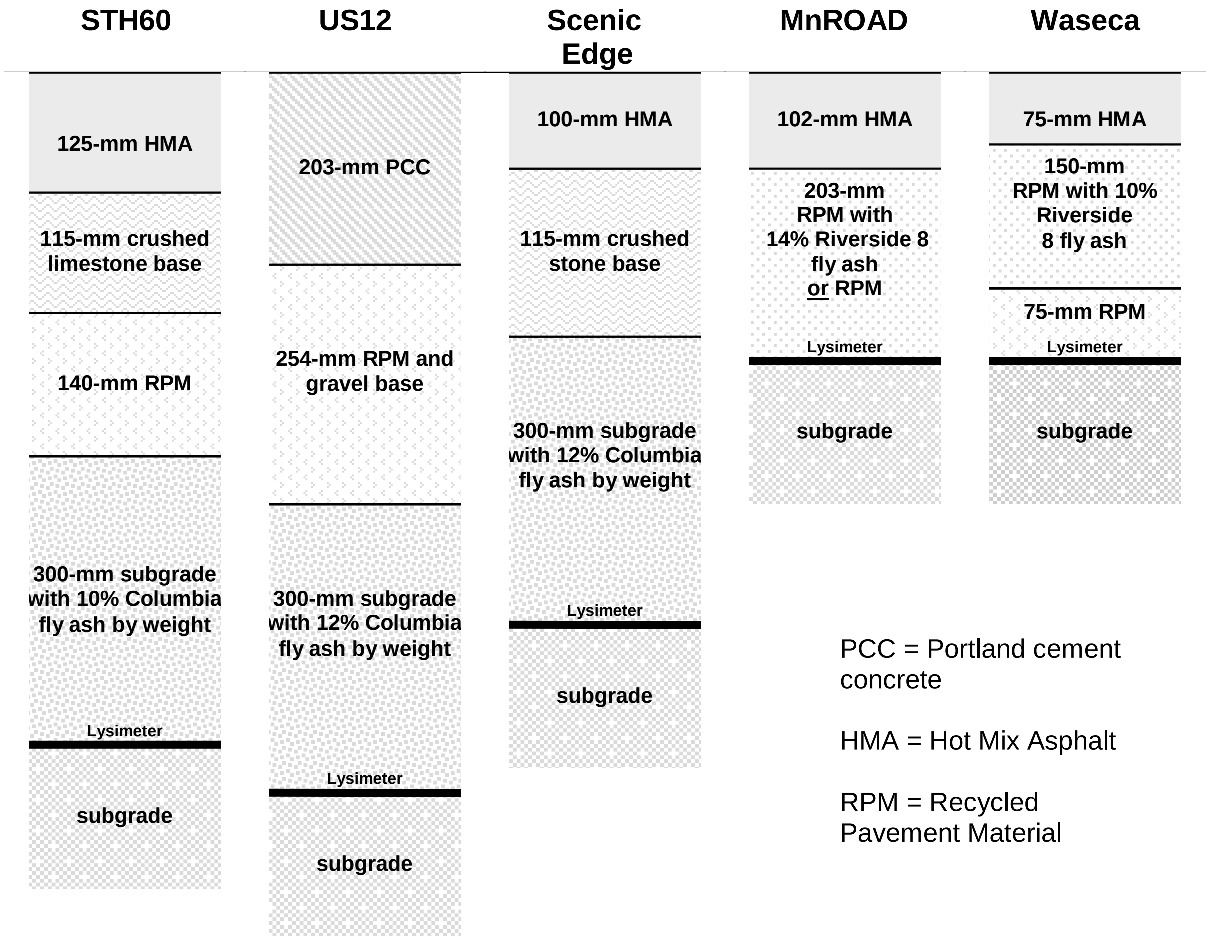


Fig. 2.1. Location of field sites in Wisconsin and Minnesota.

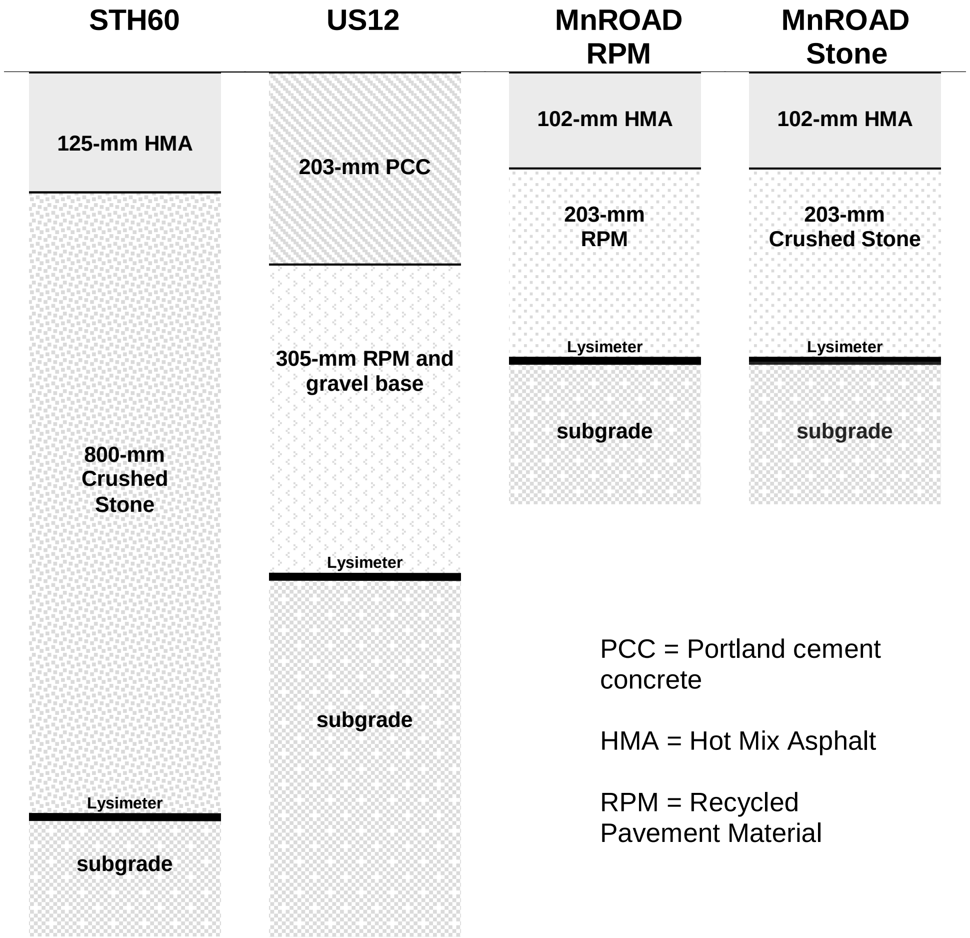


PCC = Portland cement concrete

HMA = Hot Mix Asphalt

RPM = Recycled Pavement Material

Fig. 2.2. Profiles of Fly-Ash Stabilized Roadway Sections Being Evaluated at the Field Sites.



PCC = Portland cement concrete

HMA = Hot Mix Asphalt

RPM = Recycled Pavement Material

Fig. 2.3. Profiles of Control Roadway Sections Being Evaluated at the Field Sites.

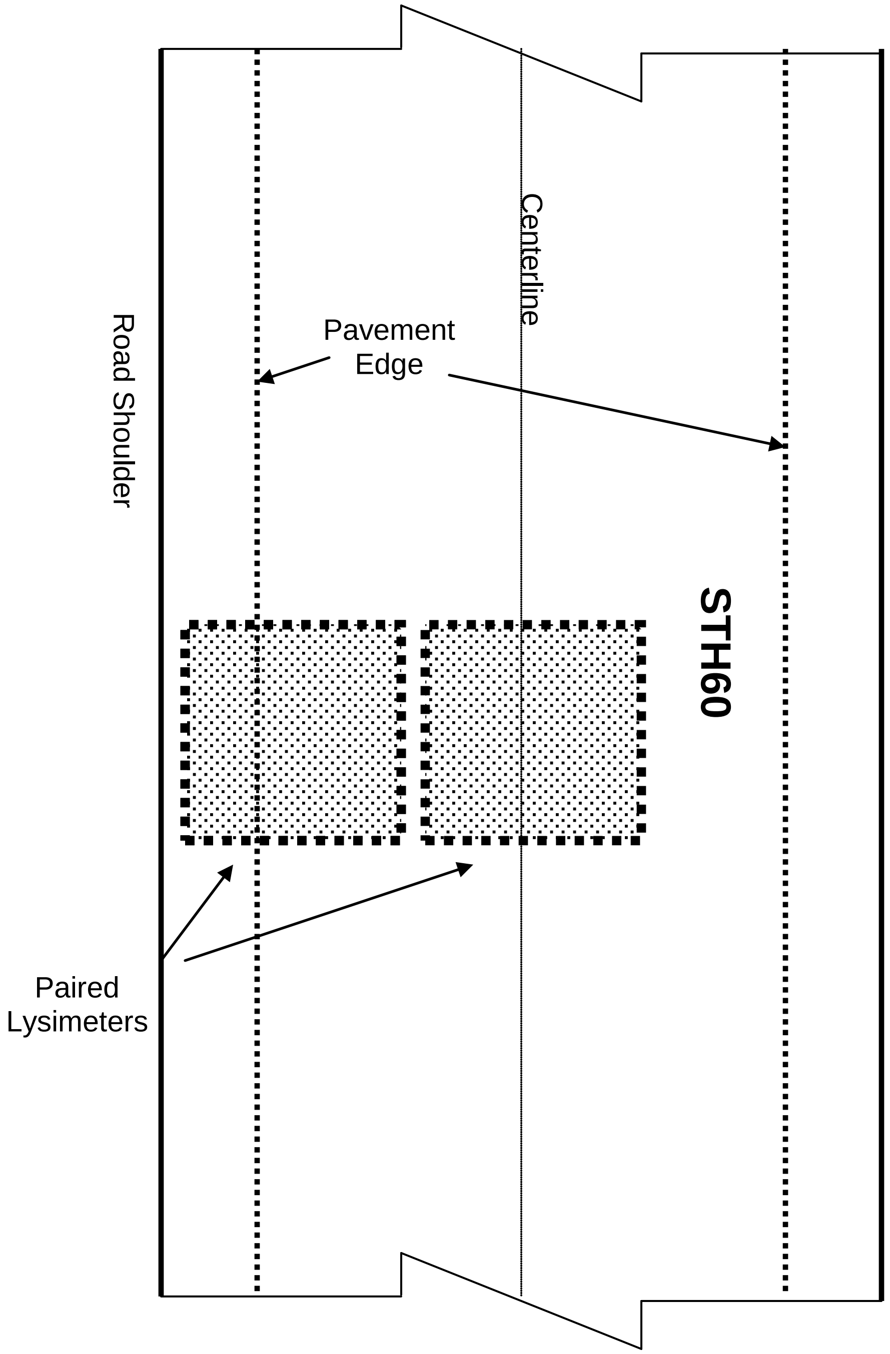


Fig. 2.4. Schematic of lysimeter pairs at STH60.

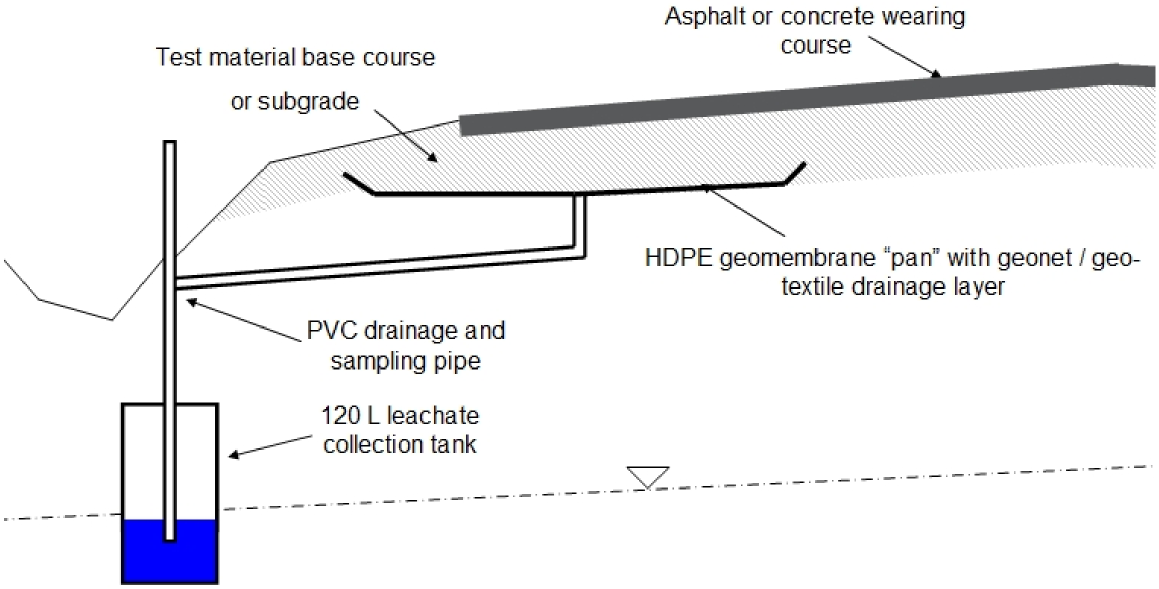


Fig. 2.5. Cross-section of typical pan lysimeter in roadway.

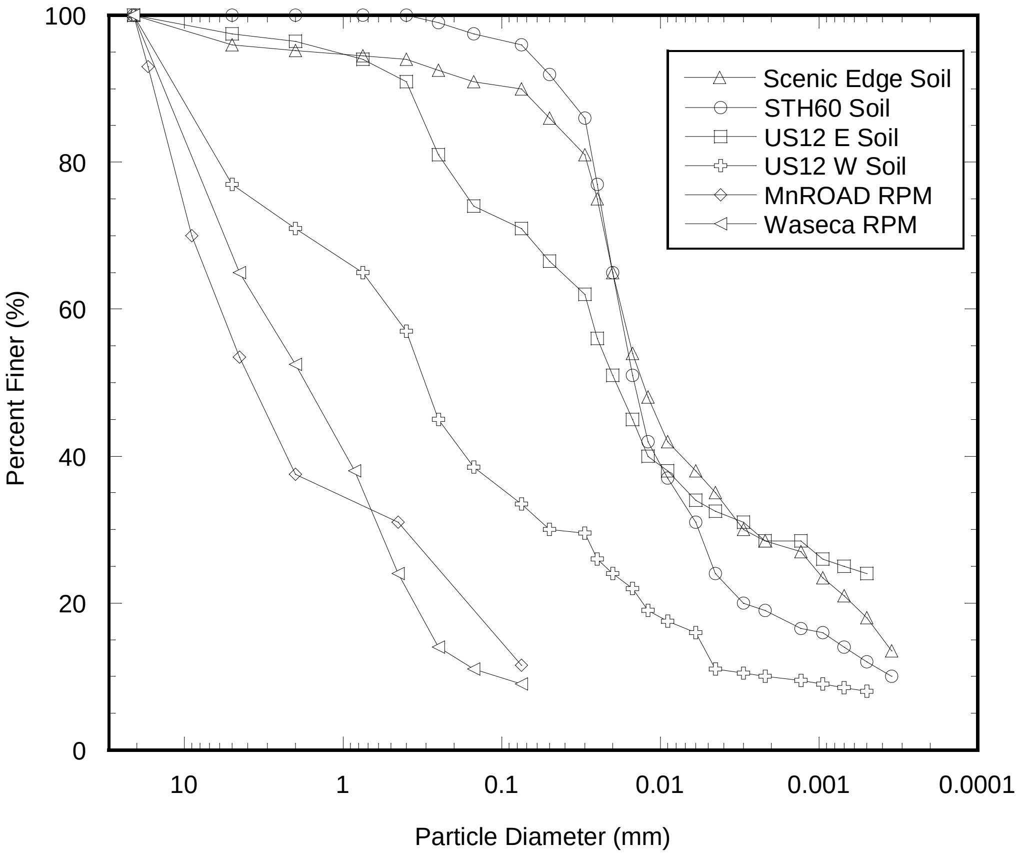


Fig. 3.1. Particle Size Distribution of Subgrade Soils and RPMs

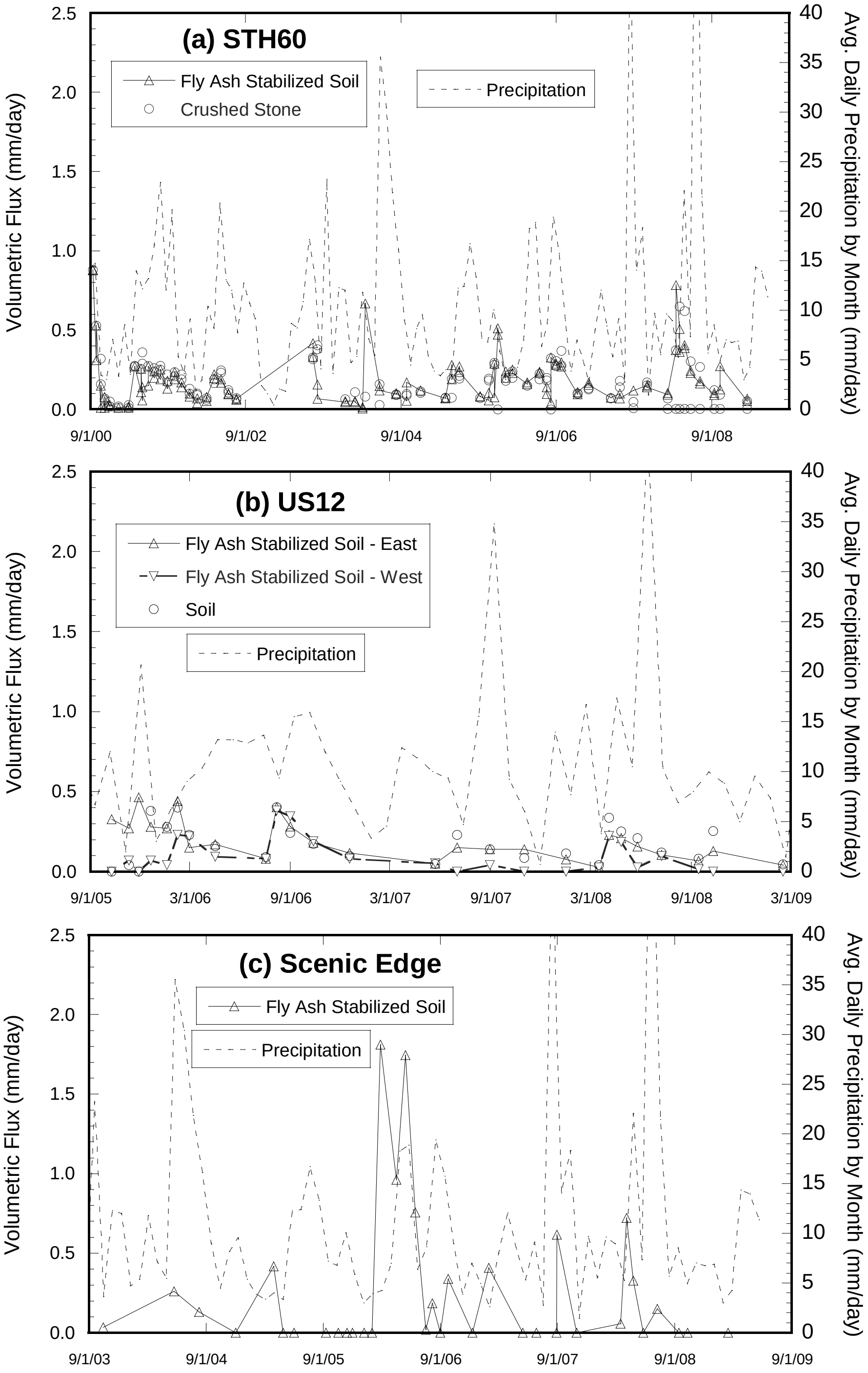


Fig. 4.1. Volumetric flux from stabilized subgrade and control layers with local average daily precipitation rates from the (a) STH60, (b) US12, and (c) Scenic Edge sites.

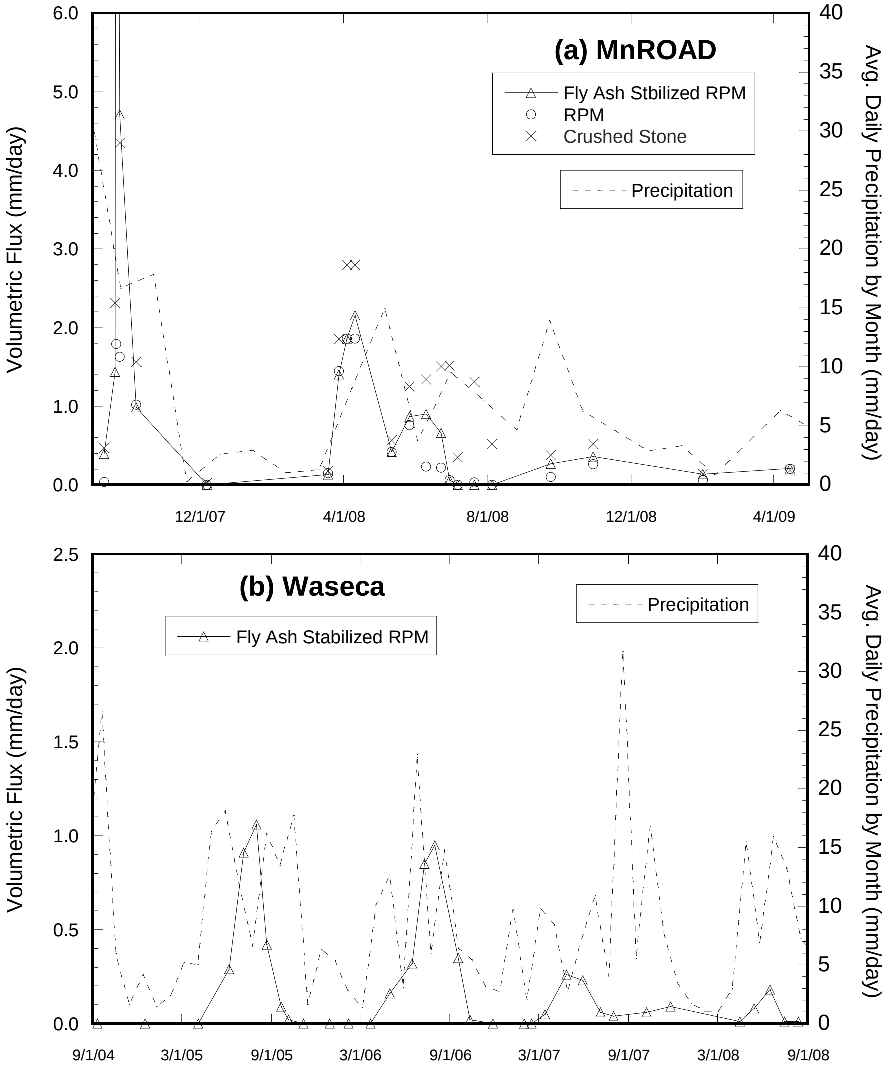


Fig. 4.2. Volumetric flux from the stabilized RPM base courses and control layers with local average daily precipitation rates from the (a) MnROAD and (b) Waseca sites.

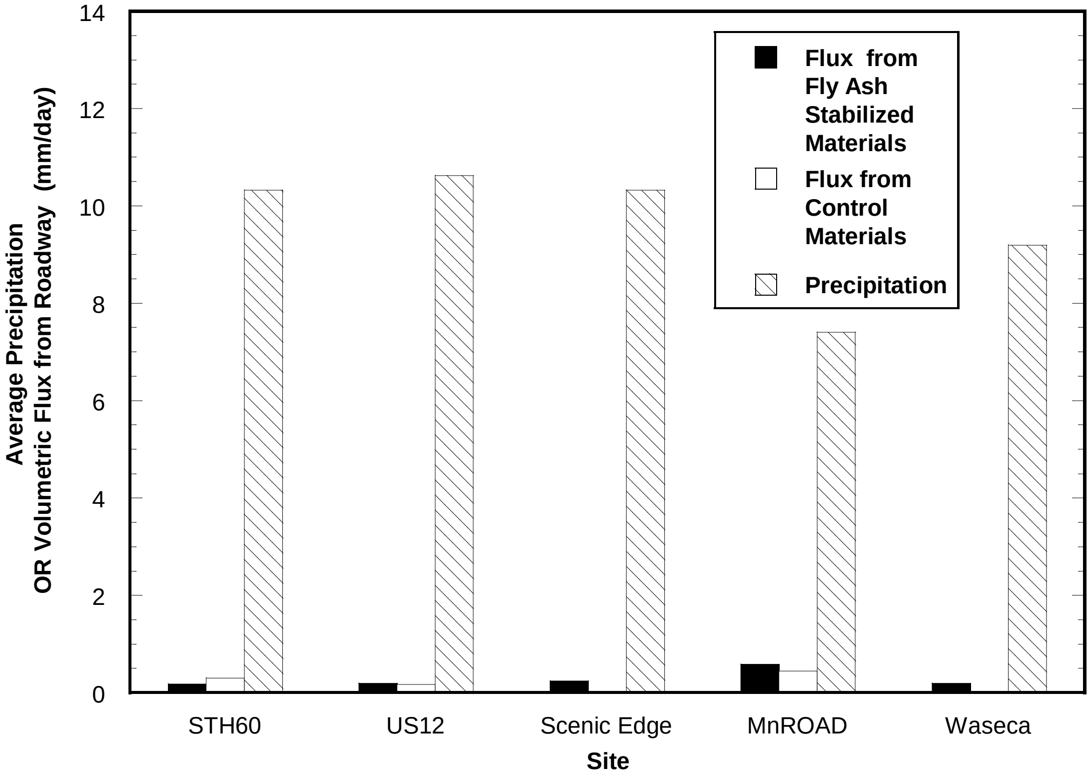


Fig. 4.3. Comparison of Long-term Volumetric Flux from the Road Layers Relative to Average Daily Precipitation.

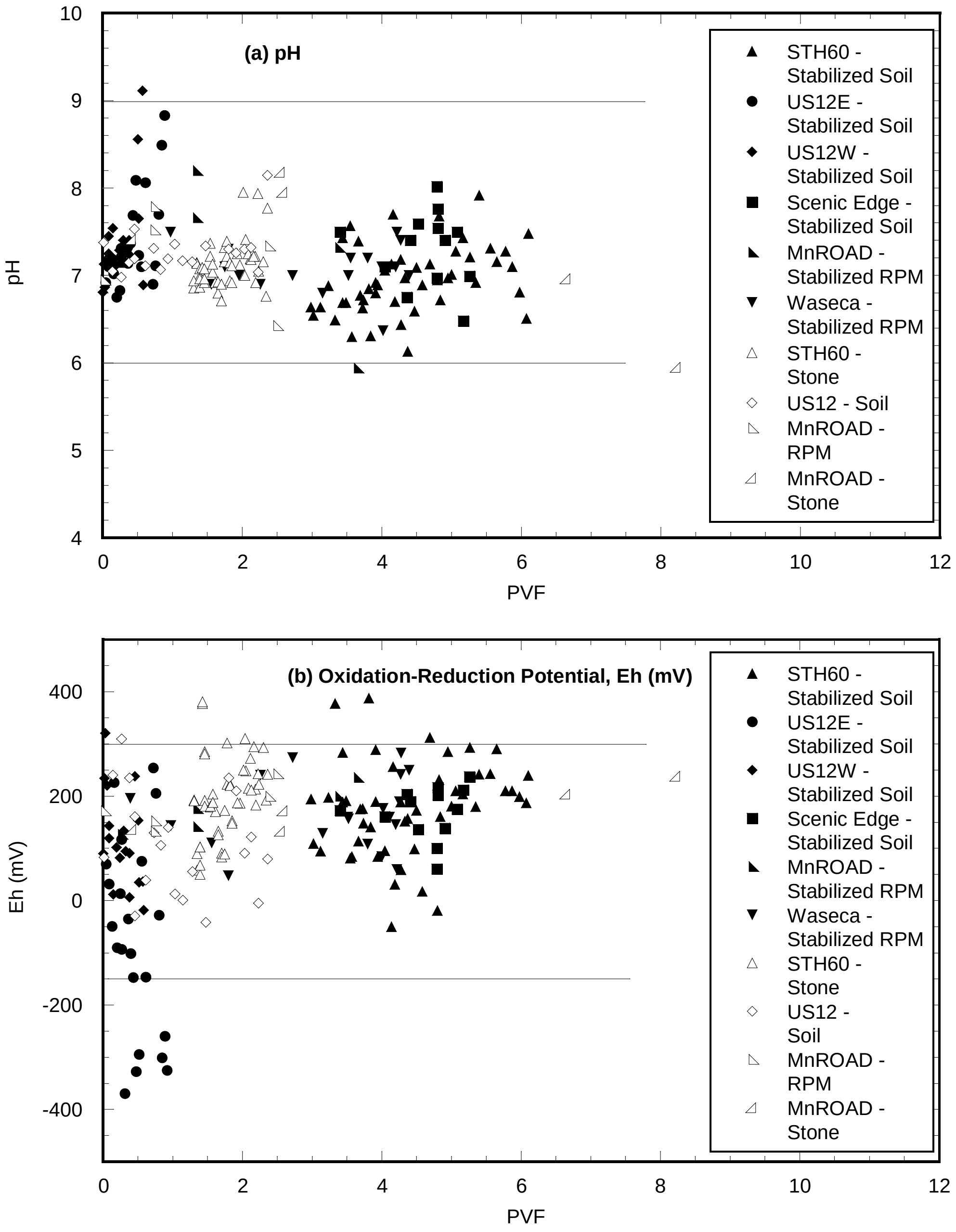


Fig. 4.4. (a) pH and (b) Eh of Leachate from Field Lysimeters for Fly-ash-stabilized and Control Materials.

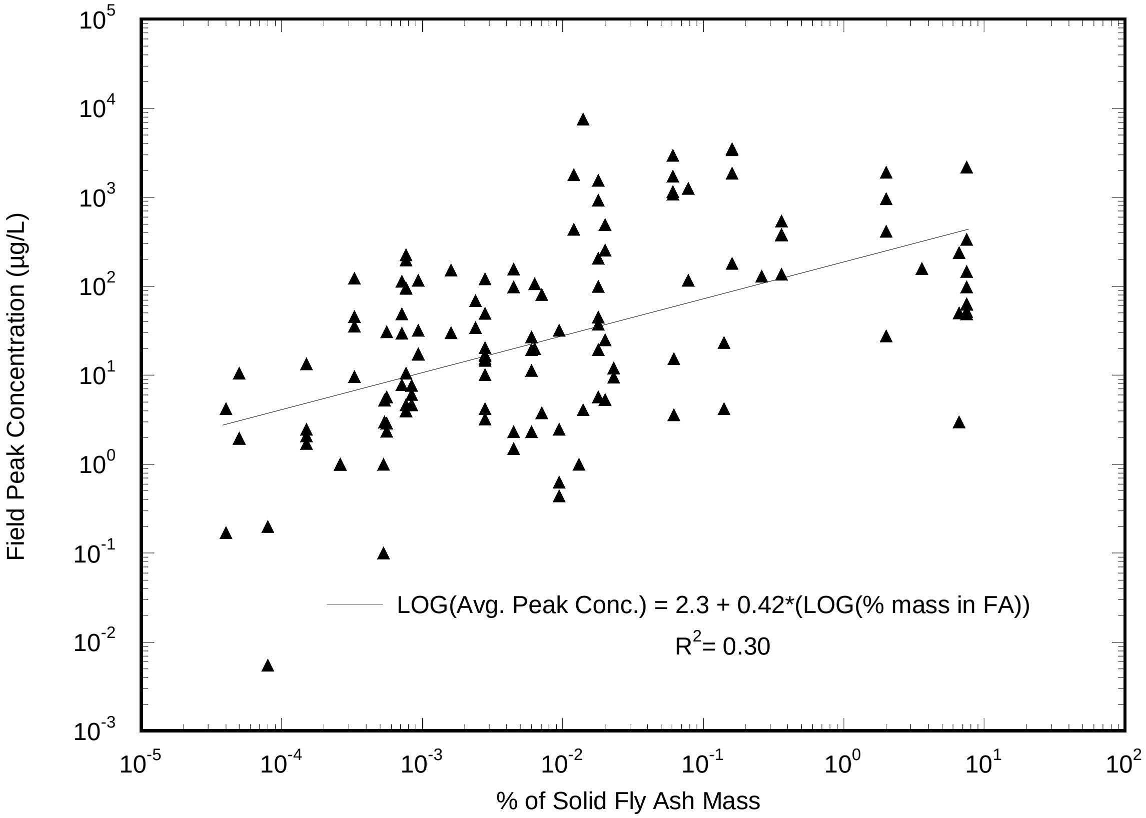
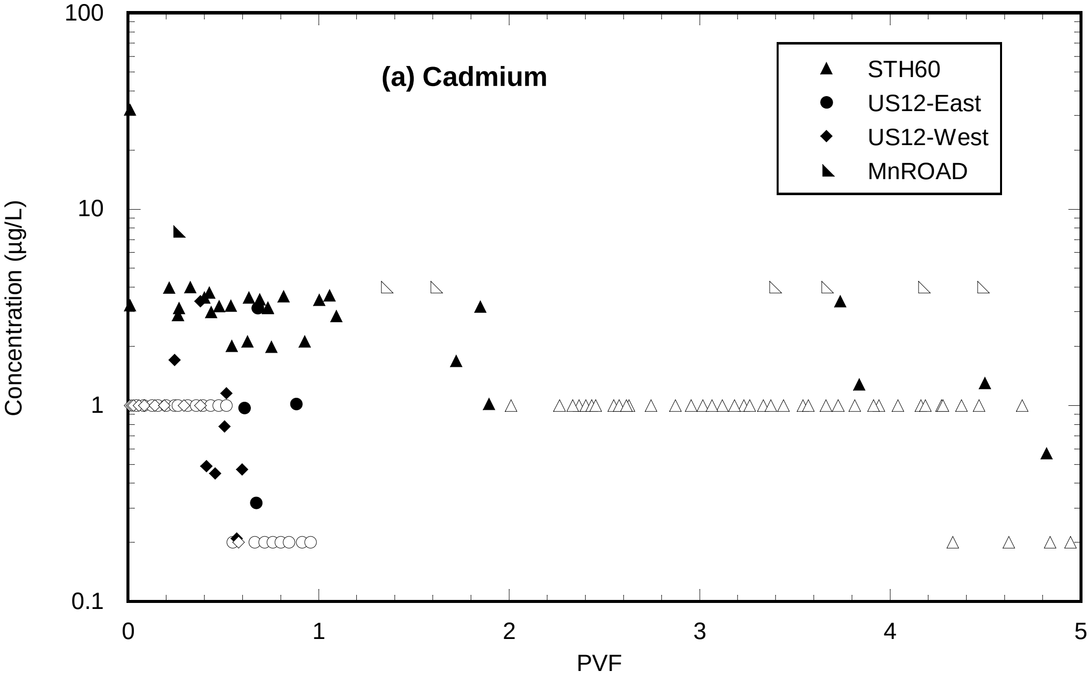


Fig. 4.5. Average Peak Concentrations from Field Relative to Percentage of Each Element in Solid Fly Ash Mass.



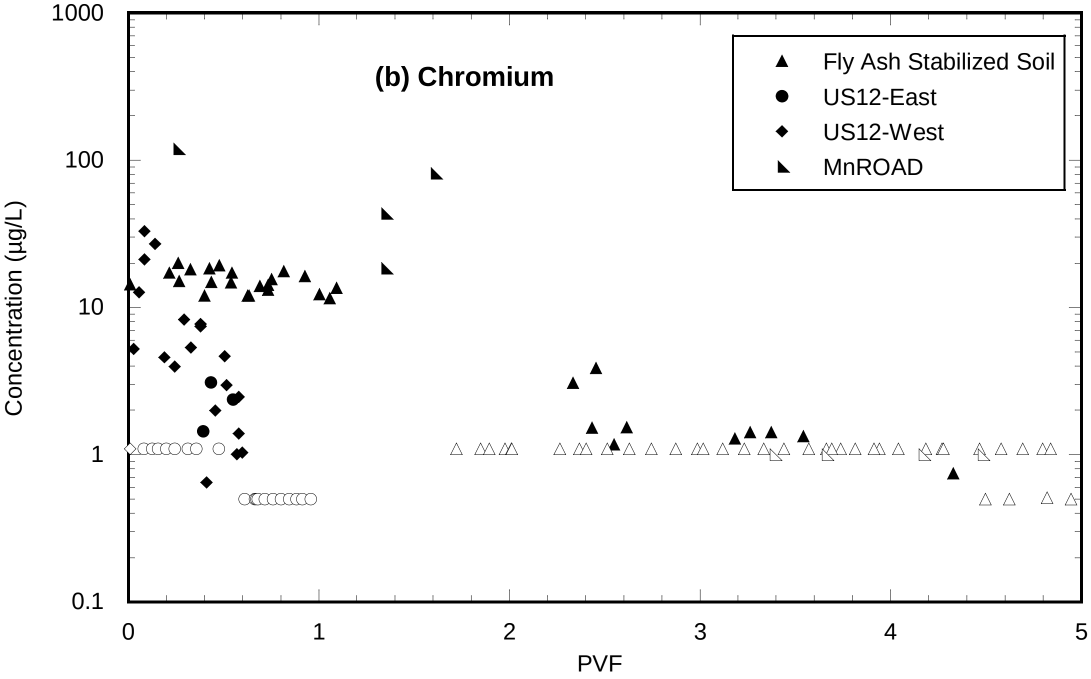


Fig. 4.6. Peak Concentrations occurring during first two PVF for (a) cadmium and (b) chromium.

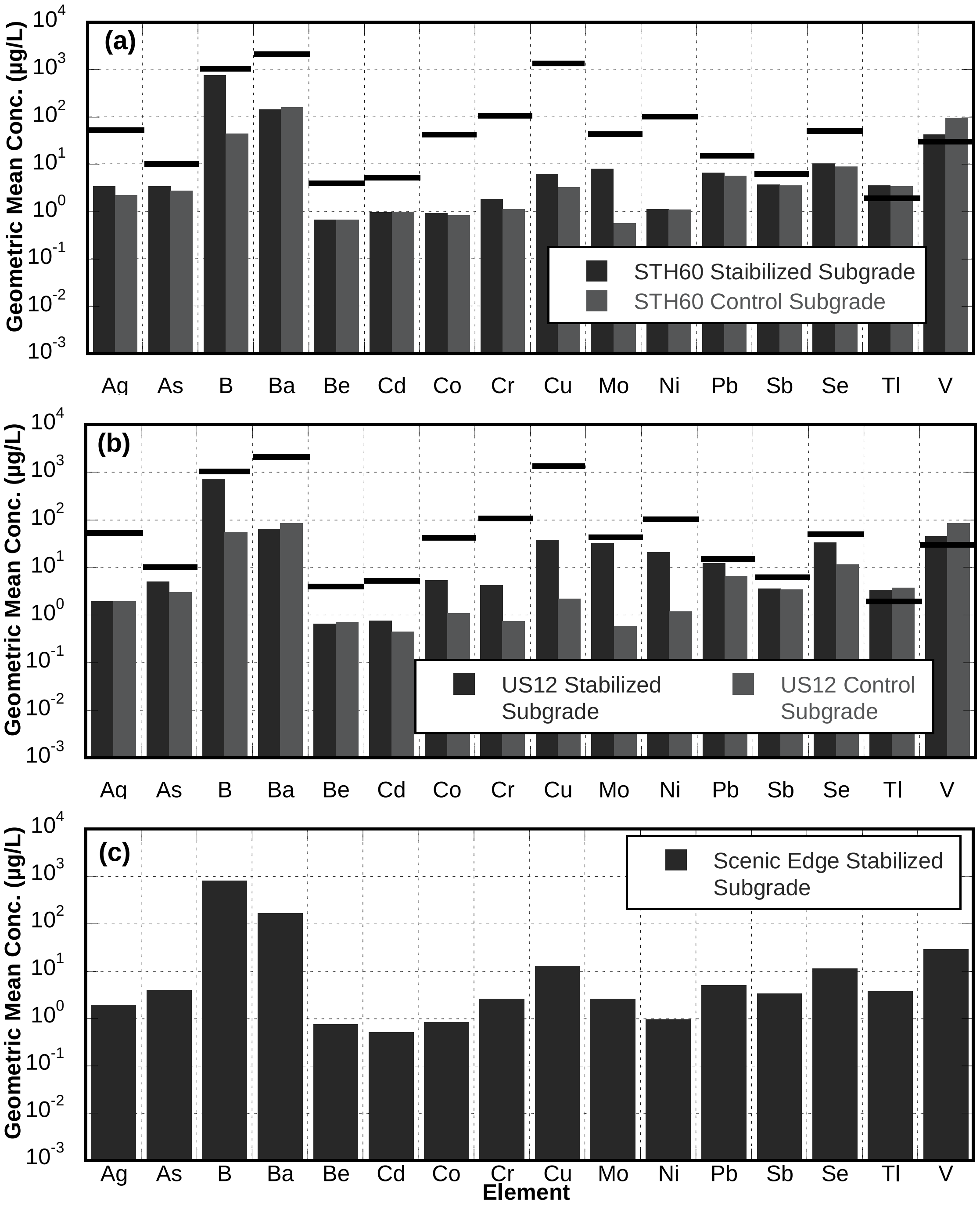


Fig. 4.7. Geometric mean concentrations over the entire study compared to MCLs (indicated by thick black bars) for the (a) STH60, (b) US12, and (c) Scenic Edge sites.

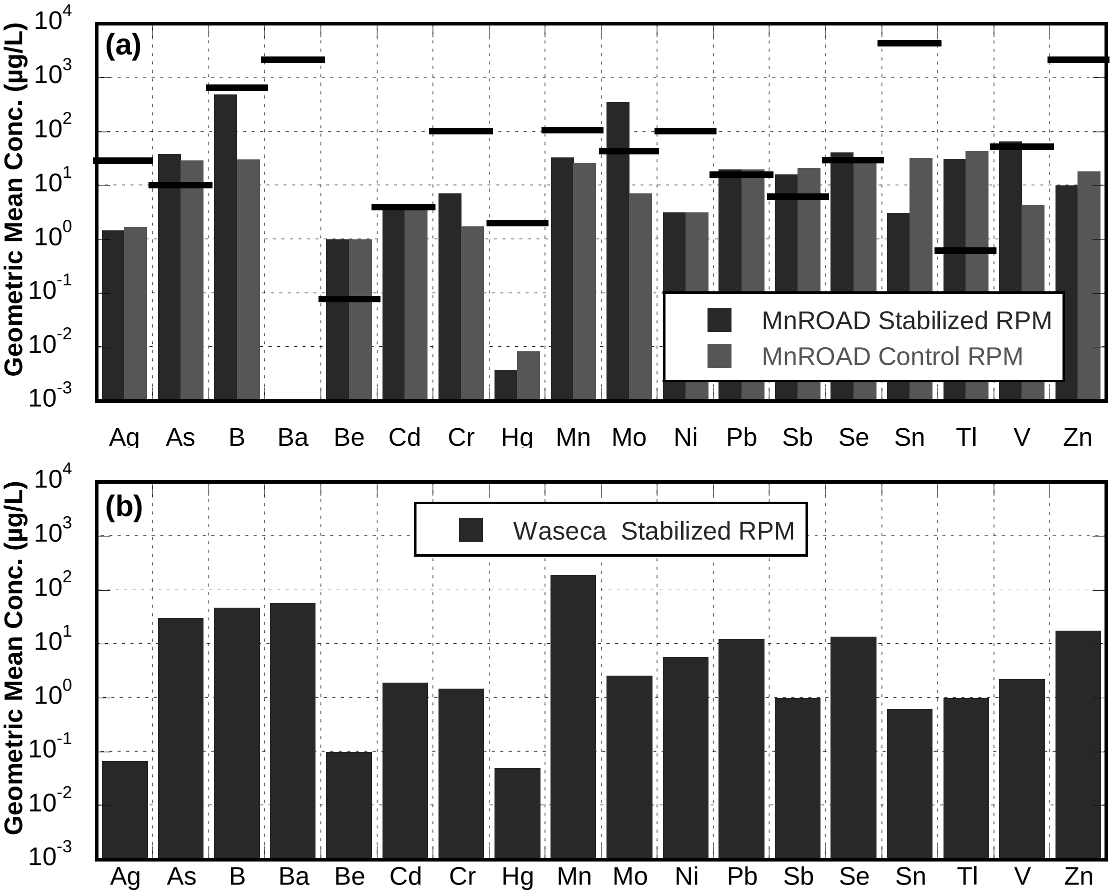


Fig. 4.8. Geometric mean concentrations over the entire study compared to MCLs (indicated by thick black bars) for the (a) MnROAD, and (b) Waseca sites.

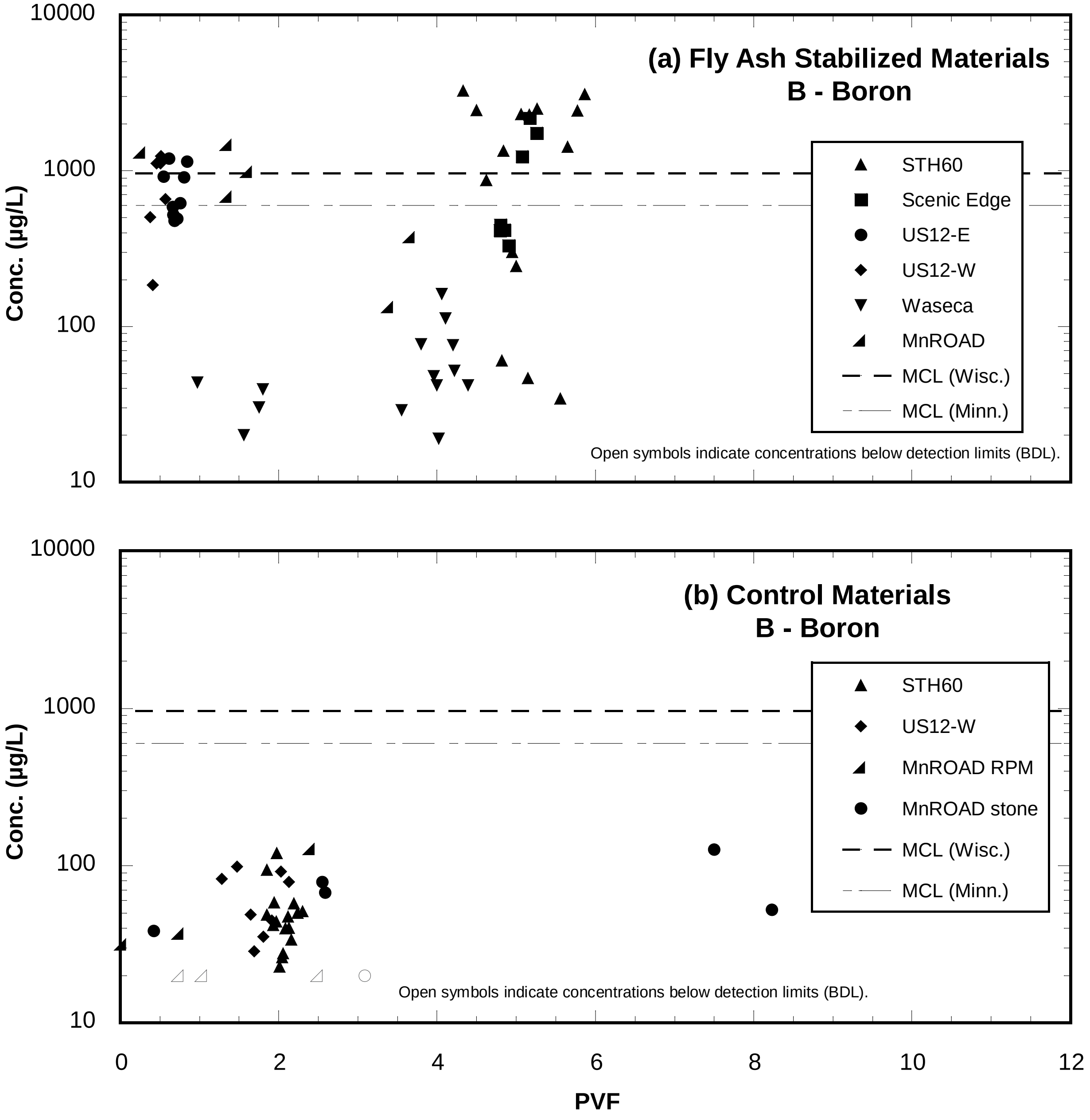


Fig. 4.9. Boron (B) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

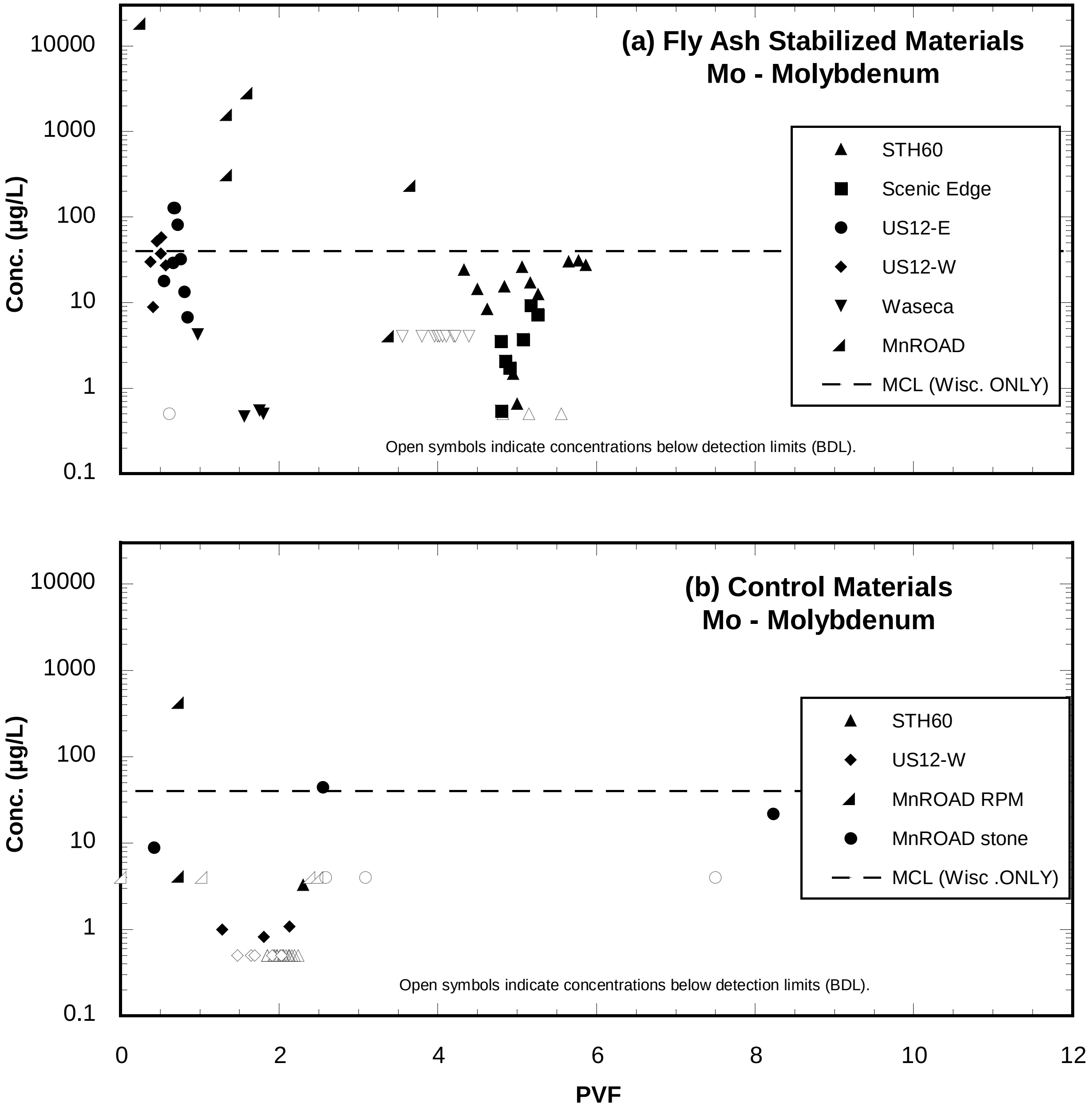


Fig. 4.10. Molybdenum (Mo) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

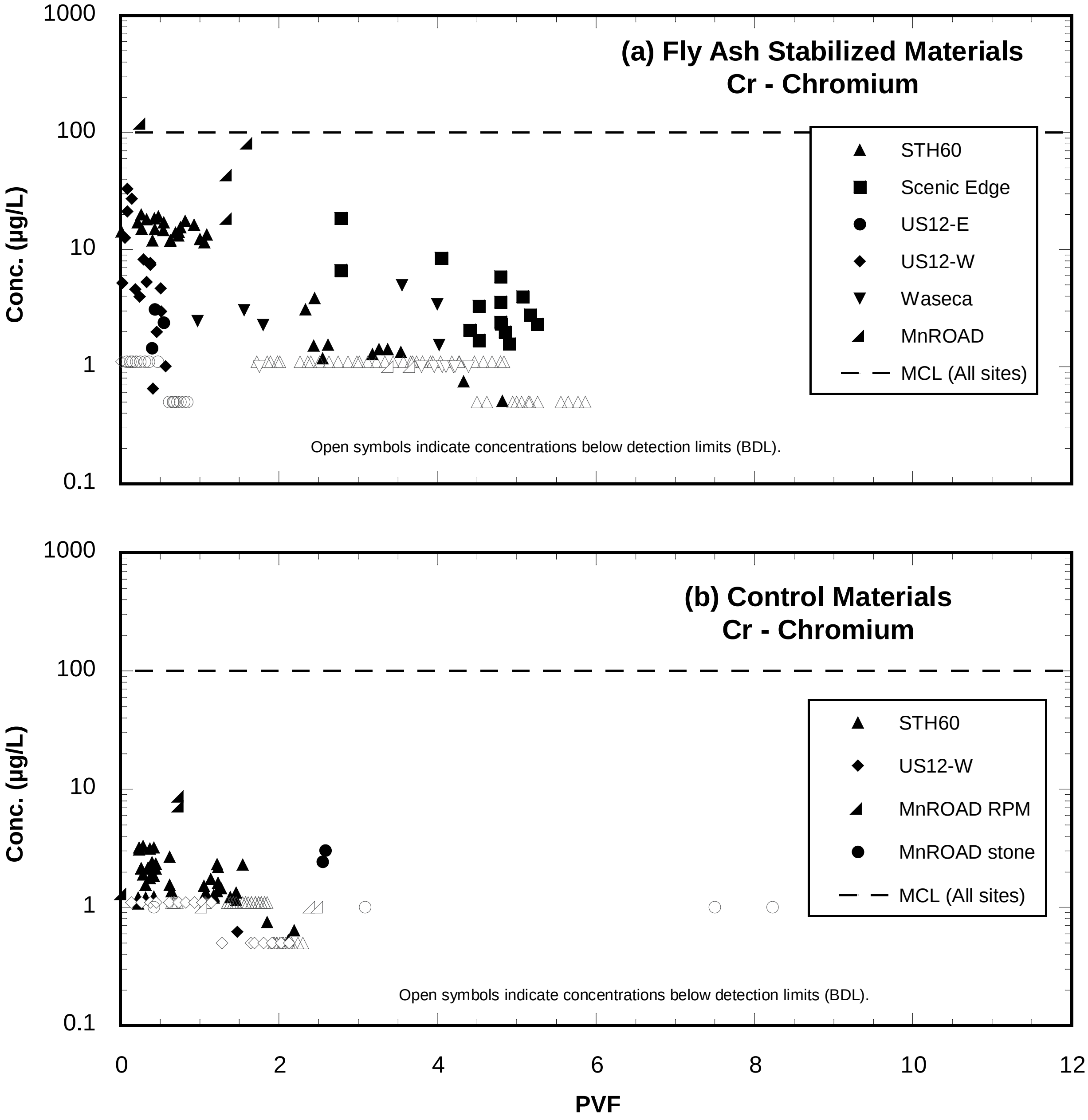


Fig. 4.11. Chromium (Cr) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

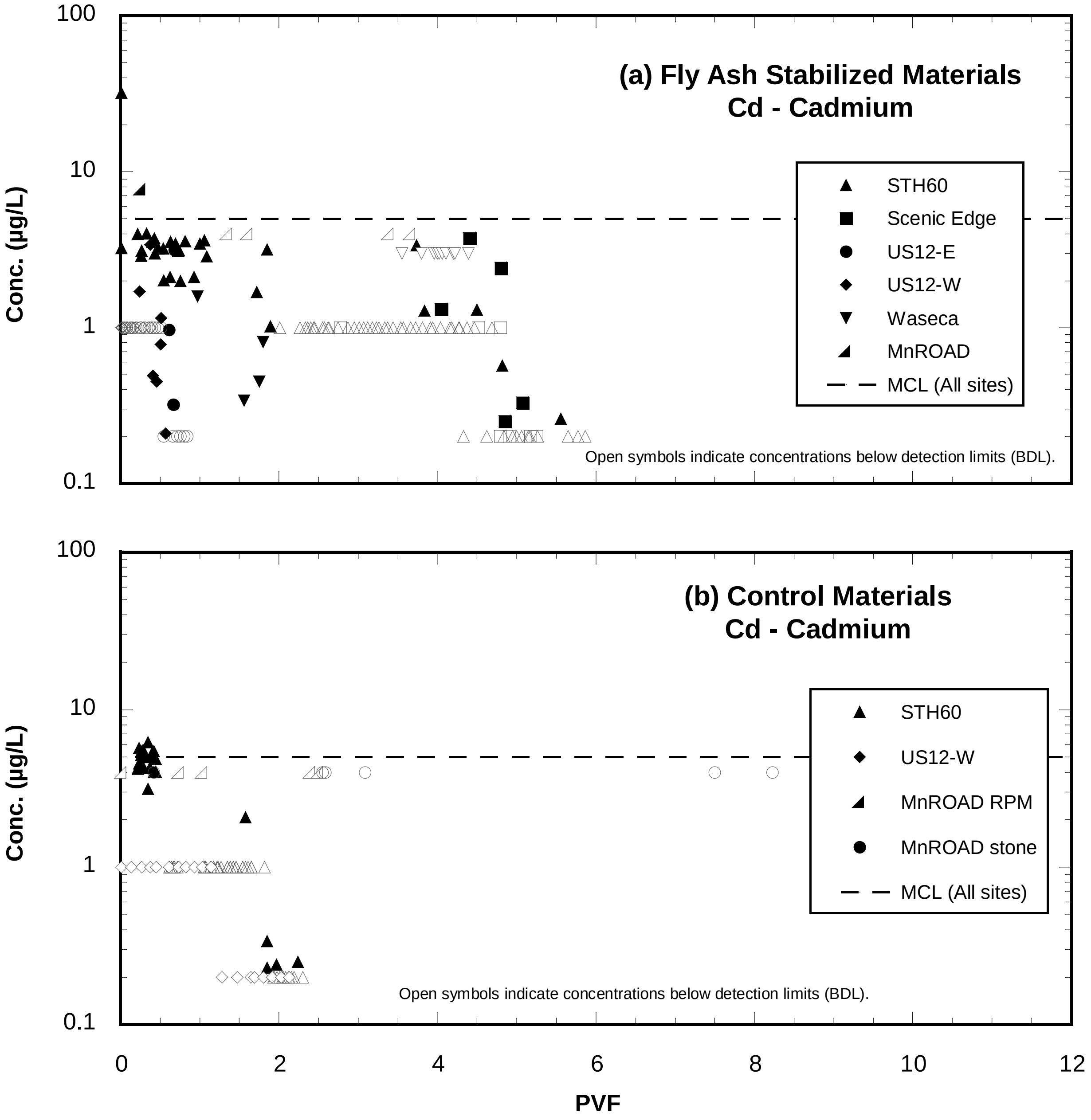


Fig. 4.12. Cadmium (Cd) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

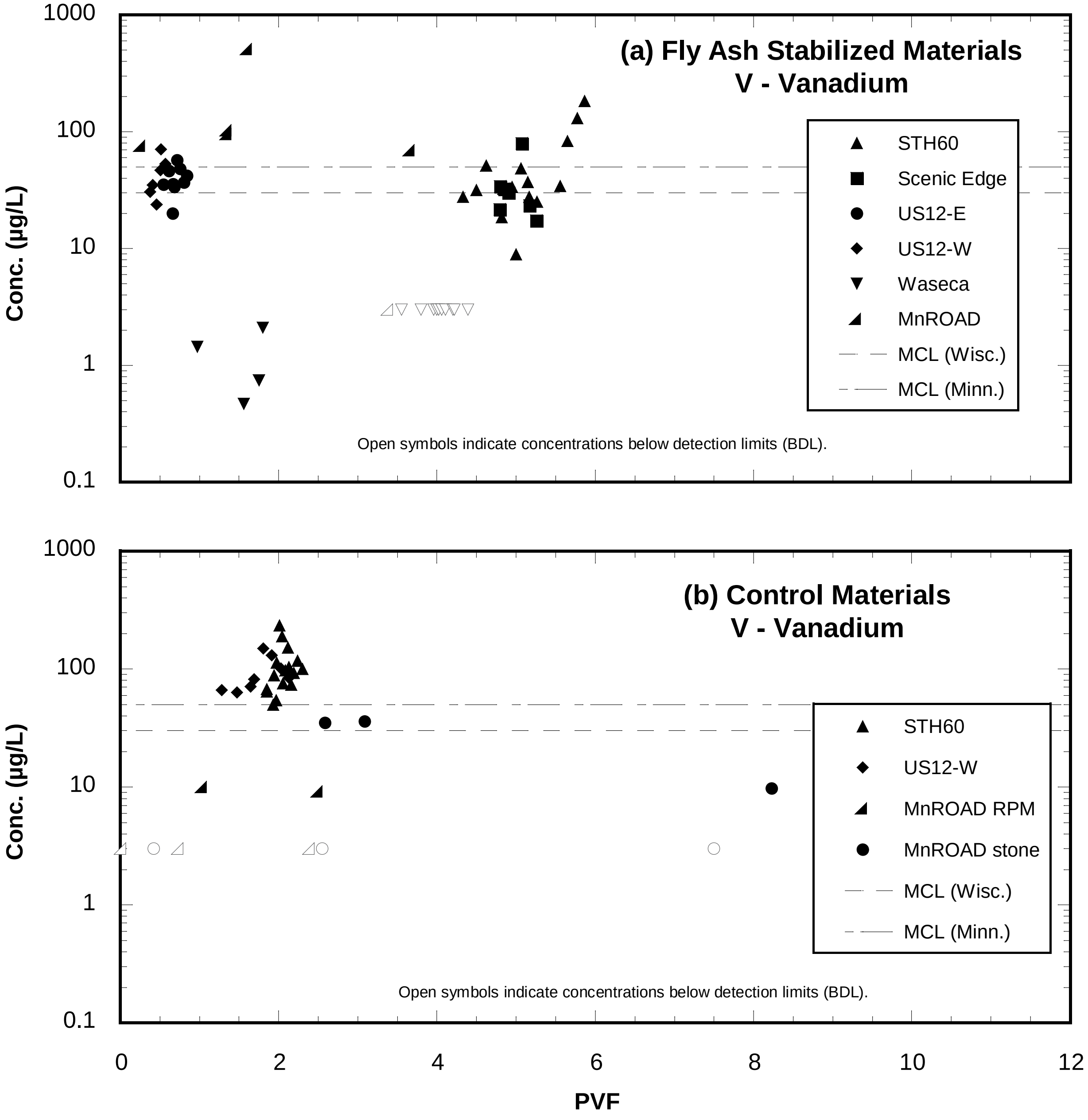


Fig. 4.13. Vanadium (V) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

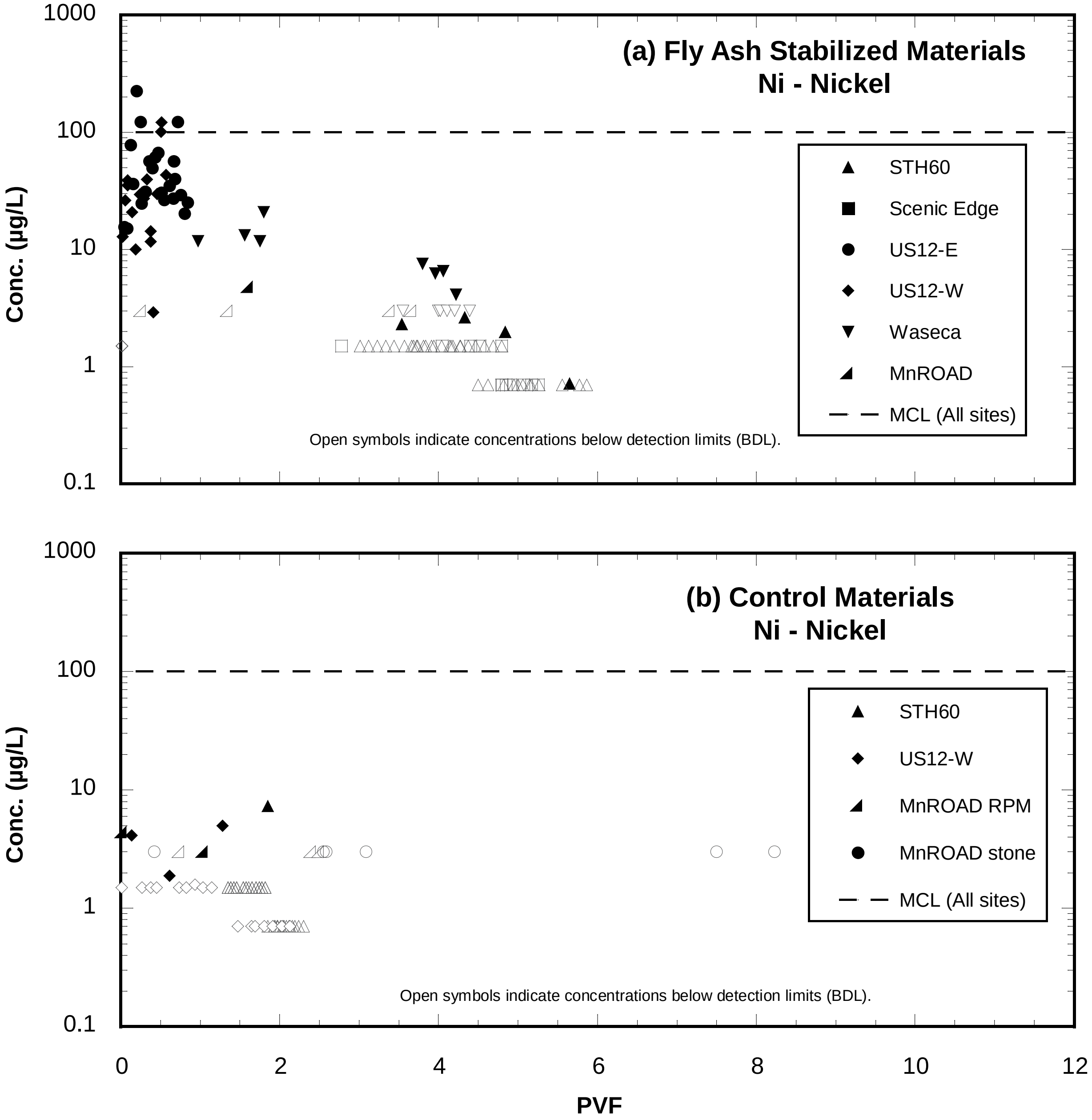


Fig. 4.14. Nickel (Ni) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

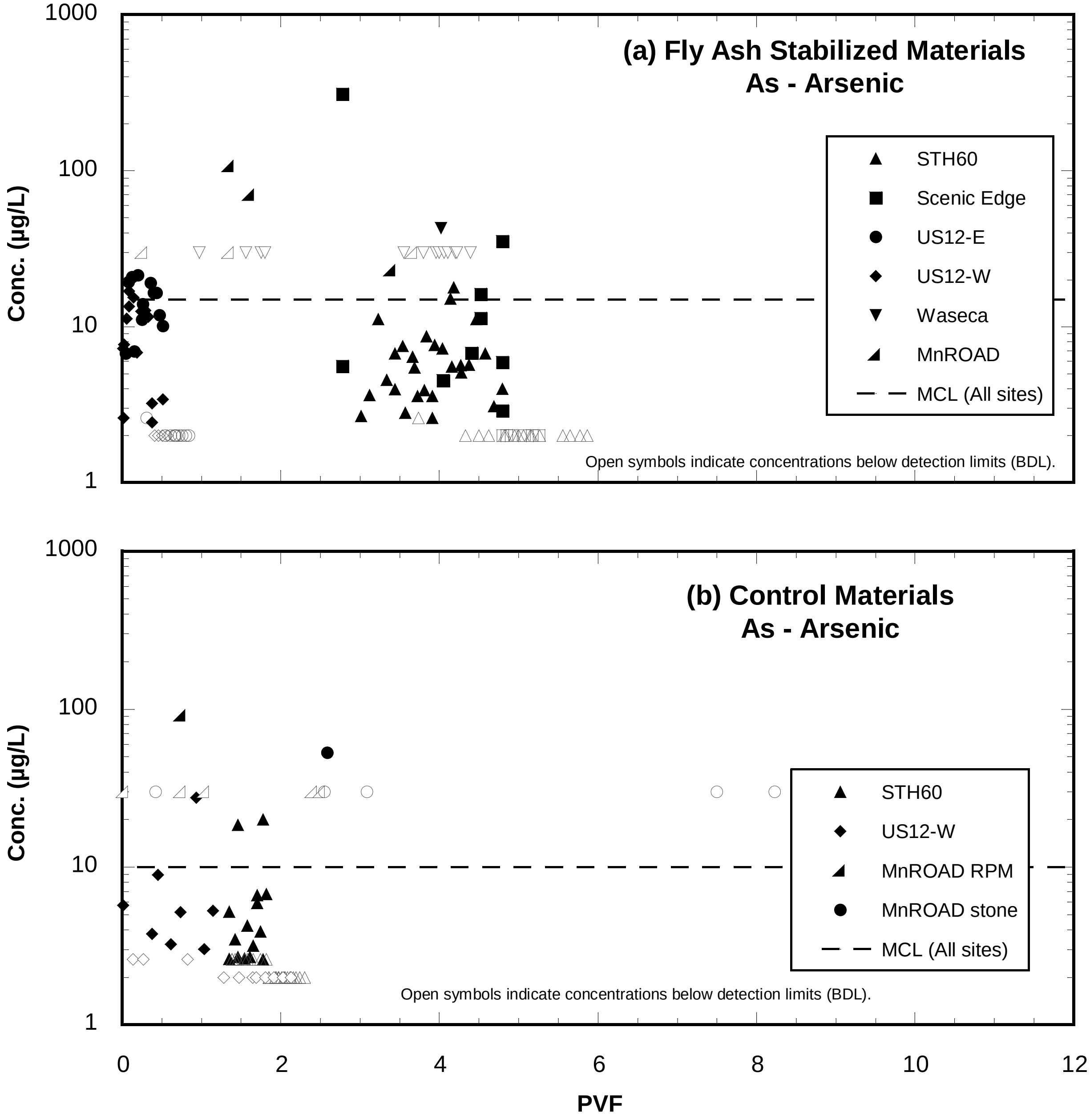


Fig. 4.15. Arsenic (As) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

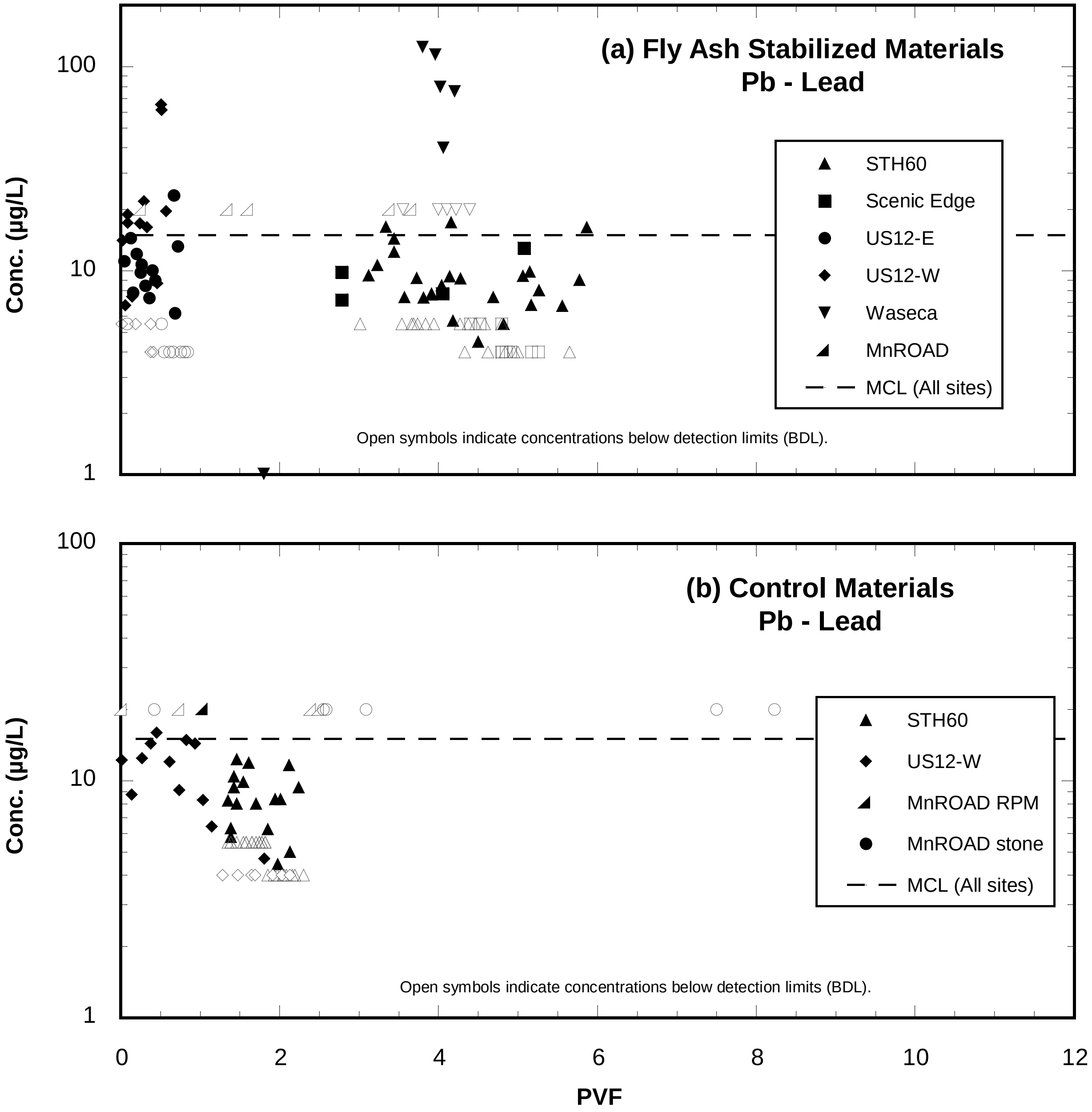


Fig. 4.16. Lead (Pb) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

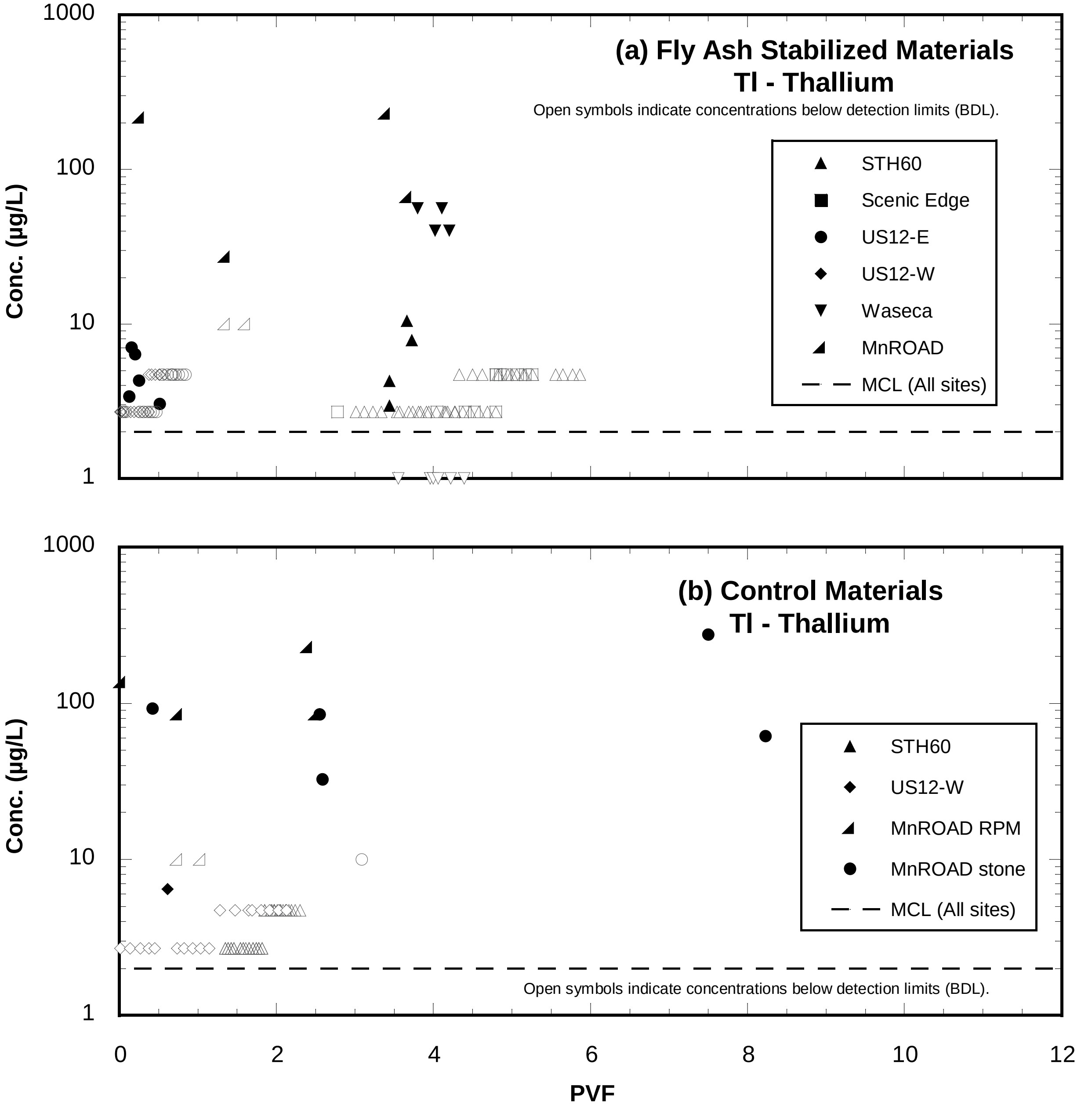


Fig. 4.17. Thallium (Tl) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

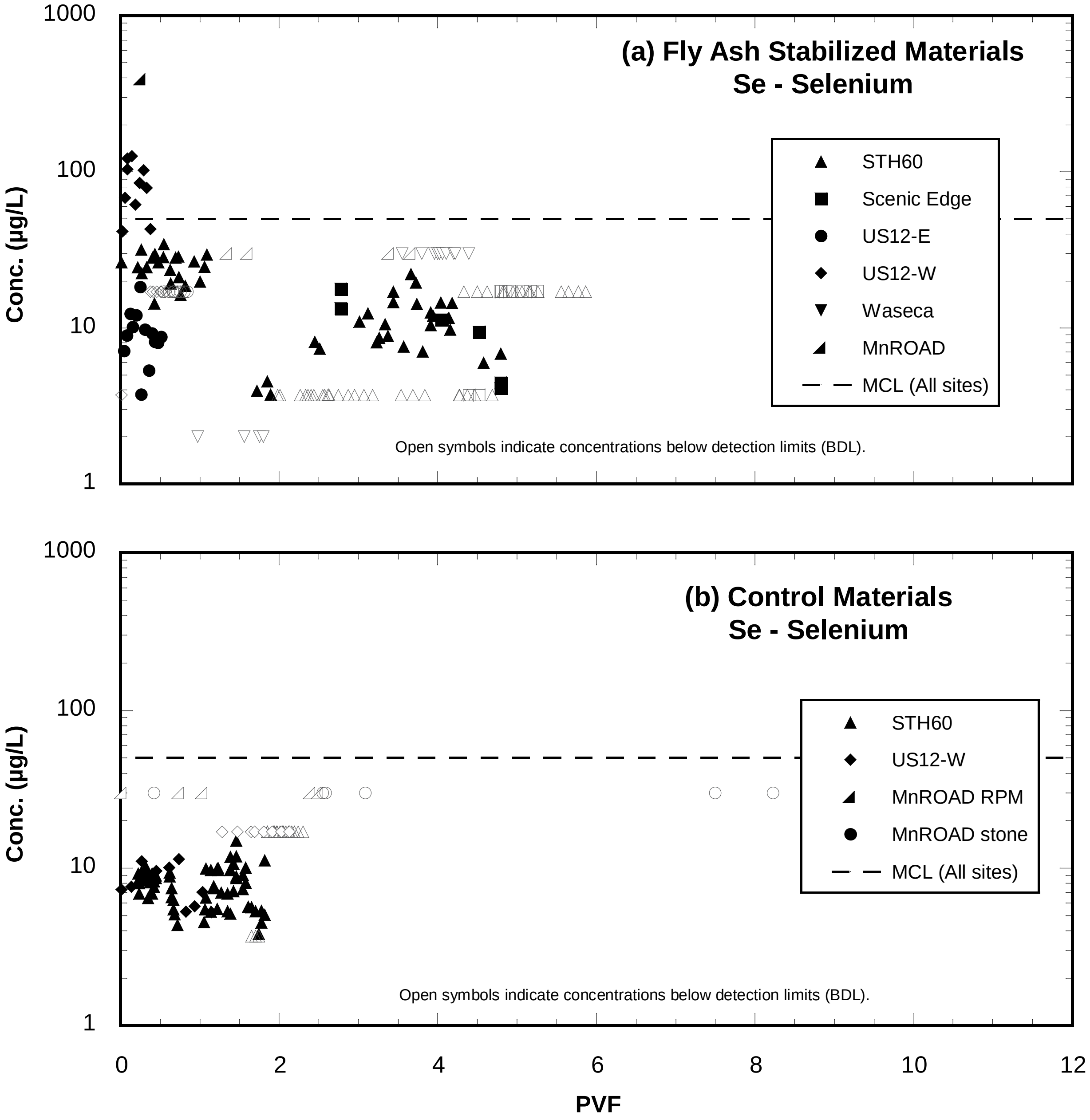


Fig. 4.18. Selenium (Se) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

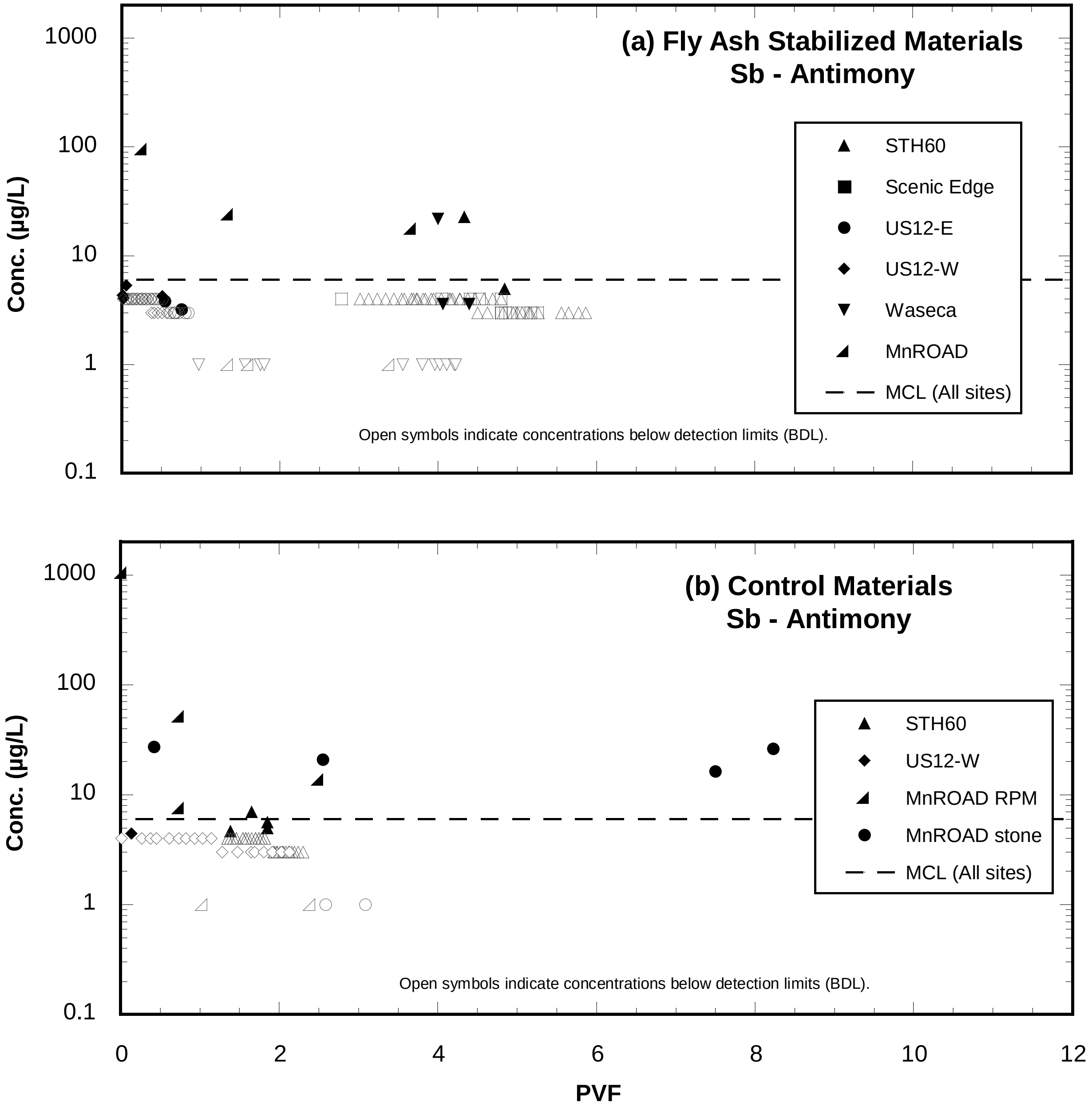


Fig. 4.19. Antimony (Sb) concentrations in leachate from field road layers composed of (a) fly-ash-stabilized materials, and (b) control materials.

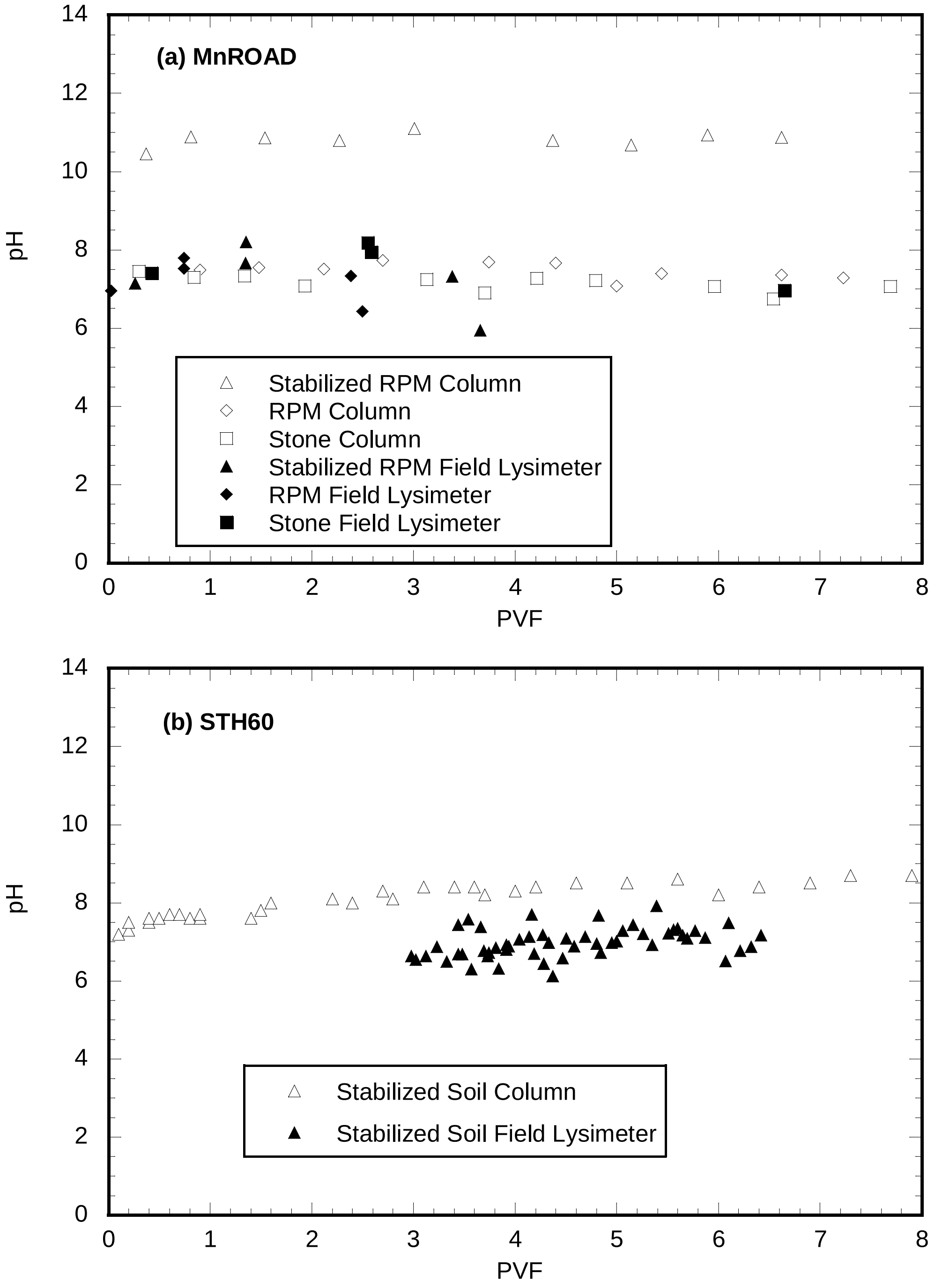


Fig. 4.20. Comparison of leachate pH from Field Lysimeters and CLTs for the (a) MnROAD and (b) STH60 sites.

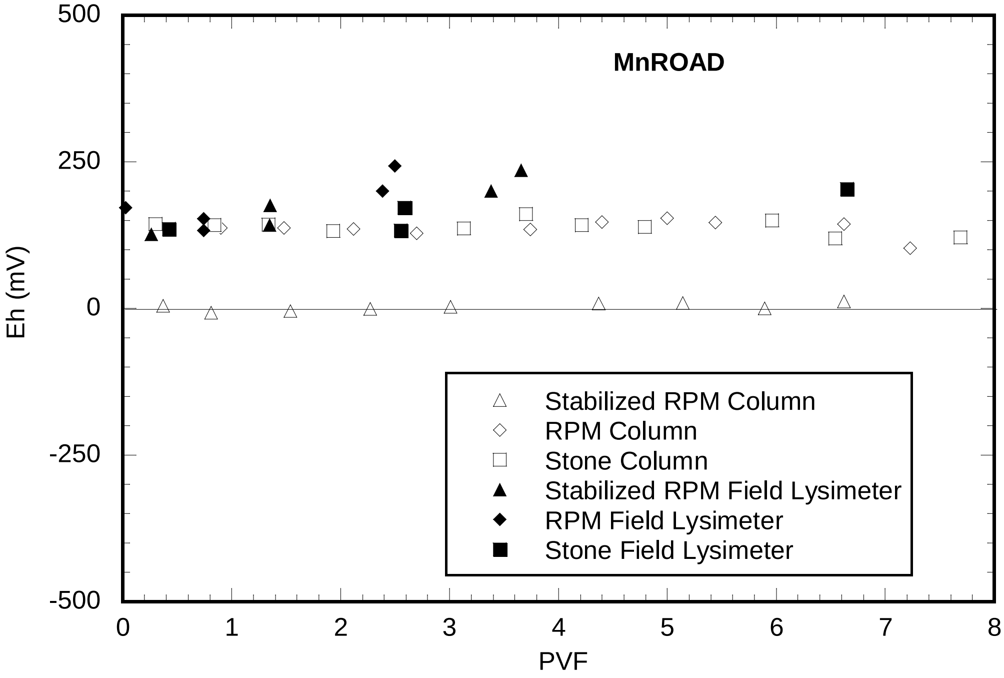


Fig. 4.21. Comparison of leachate Eh from Field Lysimeters and CLTs for the MnROAD site

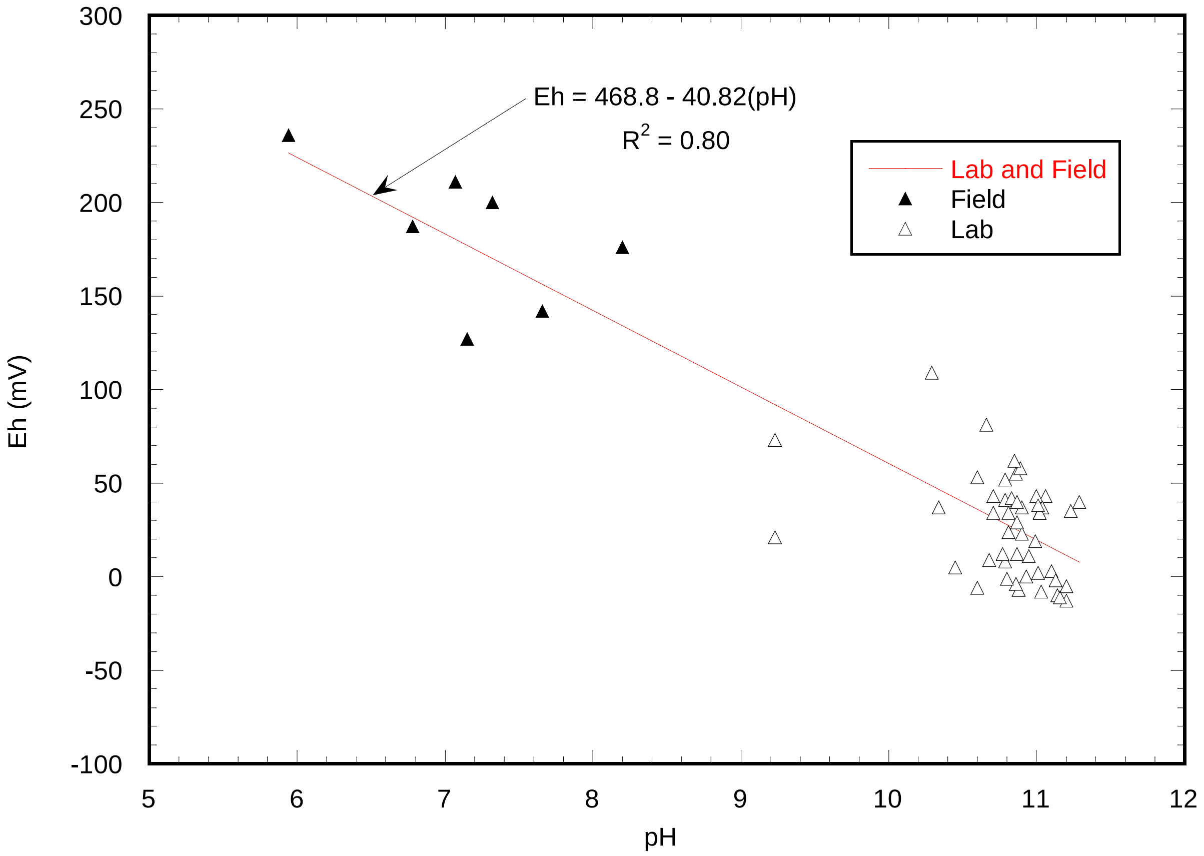


Fig. 4.22. Eh and pH relationship for MnROAD field and CLT leachate

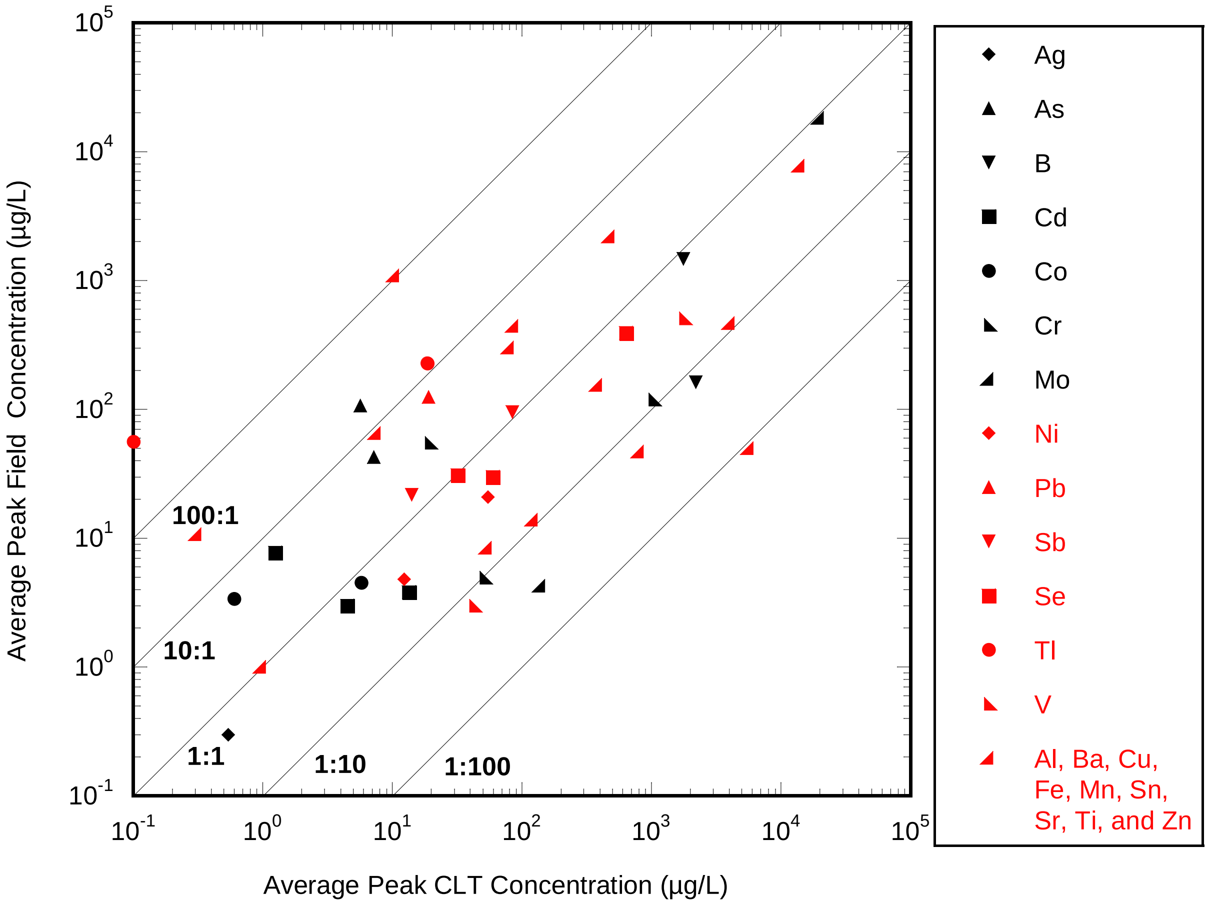


Fig. 4.23. Comparison of average peak concentrations in field lysimeters and column leach tests at STH60, MnRoad, and Waseca.

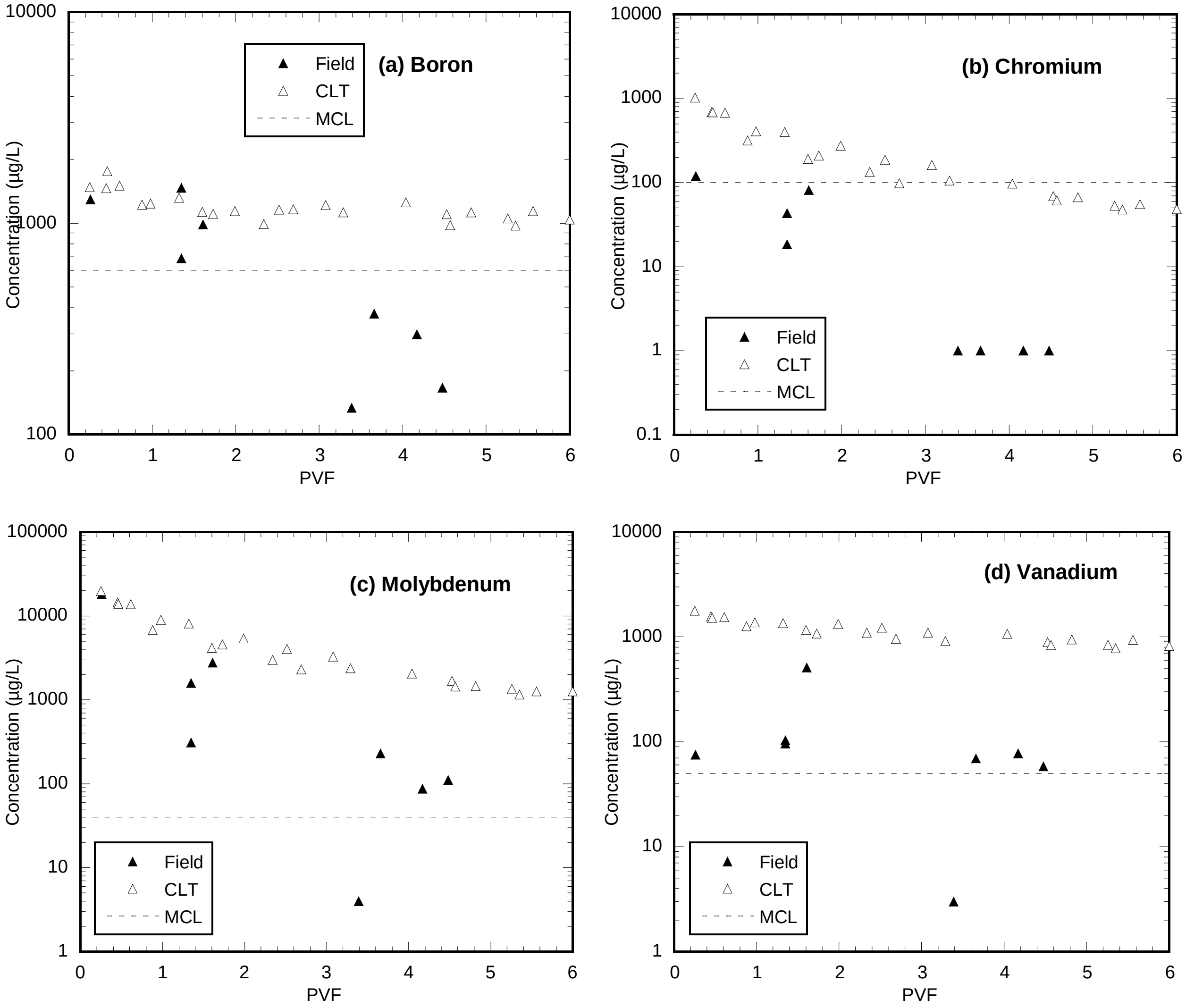


Fig. 4.24. Elements in both field and CLT Leachate that were elevated relative to the control and exceeded the MCL at the MnROAD site. Inverted triangles indicate concentrations that are BDL.

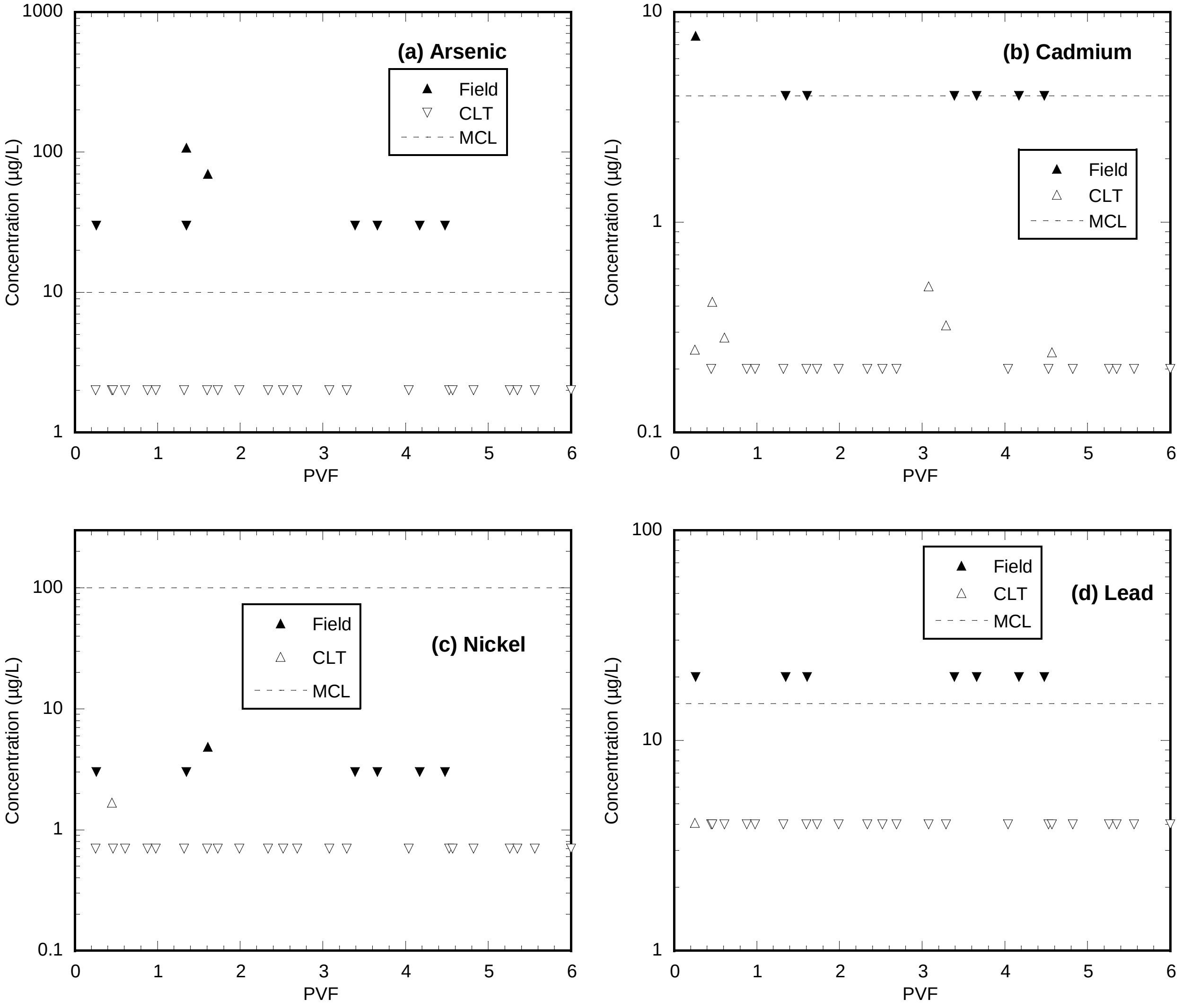


Fig. 4.25. Elements that were elevated relative to the control and exceeded the MCL in the field but not in CLT leachate at the MnROAD site. Inverted triangles indicate concentrations that are BDL.

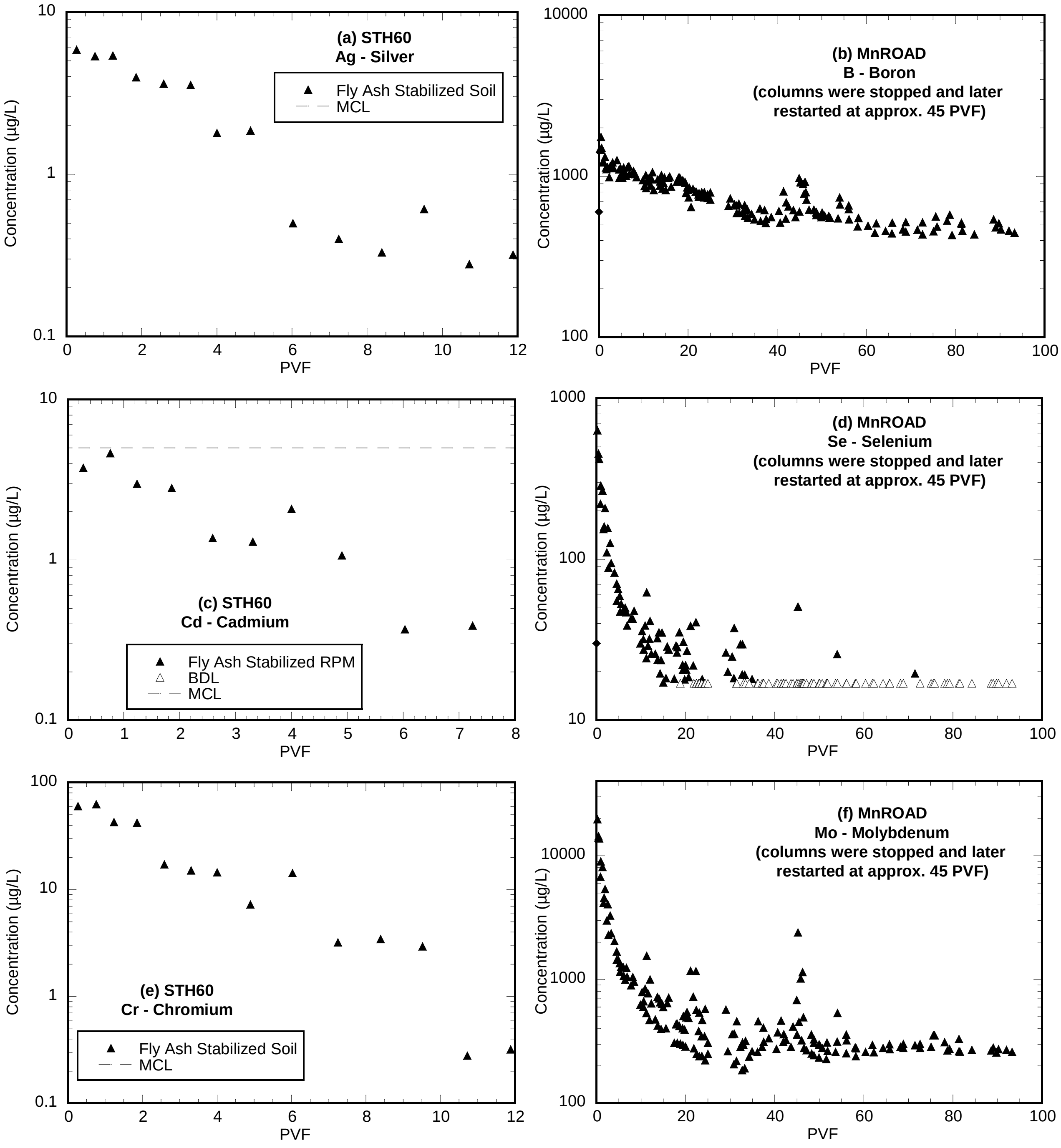
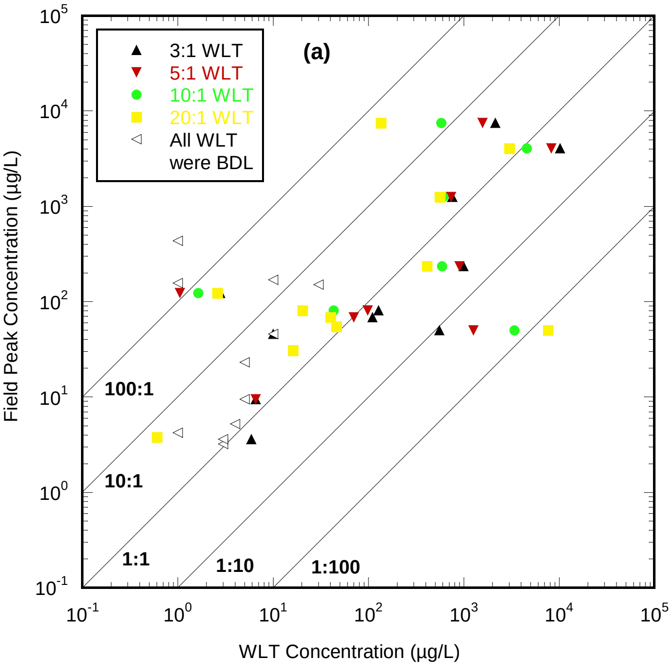


Fig. 4.26. Typical first-flush leaching patterns from CLTs for (a) Ag at STH60, (b) B at MnROAD, (c) Cd at STH60, (d) Se at MnROAD, (e) Cr at STH60, and (f) Mo at MnROAD, and increase in concentrations after MnROAD columns were left saturated with no flow (b, d, and f)



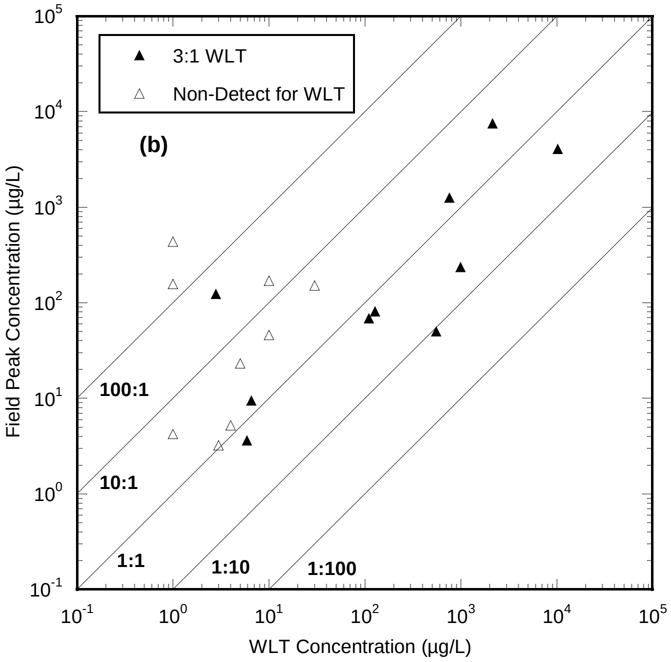


Fig. 4.27. Comparison of average peak field concentrations and WLT concentration at STH60 and MnROAD for (a) all WLT liquid:solid ratios, and (b) only the 3:1 WLT. Only elements detected in the field are shown. Open Symbols indicate WLT below detection limit.

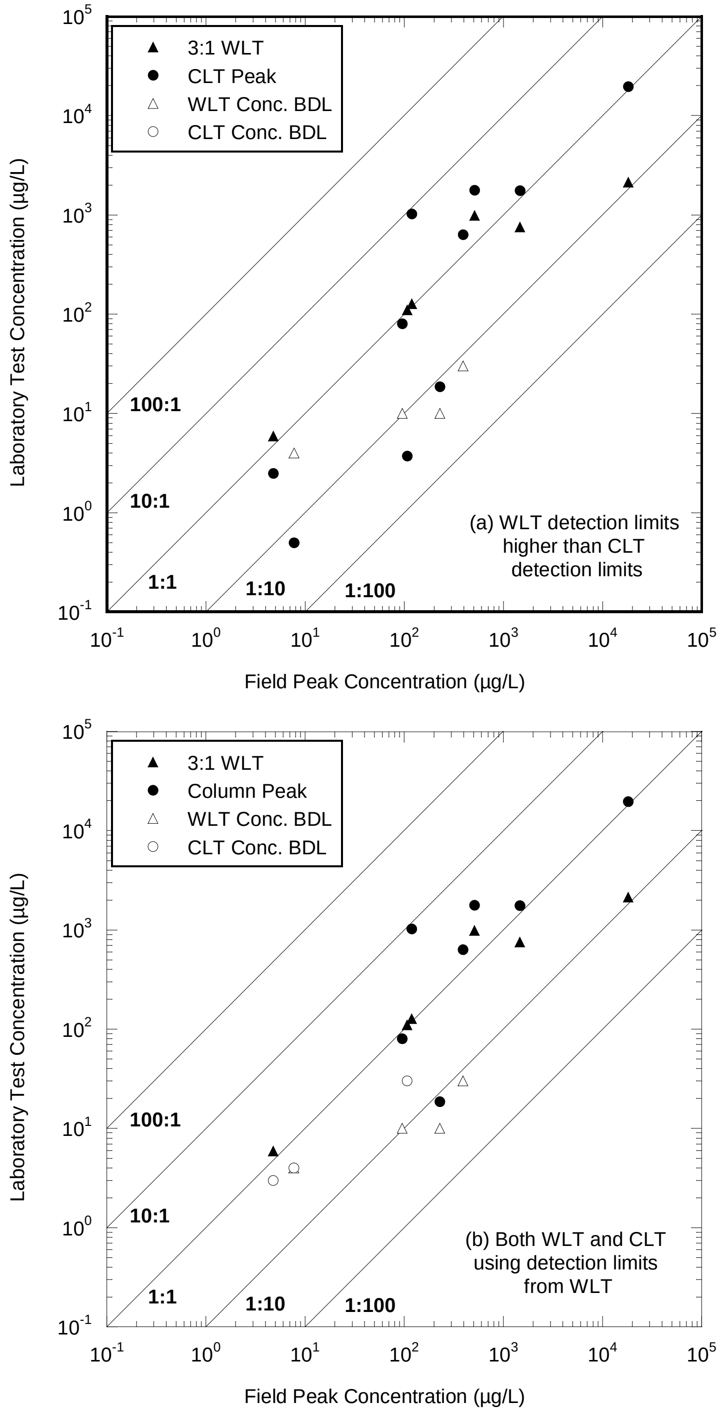


Fig. 4.28. Comparison of ability of CLT and WLT to predict peak field concentration of elements that exceeded MCLs in field leachate when (a) detection limits were lower for the CLT, and (b) when both tests use the WLT detection limits.

TABLES

Table 2.1. Properties of stabilized layers and lysimeters.

Site	**STH60**	**US12**	**Scenic Edge**	**MnROAD**	**Waseca**
Layer Stabilized	Subgrade	Subgrade	Subgrade	Base Course	Base Course
Material Stabilized	Fine Grained Soil	Fine Grained Soil	Fine Grained Soil	Recycled Paving Material	Recycled Paving Material
USCS and AASHTO Class.	CL, A-6	CL or SC, A-6	CL, A-7-6	GW-GM, A-1-a	GW-GM, A-1-a
Fly Ash Type	Columbia	Columbia	Columbia	Riverside 8	Riverside 7
Percent Fly Ash by Mass (%)	18	12	12	14	10
Compacted Dry Unit Weight of Stabilized Layer (kN/m^3)	15.4	18.9 - 20.0	15.9	19.6	15.9
Porosity	0.41	0.23 - 0.27	0.39	0.25	0.39
Water Content at Compaction Relative to Optimum Standard Proctor (w_{opt})	1% wet of w_{opt}	2% dry of w_{opt}	7% wet of w_{opt}	1% wet of w_{opt}	4% dry of w_{opt}
Stabilized Layer Thickness (mm)	300	300	300	203	150
Lysimeter Dimensions (m)	3.75 x 4.75	3.00 x 3.00	3.75 x 4.75	3.00 x 3.00	4.00 x 4.00

Table 3.1. Classification of fly ashes.

Parameter	Percent of Composition			Specifications	
	Riverside 7	Riverside 8	Columbia	ASTM C 618	AASHTO M 295
				Class C	Class C
SiO_2 (silicon dioxide) (%)	32	19	Not Tested		
Al_2O_3 (aluminum oxide) (%)	19	14	Not Tested		
Fe_2O_3 (iron oxide) (%)	6	6	Not Tested		
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	57	39	56	50 Min	50 Min
CaO (calcium oxide) (%)	24	22	23		
MgO (magnesium oxide) (%)	6	5.5	Not Tested		
SO_3 (sulfur trioxide) (%)	2	5.4	3.7	5 Max	5 Max
CaO/SiO_2	0.75	1.18	Not Tested		
$CaO/(SiO_2+Al_2O_3)$	0.47	0.68	Not Tested		
Loss on Ignition (%)	0.9	16.4	0.7	6 Max	5 Max
Moisture Content (%)	0.17	0.32	0.09	3 Max	3 Max
Specific Gravity	2.71	2.65	2.7		
Fineness, amount retained on #325 sieve (%)	12.4	15.5	<34	34 Max	34 Max
Classification	C	Off-Spec.	C		

Table 3.2. Total elemental analysis of Riverside 8 and Columbia fly ashes.

Description	**Riverside 8 Ash**		**Columbia Ash**	
	(mg/kg)	**% of Total Mass**	**(mg/kg)**	**% of Total Mass**
Ag	0.40	0.000040	0.50	0.000050
Al	66000	6.6	75000	7.5
As	24	0.0024	28	0.0028
B	780	0.078	610	0.061
Ba	2600	0.26	3600	0.36
Be	5.3	0.00053	2.6	0.00026
Ca	120000	12	240000	24
Cd	5.4	0.00054	1.5	0.00015
Co	28	0.0028	5.6	0.00056
Cr	71	0.0071	60	0.0060
Cu	230	0.023	180	0.018
Fe	36000	3.6	20000	2.0
Hg	0.80	0.000080	Not Tested	-
K	2600	0.26	3000	0.30
Mg	29000	2.9	25000	2.5
Mn	120	0.012	180	0.018
Mo	140	0.014	7.2	0.00072
Na	15000	1.5	8700	0.87
Ni	620	0.062	45	0.0045
P	4800	0.48	3400	0.34
Pb	63	0.0063	28	0.0028
S	1.1	0.00011	ND	-
Sb	3.3	0.00033	7.7	0.00077
Se	16	0.0016	9.4	0.00094
Sn	1400	0.14	200	0.020
Sr	ND		1600	0.16
Ti	130	0.013	94	0.0094
Tl	ND	-	8.4	0.00084
V	66000	6.6	75000	7.5
Zn	3.3	0.00033	7.7	0.00077

Table 3.3. Column leach testing construction and testing details.

Site	MnROAD	MnROAD	MnROAD	STH60	Waseca	CR53
Material	RPM	Class 5 crushed stone	Stabilized RPM	Stabilized Soil	Stabilized RPM	Stabilized RSG
Rigid or Flexible Wall Permeameter	Rigid	Rigid	Rigid	Flexible	Flexible	Flexible
Specimen Diameter (mm)	202	202	202	102	102	102
Specimen Length (mm)	102	102	102	114	116	116
Specimen Volume (mL)	3269	3269	3269	932	948	948
Effective Confining Pressure (kPa)	0	0	0	15	15	15
Porosity	0.25	0.21	0.25	0.41	0.26	0.26
Dry Unit Weight (kN/m3)	19.4	20.5	19.6	15.4	19.1	19.3
Approx. Darcy Flux (mm/day)	16	16	16	9 for first 1.5 PVF, 2 after 1.5 PVF	2	2

Table 3.4. Minimum detection limits of chemical analytical methods used throughout the monitoring program. All MDLs are in µg/L. Hyphens indicate elements that were not tested with the method indicated.

Site	**STH60**				**US12 & Scenic Edge**			**Waseca**	**CR53**	**MnROAD**	
Element	2000-2005	2005-2007	2007-2009	2008-2009	2005-2007	2007-2009	2008-2009	2004-2008	2004-2006	2007-2009	2008-2009
	AA	ICP-MS	ICP-OES	OPT-CVAFS	ICP-MS	ICP-OES	OPT-CVAFS	ICP-MS	ICP-MS	ICP-OES	OPT-CVAFS
Ag	0.2	1.9	-	-	1.9		-	0.02	0.02		-
Al	-	3.0	2.5	-	3.0	2.5	-	-	-	2.5	-
As		2.6	2.0	-	2.6	2.0	-	30	30	2.0	-
B		-	4.0	-	-	4.0	-	3.0	3.0	4.0	-
Ba	-	1.2	0.04	-	1.2	0.04	-	0.08	0.08	0.04	-
Be	-	0.5	1.0	-	0.5	1.0	-	0.1	0.1	1.0	-
Cd	0.1	1.0	0.2	-	1.0	0.2	-	3.0	3.0	0.2	-
Co		1.0	0.6	-	1.0	0.6	-	4.0	4.0	0.6	-
Cr	2.0	1.1	0.5	-	1.1	0.5	-	1.0	1.0	0.5	-
Cu	-	2.0	0.7	-	2.0	0.7	-	1.0	1.0	0.7	-
Hg	-	-	-	0.001	-		0.001	0.02	0.02		0.001
Fe	-	1.5	3.2	-	1.5	3.2	-	-	-	3.2	-
Mn	-	0.8	0.05	-	0.8	0.05	-	0.5	0.5	0.05	-
Mo	-	-	0.5	-		0.5	-	4.0	4.0	0.5	-
Ni	-	1.5	0.7	-	1.5	0.7	-	3.0	3.0	0.7	-
Pb	-	5.5	4.0	-	5.5	4.0	-	20	20	4.0	-
Sb	-	4.0	3.0	-	4.0	3.0	-	1.0	1.0	3.0	-
Se	2.0	3.7	17	-	3.7	17	-	30	30	17	-
Sn	-	-	5.0	-	-	5.0	-	1.0	1.0	5.0	-
Sr	-	-	0.3	-	-	0.3	-	1.0	1.0	0.3	-
Ti	-	-	0.4	-	-	0.4	-	- -		0.4	-
Tl	-	2.7	4.7	-	2.7	4.7	-	1.0	1.0	4.7	-
V	-	-	0.1	-	-	0.1	-	3.0	3.0	0.1	-
Zn	-	0.8	0.1	-	0.8	0.1	-	1.0	1.0	0.1	-

Table 4.1. Magnitude of peak concentrations and the average of three highest concentrations in field leachate.

	STH60 - Stabilized Soil		US12 East - Stabilized Soil		US12 West - Stabilized Soil		Scenic Edge - Stabilized Soil		MnROAD - Stabilized RPM		Waseca - Stabilized RPM	
Element	**Peak Conc. (µg/L)**	**Average Peak Conc. (µg/L)**	**Peak Conc. (µg/L)**	**Average Peak Conc. (µg/L)**	**Peak Conc. (µg/L)**	**Average Peak Conc. (µg/L)**	**Peak Conc. (µg/L)**	**Average Peak Conc. (µg/L)**	**Peak Conc. (µg/L)**	**Average Peak Conc. (µg/L)**	**Peak Conc. (µg/L)**	**Average Peak Conc. (µg/L)**
Mo #	31.12	29.69	128.71	112.97	58.16	49.17	9.23	7.78	@ 18176	7511.14	4.28	4.09
Sr #	4687.56	3406.28	3913.35	3486.59	280.45	180.68	3450.61	1867.11	7770.00	4057.37	468.00	320.33
Al ^	164.47	98.44	418.44	334.93	4243.35	2182.92	77.85	62.67	All BDL	All BDL	NT	NT
Fe ^	712.00	413.19	1560.83	968.78	3314.73	1926.45	38.14	27.80	442.81	157.75	NT	NT
B #	3267.55	2959.54	1195.96	1085.05	1243.07	1156.21	2181.14	1731.36	1470.55	1252.82	162.00	117.33
Mn ^	1204.54	929.27	2103.38	1538.82	127.83	100.31	26.26	19.35	1094.57	438.17	2200.00	1785.23
Sn #	41.71	24.95	414.29	253.16	891.06	491.03	6.02	5.34	65.50	23.17	10.70	4.23
Ba ^	604.05	540.87	406.24	376.36	185.31	137.40	396.21	381.92	NT	NT	155.00	129.00
V #	183.03	146.77	57.17	52.13	70.56	63.46	79.74	48.72	510.00	236.48	All BDL	All BDL
Se *	34.21	31.89	18.34	17.45	126.11	116.99	17.83	17.28	392.84	150.95	All BDL	All BDL
Zn ^	285.04	198.04	110.59	95.32	378.74	225.58	154.01	94.54	301.58	123.82	47.01	35.55
As ^	17.94	14.75	21.35	20.53	16.92	15.25	311.76	121.09	107.46	69.15	42.81	34.27
Cu ^	44.14	37.72	9.91	5.71	309.61	206.58	52.75	45.01	8.44	9.47	14.00	12.00
Tl ^	10.50	7.68	7.02	6.03	All BDL	All BDL	All BDL	All BDL	228.80	170.40	55.90	50.67
Ni ^	2.65	2.32	225.72	157.19	121.62	98.56	All BDL	All BDL	4.84	3.61	20.81	15.28
Pb ^	17.23	16.68	23.40	17.00	65.44	49.63	12.96	10.19	All BDL	All BDL	125.00	106.67
Cr *	20.15	19.34	3.11	2.31	32.96	27.09	18.59	11.24	119.18	81.25	4.94	3.78
Sb ^	22.75	10.58	All BDL	All BDL	5.32	4.64	All BDL	All BDL	95.20	45.73	21.80	9.67
Ti #	1.09	0.63	3.11	2.46	44.41	31.96	0.52	0.44	1.00	1.00	NT	NT
Co ^	3.54	2.90	11.57	5.70	32.43	30.62	3.09	2.34	3.44	3.22	4.53	4.18
Cd *	32.10	13.37	3.14	1.72	3.40	2.09	3.74	2.49	7.69	5.23	3.00	3.00
Ag *	11.30	10.65	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL	2.80	4.23	0.30	0.17
Hg $	NT	NT	NT	NT	NT	NT	NT	NT	0.01	0.01	0.20	0.20
Be ^	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL	All BDL

BDL - below detection limit

NT - element not tested for at site

* - Element NT for at Scenic Edge for first 65 months of study

^ - Element NT for at Scenic Edge for first 65 months of study, or at STH60 for first 60 months of study

- Element NT for at Scenic Edge and STH60 for first 80 months of study, or at US12 for first 18 months of study

$ - Long term monitoring of Hg only at MnROAD and Waseca sites

@ - concentration is out of method calibration range, and is estimated from linear extrapolation

Table 4.2. Elements with peak concentrations occurring during or after the first 2 PVF.

Element	**Site**				
	STH60	**US12**	**Scenic Edge**	**MnROAD**	**Waseca**
Ag	▼	ND	NT	▼	X
Al	NT	▼	NT	ND	NT
As	NT	▼	NT	▼	X
B	NT	NT	NT	▼	X
Ba	NT	▼	NT	NT	X
Be	NT	ND	NT	ND	ND
Cd	▼	▼	NT	▼	ND
Co	NT	▼	NT	▼	▼
Cr	▼	▼	NT	▼	X
Cu	NT	▼	NT	▼	X
Fe	NT	X	NT	X	X
Hg	NT	NT	NT	NT	ND
Mn	NT	X	NT	X	X
Mo	NT	NT	NT	▼	▼
Ni	NT	▼	NT	▼	▼
Pb	NT	▼	NT	ND	X
Sb	NT	▼	NT	▼	X
Se	▼	▼	NT	▼	ND
Sn	NT	NT	NT	X	X
Sr	NT	NT	NT	▼	X
Ti	NT	NT	NT	ND	NT
Tl	NT	▼	NT	X	X
V	NT	NT	NT	▼	ND
Zn	NT	▼	NT	X	X

▼ - Peak Concentration occurred during the first 2 PVF
X - Peak Concentration occurred after the first 2 PVF
NT - Element was not tested for at the beginning of site operation
ND - All concentrations were below detection limit

Table 4.3. Comparison of field concentrations from fly ash stabilized sections and control sections to determine if element is statistically elevated in the stabilized material leachate.

Element	**Avg. Magnitude of elevated concentration (µg/L)**	
	Average Peak Concentration	**Geometric Mean of Concentrations**
Sr	-12187.36	-4512.66
Mo	-15021.91	-629.6
Al	-4828.99	-2721.92
V	-1473.99	-764.32
B	-1168.34	-667.87
Cr	-790.71	-16.48
Ba	-325.89	-168.48
Cu	-37.78	-0.41
Sb	-31.39	3.57
Ni	-3.36	0.07
Be	-3.24	0.05
Ti	-0.1	0.01
Co	0.03	0.03
Cd	0.67	0.02
As	2.13	0.51
Sn	2.89	1.9
Pb	2.88	2.07
Zn	23.46	0.81
Se	-4.66	29.71
Tl	25.02	10.77
Fe	64.04	3.12
Mn	980.51	14.42

* - more negative number indicates concentration from stabilized materials is more elevated relative to the concentrations from control materials

Table 4.4. USEPA, Minnesota, and Wisconsin maximum contaminant limits (MCLs) for groundwater and drinking water.

Element	**MN MCL (µg/L)**	**USEPA MCL (µg/L)**	**WI MCL (µg/L)**
Ag	-	30	50
As	10	-	10
B	600	-	960
Ba	2000	2000	2000
Be	4	0.08	4
Cd	4	5	5
Co	-	-	40
Cr	100	100	100
Cu	-	-	1300
Hg	2	-	2
Mo*	-	-	40
Ni	100	-	100
Pb	15	-	15
Sb	6	6	6
Se	30	50	50
Sn	4000	-	-
Tl	0.6	2	2
V	50	-	30
Zn	-	2000	-

* - Minnesota does not have a MCL for Mo, the Wisconsin MCL was used to compare Mo concentrations from Minnesota sites.

Table 4.5. Ratio of average peak concentration or geometric mean of all concentrations to MCLs in field leachate.

Average Peak Concentrations

Fly-Ash-Stabilized Materials

Site	As	B	Cd	Cr	Mo	Ni	Pb	Sb	Se	Tl	V
STH60	1.8	5.4	6.4	-	□	□	1.1	5.7	1.1	18	3.7
US12	1.7	2.1	-	-	1.5	1.2	4.4	1.3	4.2	7.8	1.4
Scenic Edge	31	3.6	□	□	□	□	□	□	□	7.8	1.6
MnROAD	11	2.5	1.5	1.2	450*	-	1.3	24	13	380	10
Waseca	4.3	-	-	-	-	-	8.3	5.5	-	93	-

Control Materials

Site	As	B	Cd	Cr	Mo	Ni	Pb	Sb	Se	Tl	V
STH60 Stone	2	□	1.2	-	□	□	□	1.7	-	7.8	4.7
US12 Soil	2.7	□	-	-	-	-	1.1	1.1	-	11	3
MnROAD RPM	9.1	-	-	-	11*	-	1.3	260	-	380	-
MnROAD Stone	5.3	-	-	-	-	-	1.3	6.8	-	460	-

Geometric Mean of Concentrations

Fly-Ash-Stabilized Materials

Site	As	B	Cd	Cr	Mo	Ni	Pb	Sb	Se	Tl	V
STH60	□	□	□	□	□	□	□	□	□	1.8	1.4
US12	-	□	-	-	□	-	-	-	-	2.0	1.5
Scenic Edge	□	□	□	□	□	□	□	□	□	1.8	□
MnROAD	3.8	-	1.1	-	8.7	-	1.3	2.7	-	52.0	1.3
Waseca	3.1	-	-	-	-	-	-	-	-	1.7	-

Control Materials

Site	As	B	Cd	Cr	Mo	Ni	Pb	Sb	Se	Tl	V
STH60 Stone	□	□	□	□	□	□	□	□	□	1.7	3.2
US12 Soil	-	□	-	-	□	-	-	-	-	1.9	2.8
MnROAD RPM	2.9	-	-	-	-	-	1.3	3.6	-	73.9	-
MnROAD Stone	3.2	-	-	-	-	-	1.3	2.5	-	87.2	-

□ - Was not tested for during the early operation of the site.
May have exceeded the MCL prior to testing began.
* - Minnesota has no MCL for Mo, but the concentration exceeded the
Hyphen indicates element did not exceed MCL

Table 4.6. Speciation of select trace elements under Eh-pH Conditions.

<table>
<tr><th rowspan="3">Element</th><th rowspan="3">pH</th><th colspan="4">Species</th></tr>
<tr><th colspan="4">Eh (mV)</th></tr>
<tr><th>-150</th><th>0</th><th>150</th><th>+300</th></tr>
<tr><td rowspan="4">As</td><td>6</td><td colspan="2" rowspan="2">$HAsO_2^{(aq)}$</td><td colspan="2">$H_2AsO_4^{[-]}$</td></tr>
<tr><td>7</td><td colspan="2">$HAsO_4^{[2-]}$</td></tr>
<tr><td>8</td><td>$HAsO_2^{(aq)}$</td><td colspan="3" rowspan="2">$HAsO_4^{[2-]}$</td></tr>
<tr><td>9</td><td>$HAsO_4^{[2-]}$</td></tr>
<tr><td rowspan="4">B</td><td>6</td><td colspan="4" rowspan="4">$H_3BO_3^{(aq)}$</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">Cd</td><td>6</td><td colspan="4" rowspan="4">$Cd^{[2+]}$</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">Cr</td><td>6</td><td colspan="4" rowspan="2">$CrOH^{[2+]}$</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td><td colspan="4">$Cr_2O_3^{(s)}$</td></tr>
<tr><td>9</td><td colspan="3">$Cr_2O_3^{(s)}$</td><td>$CrO_4^{[2-]}$</td></tr>
<tr><td rowspan="4">Mo</td><td>6</td><td colspan="4" rowspan="4">$MoO_4^{[2-]}$</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">Ni</td><td>6</td><td colspan="4" rowspan="4">$Ni^{[2+]}$</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">Pb</td><td>6</td><td colspan="4">$Pb^{[2+]}$</td></tr>
<tr><td>7</td><td colspan="4" rowspan="3">$PbOH^{[+]}$</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">Sb</td><td>6</td><td colspan="4">$HSbO_2^{(aq)}$</td></tr>
<tr><td>7</td><td colspan="3" rowspan="3">$HSbO_2^{(aq)}$</td><td rowspan="3">$SbO4^{(s)}$</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">Se</td><td>6</td><td rowspan="4">$HSe^{[-]}$</td><td rowspan="2">$HSe^{[-]}$</td><td colspan="2" rowspan="2">$HSeO_3^{[-]}$</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td><td colspan="3" rowspan="2">$SeO_3^{[2-]}$</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">Tl</td><td>6</td><td colspan="4" rowspan="4">$Tl^{[+]}$</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td rowspan="4">V</td><td>6</td><td colspan="2">$VO^{[2+]}$</td><td colspan="2">$VO_3^{[-]}$</td></tr>
<tr><td>7</td><td colspan="4" rowspan="2">$VO_3^{[-]}$</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td><td colspan="4">$HVO_4^{[2-]}$</td></tr>
</table>

Table 4.7. Concentrations of elements elevated in the CLT stabilized leachate relative to the control leachate.

Element	**Avg. Magnitude of elevated concentration (µg/L)** (more negative indicates a greater difference between stabilized and control concentrations	
	Average Peak Concentration	Geometric Mean Concentration
Ag	Not Tested in CLT	Not Tested in CLT
Al	-4828.99	-2721.92
As	2.13	0.51
B	-1168.34	-667.87
Ba	-325.89	-168.48
Be	-3.24	0.05
Cd	0.67	0.02
Co	0.03	0.03
Cr	-790.71	-16.48
Cu	-37.78	-0.41
Fe	64.04	3.12
Hg	Not Tested in CLT	Not Tested in CLT
Mn	980.51	14.42
Mo	-15021.91	-629.6
Ni	-3.36	0.07
Pb	2.88	2.07
Sb	-31.39	3.57
Se	-4.66	29.71
Sn	2.89	1.9
Sr	-12187.36	-4512.66
Ti	-0.1	0.01
Tl	25.02	10.77
V	-1473.99	-764.32
Zn	23.46	0.81

Table 4.8. Comparison of field and CLT leachate concentrations exceeding MCL and concentrations relative to control materials.

All Elements	Elevated in the field	Exceeded MCL in Field	**Exceeded MCL and Elevated**	Exceeded MCL but the same or less than Controls (Field)	Elevated in Columns	Exceeded MCL in Columns	**Exceeded MCL and Elevated in Columns**	Exceeded MCL but the same or less than Controls (Columns)
Ag	Ag				Ag			
Al	Al				Al			
As	As	As	**As**					
B	B	B	**B**		B	B	**B**	
Ba	Ba				Ba			
Be								
Cd	Cd	Cd	**Cd**					
Co	Co							
Cr	Cr	Cr	**Cr**		Cr	Cr	**Cr**	
Cu	Cu				Cu			
Fe	Fe							
Hg								
Mn	Mn							
Mo	Mo	Mo	**Mo**		Mo	Mo	**Mo**	
Ni	Ni	Ni	**Ni**		Ni			
Pb	Pb	Pb	**Pb**					
Sb		Sb		Sb	Sb	Sb	**Sb**	
Se		Se		Se	Se	Se	**Se**	
Sn	Sn							
Sr	Sr				Sr			
Ti	Ti				Ti			
Tl		Tl		Tl		Tl		Tl
V	V	V	**V**		V	V	**V**	
Zn	Zn							

Note; Bold indicates elements that were both elevated and exceeding the MCL

APPENDIX A - PHOTOGRAPHS

A-1. WASECA CONSTRUCTION PHOTOGRAPHS

Fig. A1-1. RPM before placement of fly ash.

Fig. A1-2. Lay-down truck placing fly ash on RPM.

Fig. A1-3. Water truck and road-reclaimer blending fly ash, water, and RPM.

Fig. A1-4. Surface of fly ash and RPM after compaction.

Fig. A1-5. Mid-section of road-reclaimer showing tines used to blend fly ash, water, and RPM.

Fig. A1-6. Measuring water content and unit weight of stabilized RPM after compaction.

Fig. A1-7. Installing geomembrane for lysimeter.

Fig. A1-8. Installing collection tank for lysimeter.

A-2. MnROAD CONSTRUCTION, SAMPLING, AND LABORATORY PHOTOGRAPHS

Fig. A2-1. Preparing indentation in sub-base for lysimeter geomembrane.

Fig. A2-2. Preparing drainage pipe from lysimeter to collection tank.

Fig. A2-3. Installing geomembrane for lysimeter.

Fig. A2-4. Welding geomembrane to lysimeter drainage pipe assembly.

Fig. A2-5. Preparing hole for leachate collection tank and trench for drainage pipe.

Fig. A2-6. Assembling leachate collection tank.

Fig. A2-7. Installing leachate collection tank.

Fig. A2-8. Installing leachate collection tank.

Fig. A2-9. Collecting lysimeter leachate using submersible pump.

Fig. A2-10. Column leach test on MnROAD materials.

Fig. A2-11. Water leach test rotator.

Fig. A2-12.   MnROAD water leach test samples immediately after rotation.

APPENDIX B – LYSIMETER LEACHATE CHEMICAL CONCENTRATIONS

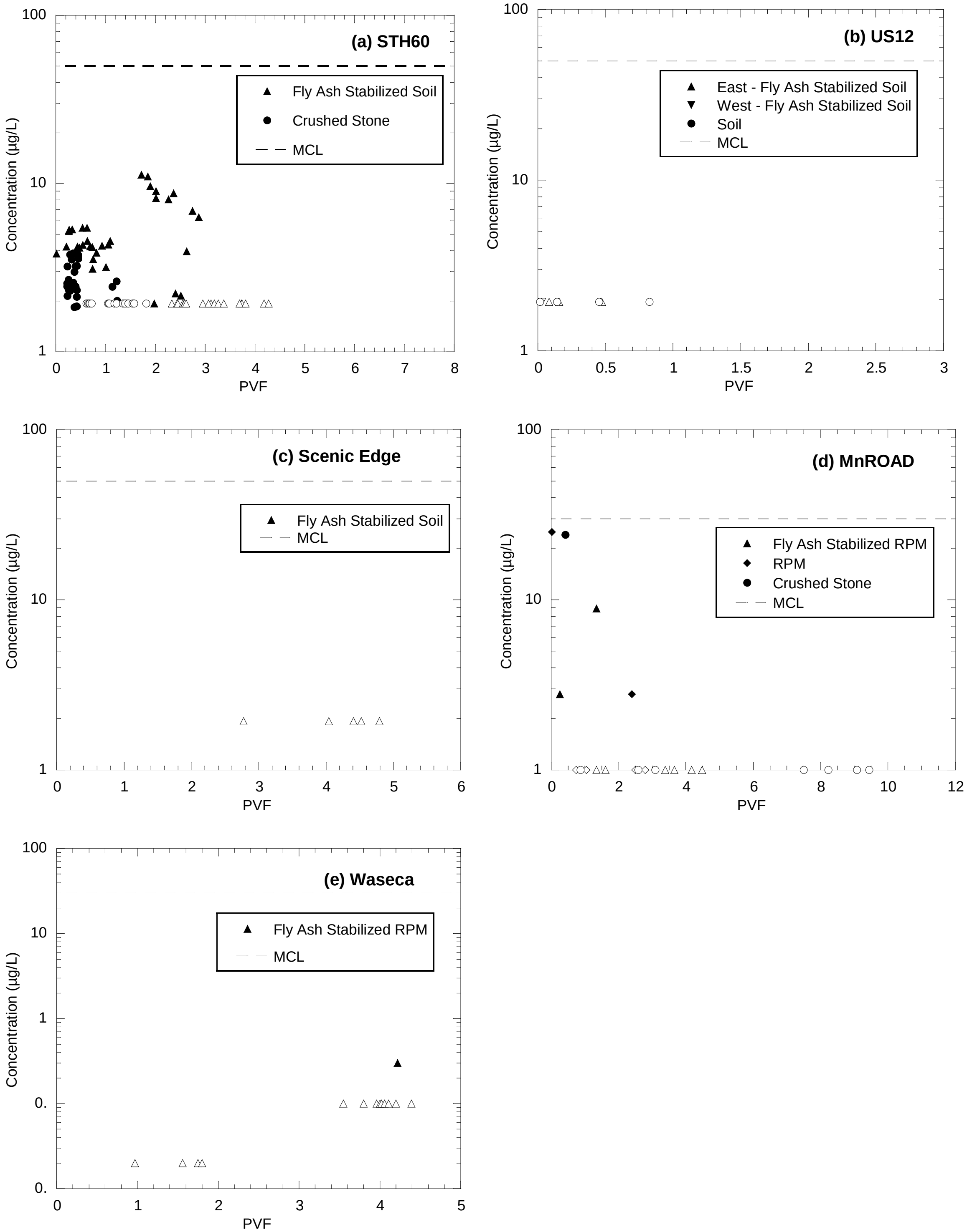


Fig. B-1. Silver (Ag) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

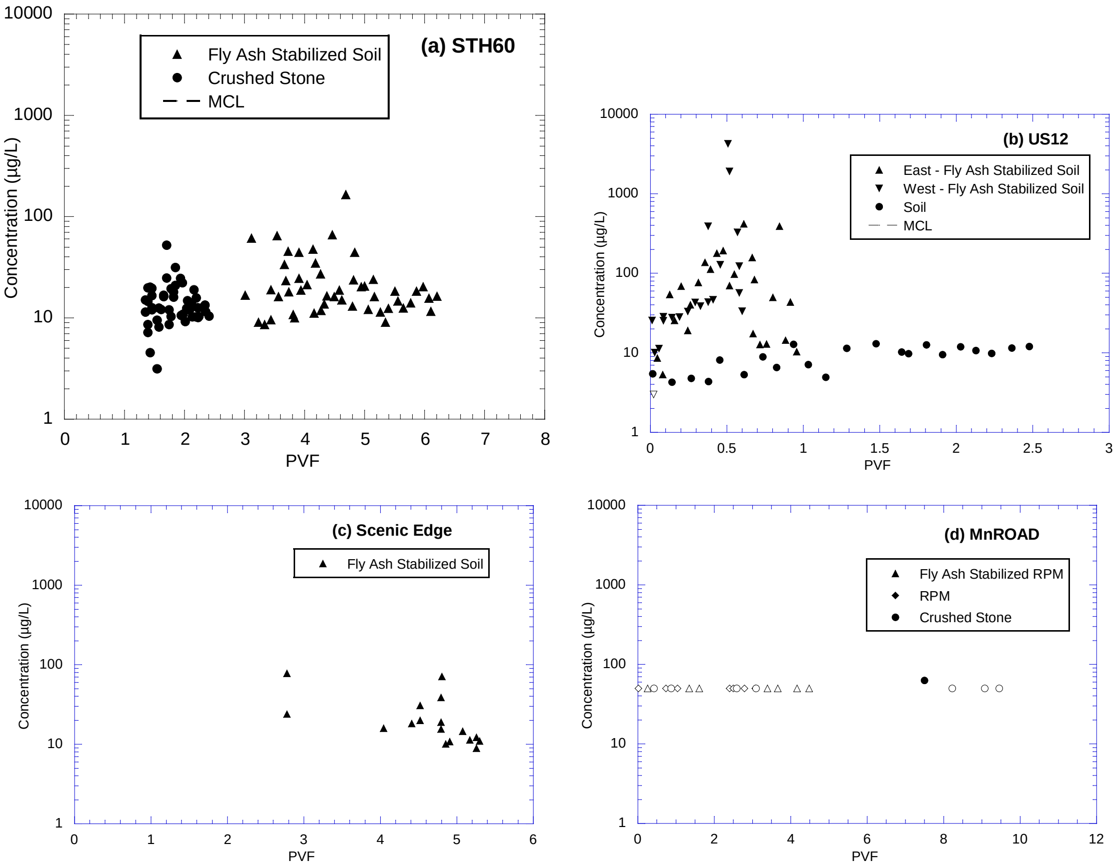


Fig. B-2. Aluminum (Al) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

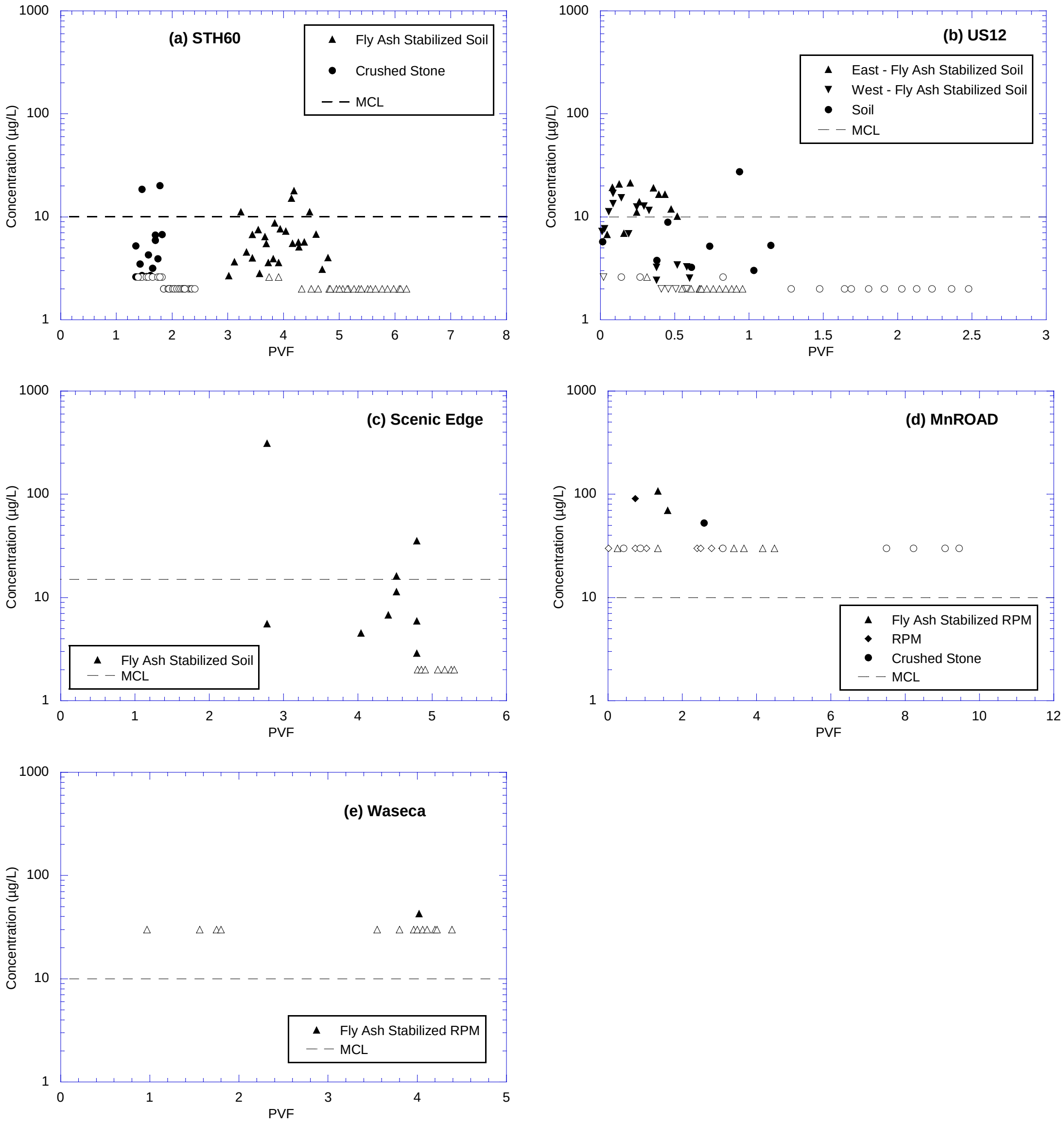


Fig. B-3. Arsenic (As) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

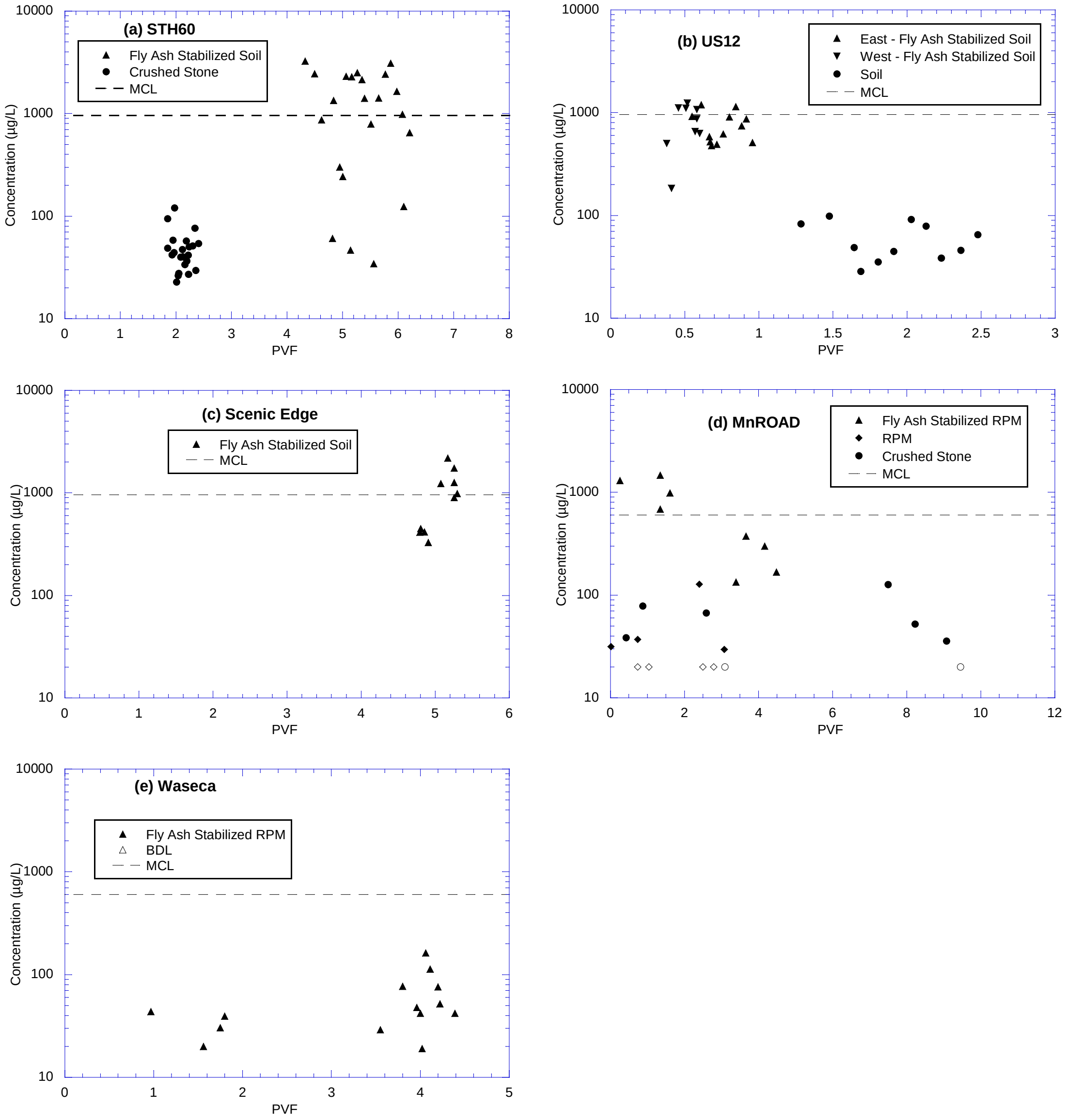


Fig. B-4. Boron (B) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

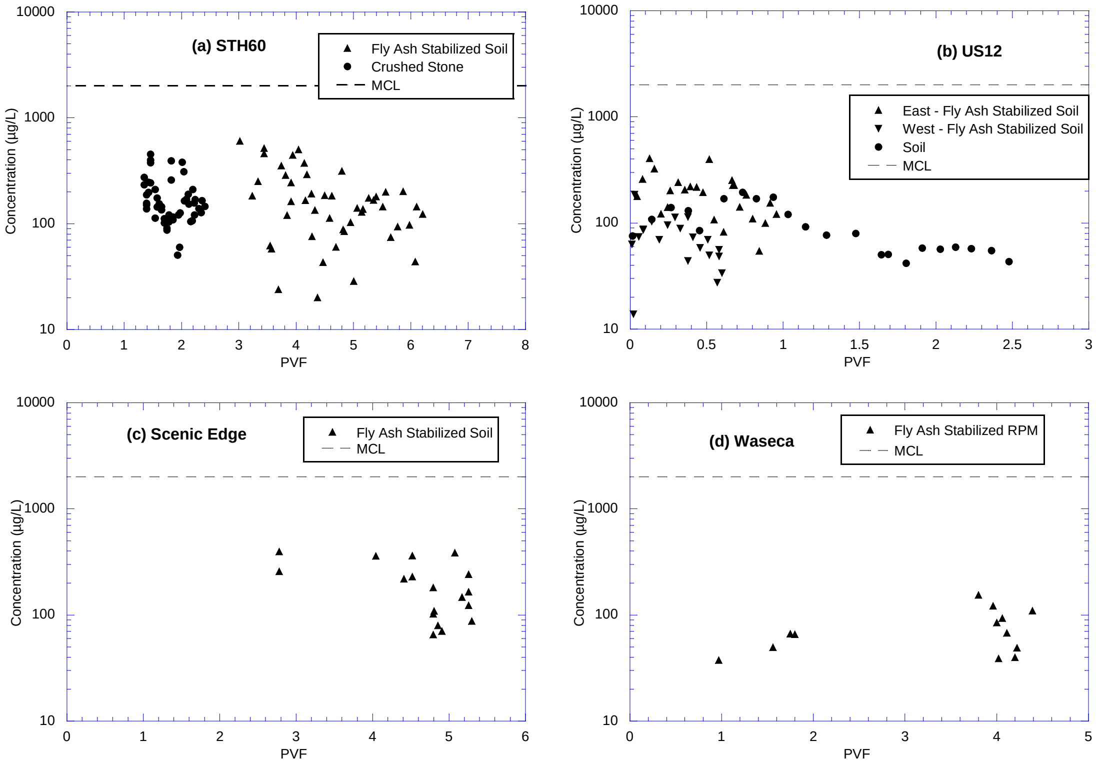


Fig. B-5. Barium (Ba) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

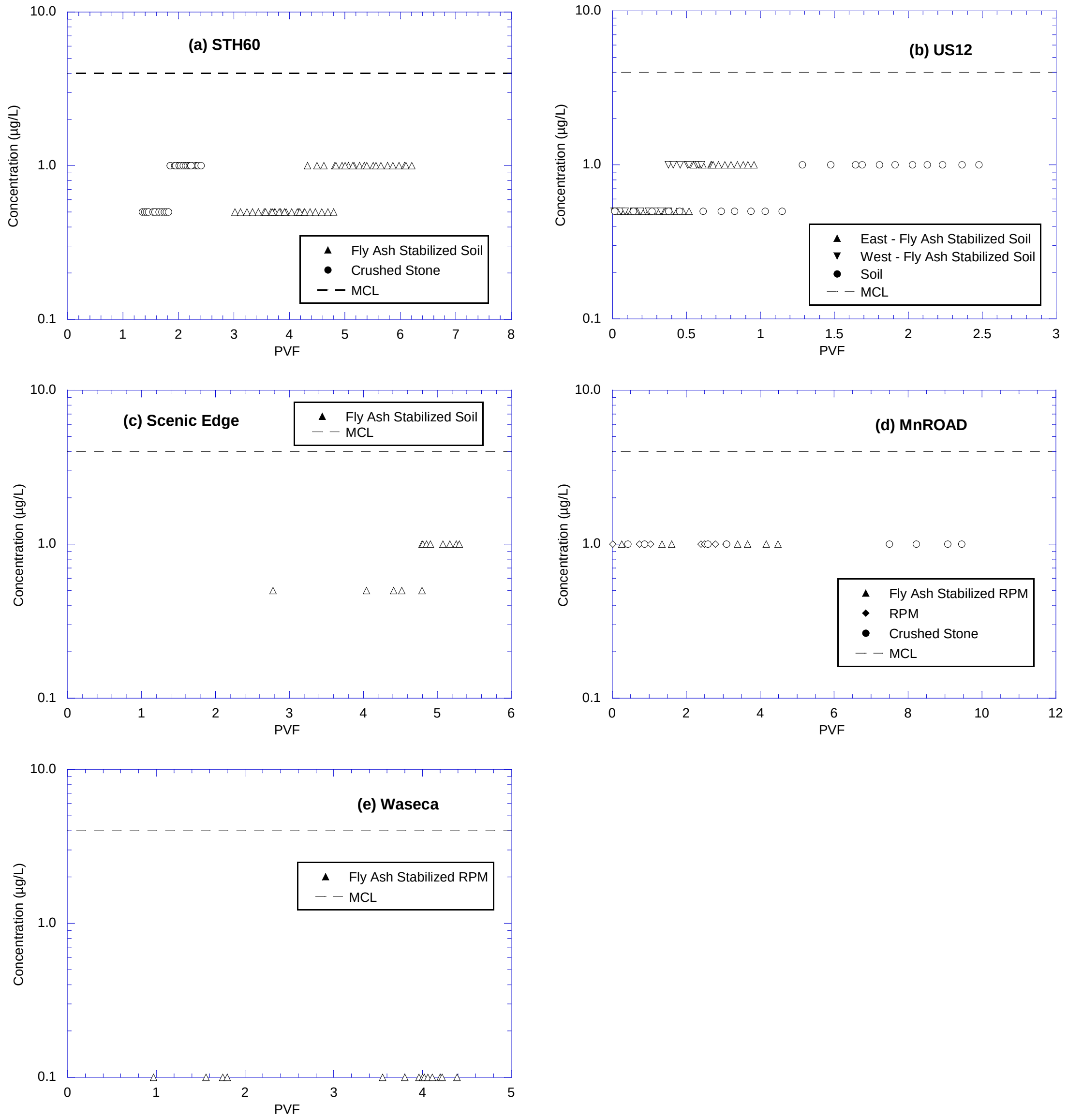


Fig. B-6. Beryllium (Be) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

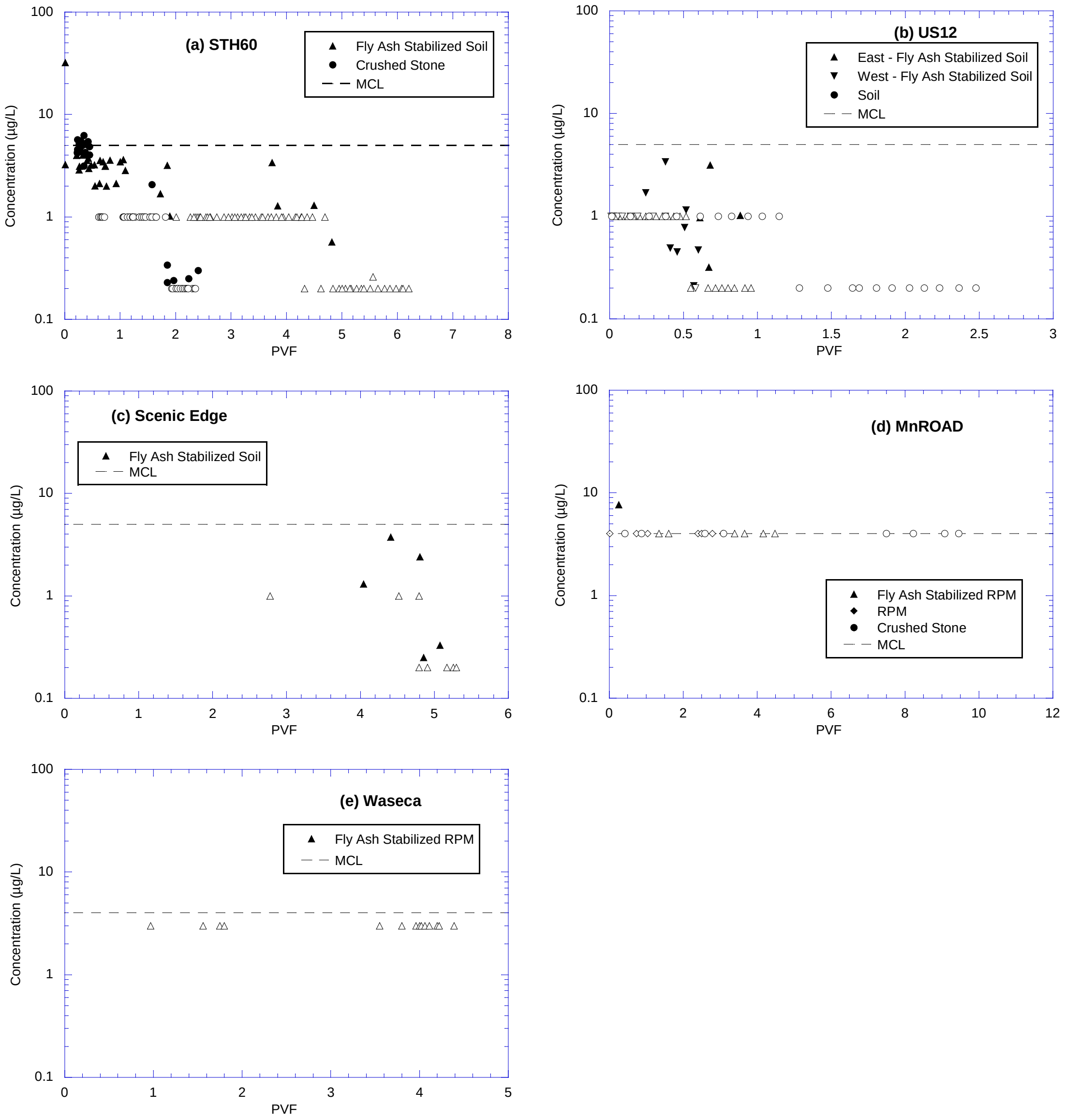


Fig. B-7. Cadmium (Cd) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

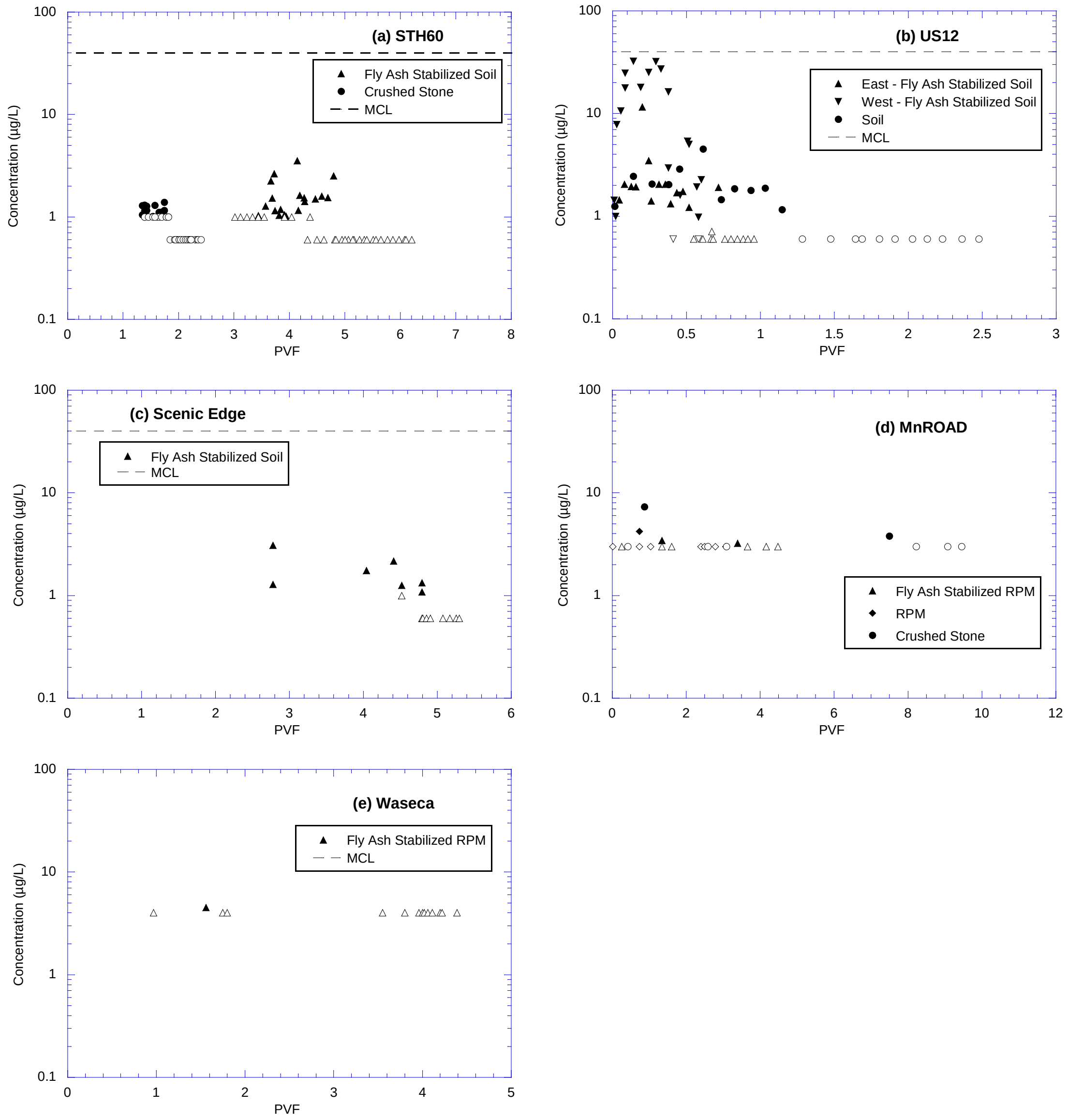


Fig. B-8. Cobalt (Co) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

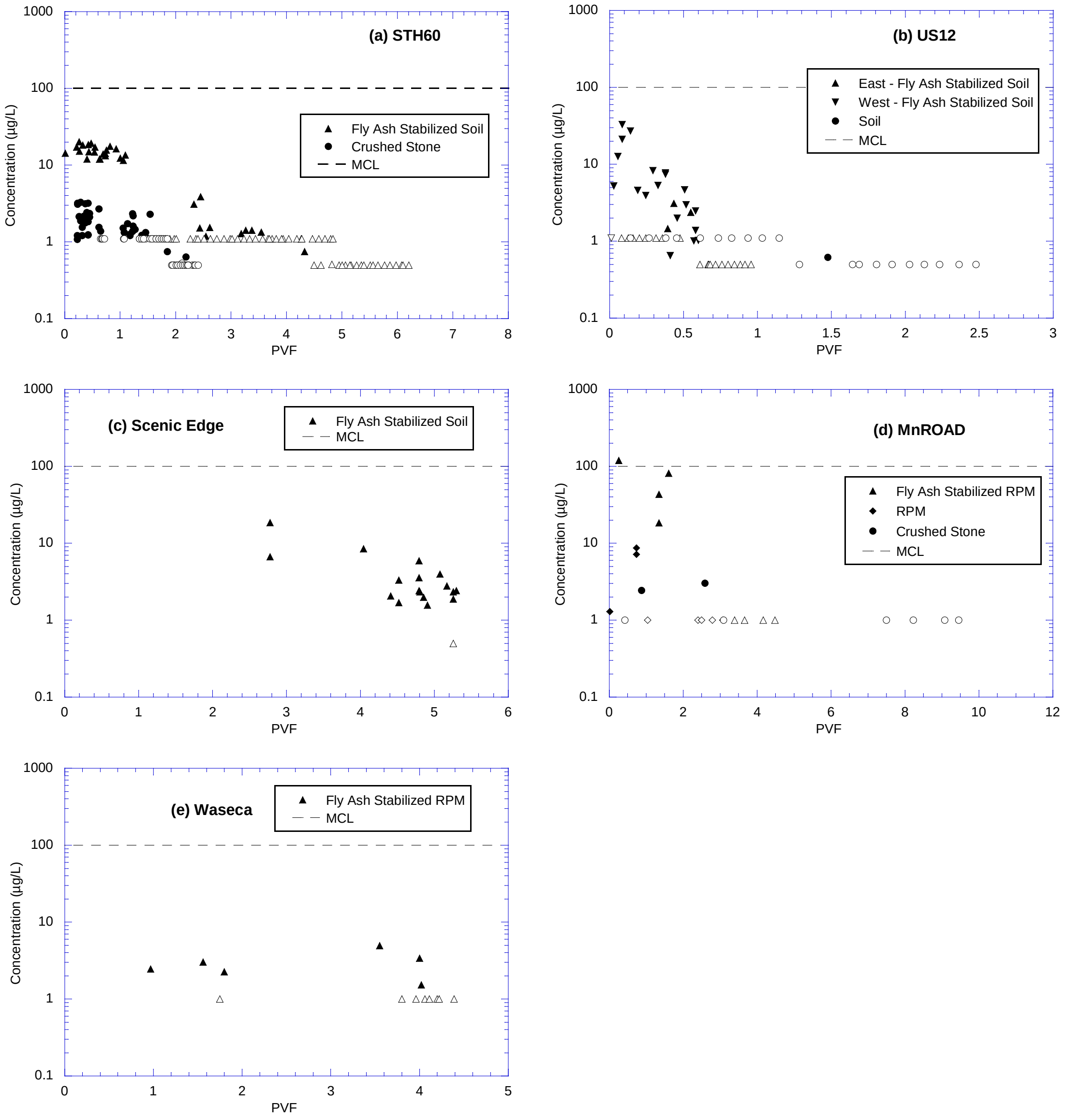


Fig. B-9. Chromium (Cr) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

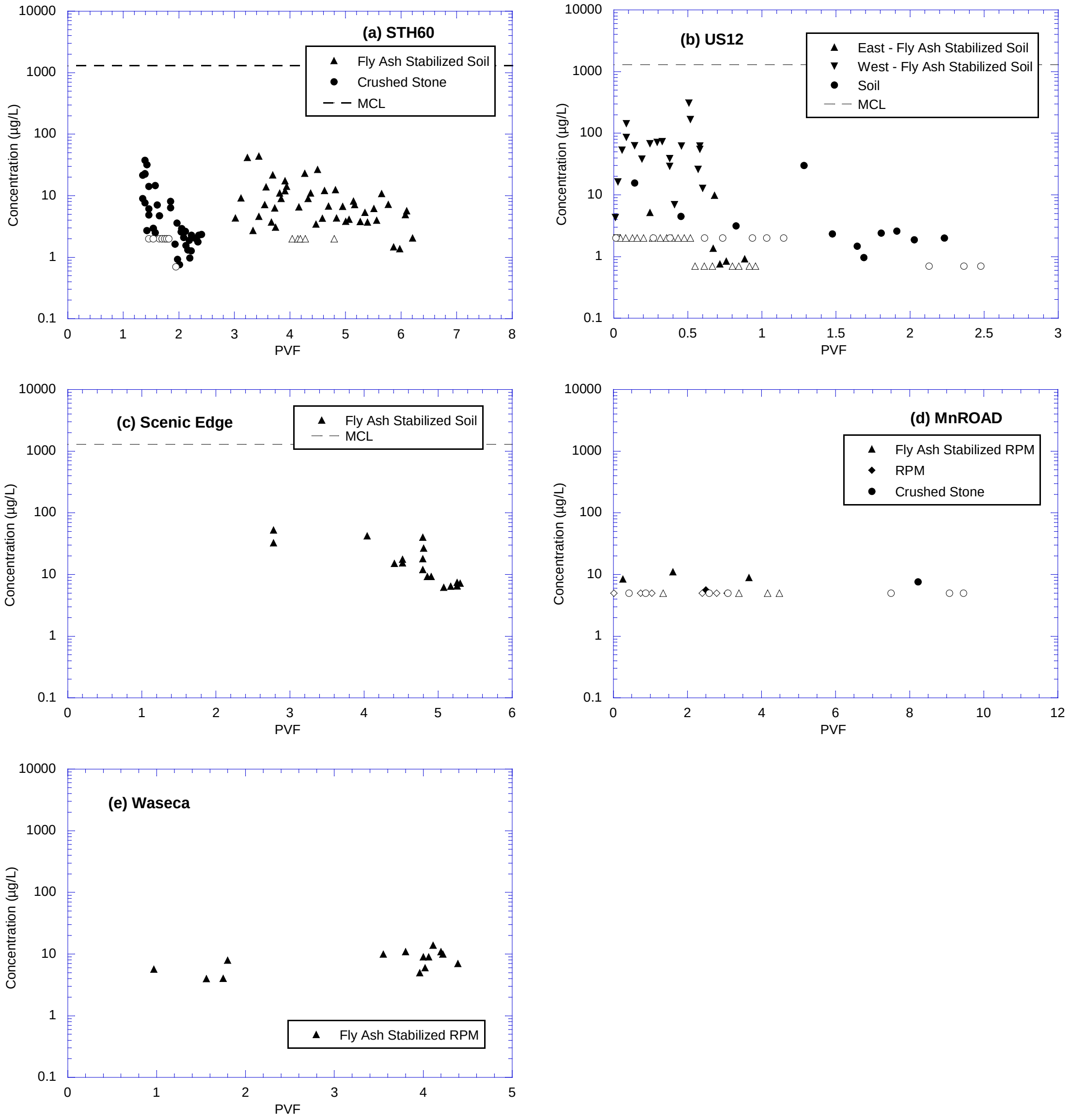


Fig. B-10. Copper (Cu) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

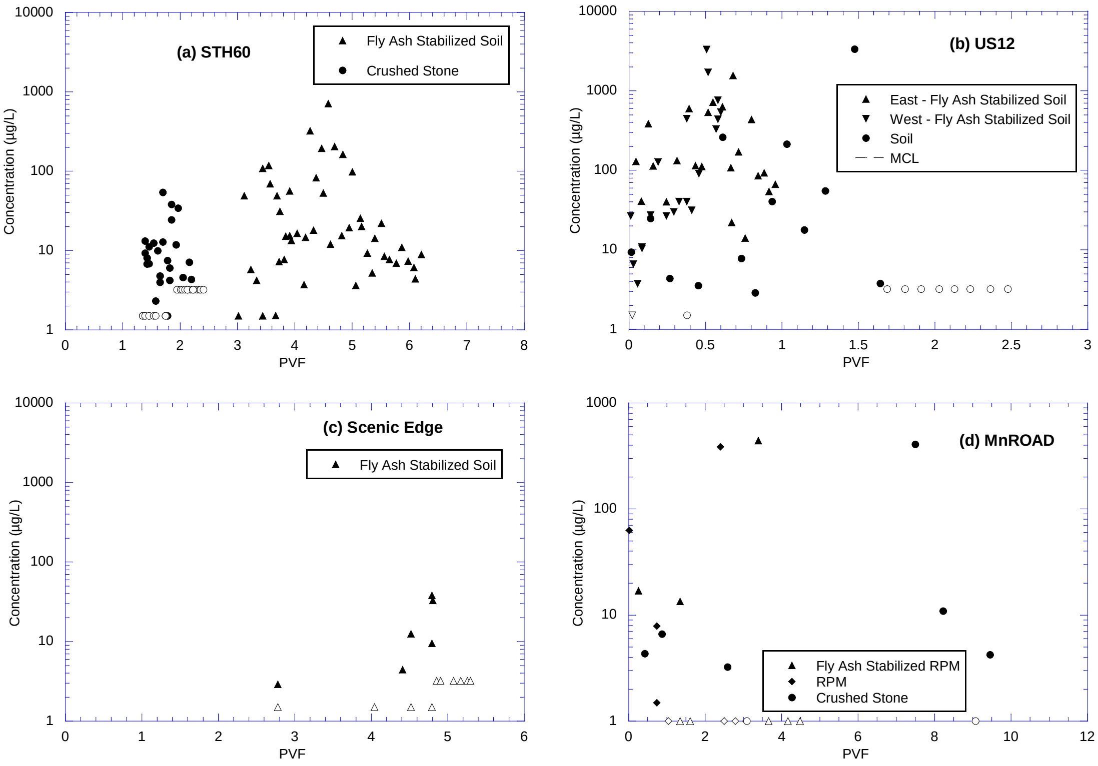


Fig. B-11. Iron (Fe) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

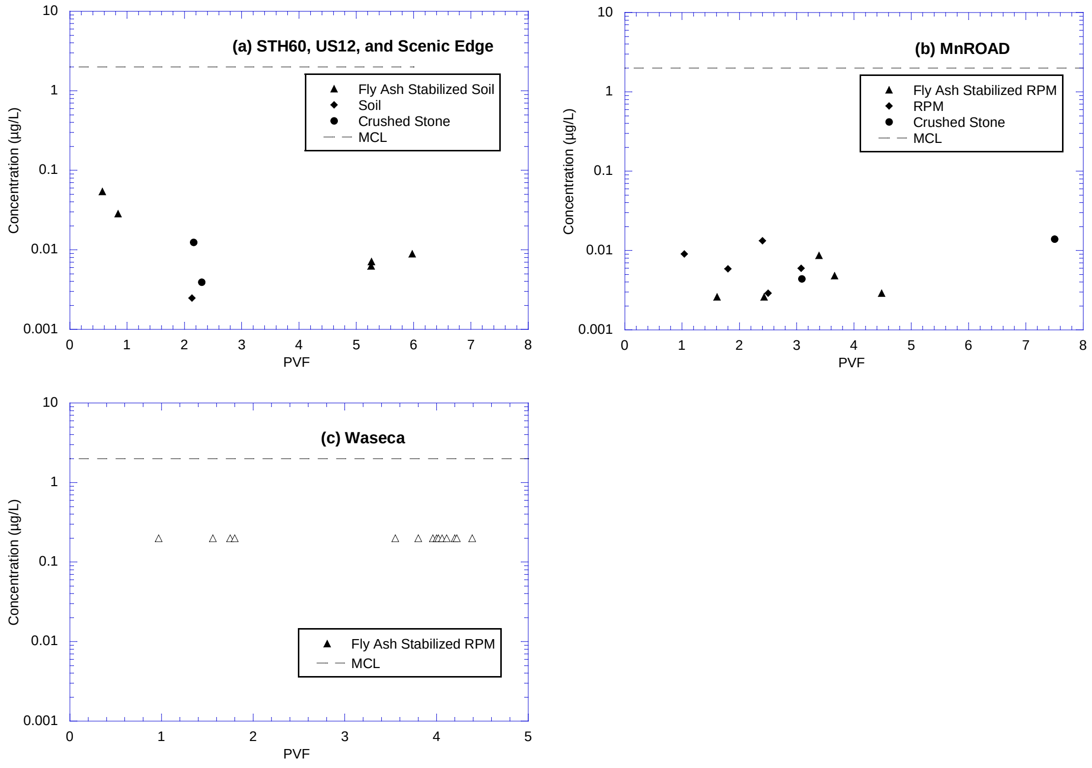


Fig. B-12. Mercury (Hg) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

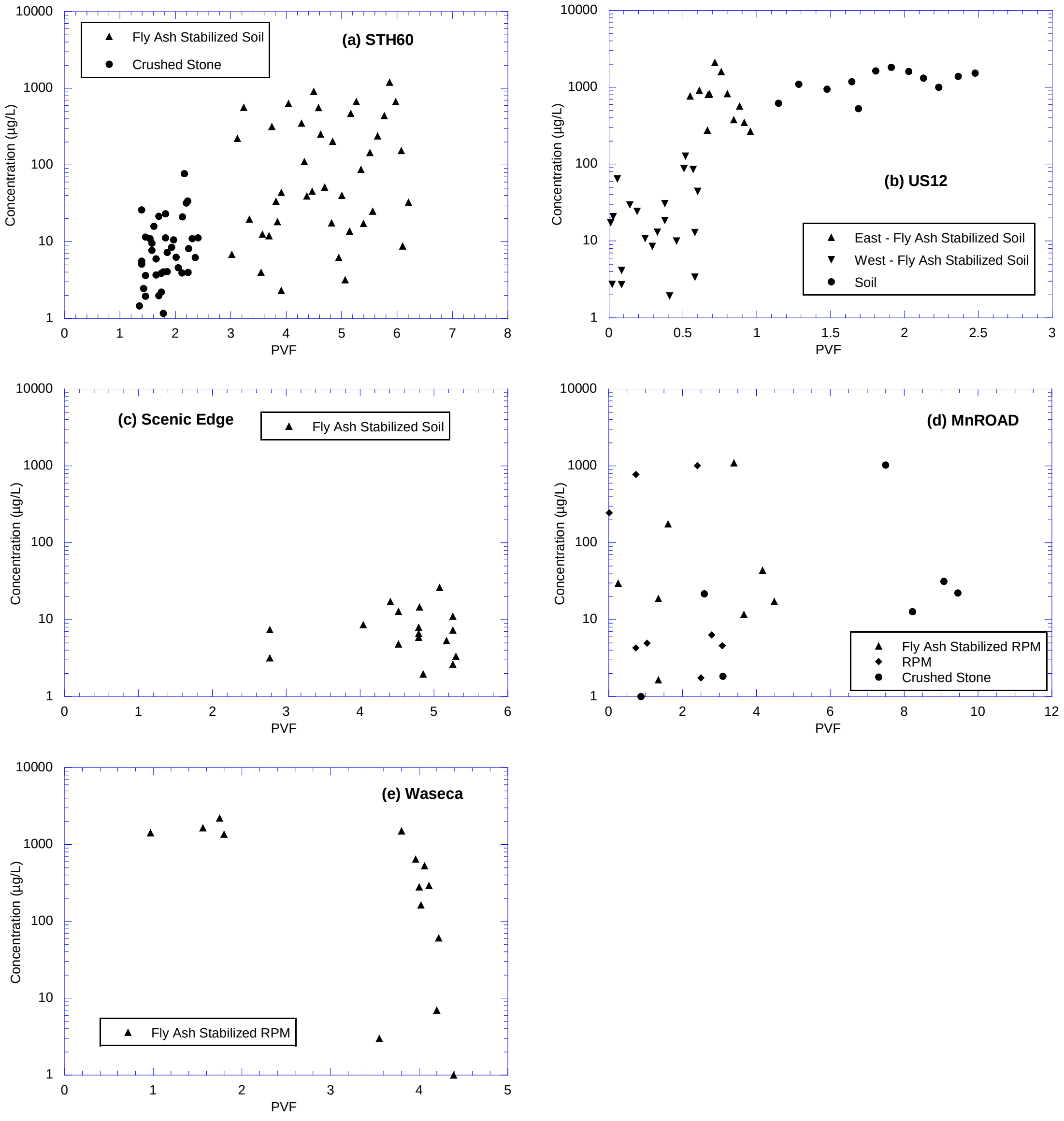


Fig. B-13. Manganese (Mn) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

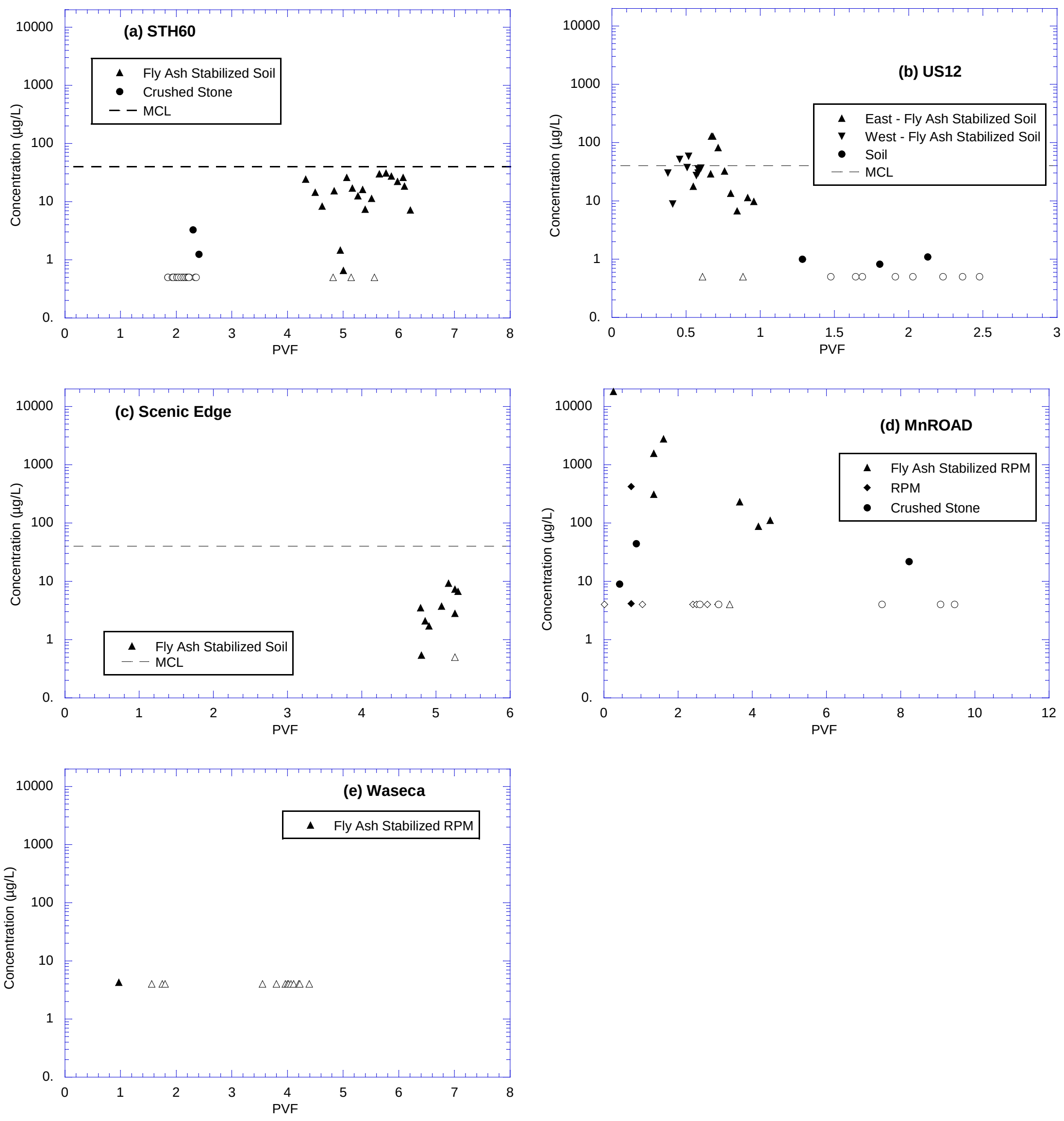


Fig. B-14. Molybdenum (Mo) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

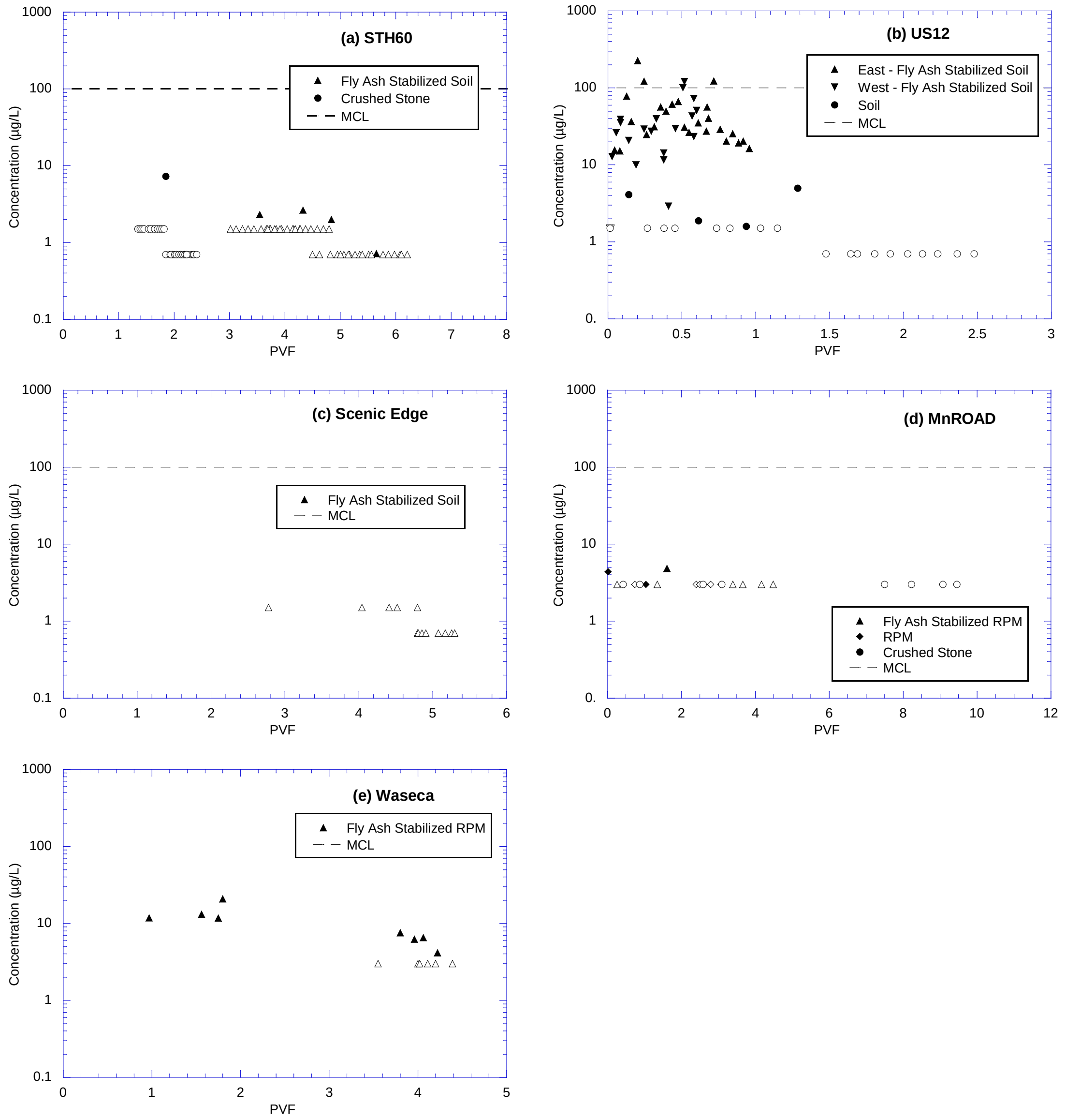


Fig. B-15. Nickel (Ni) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

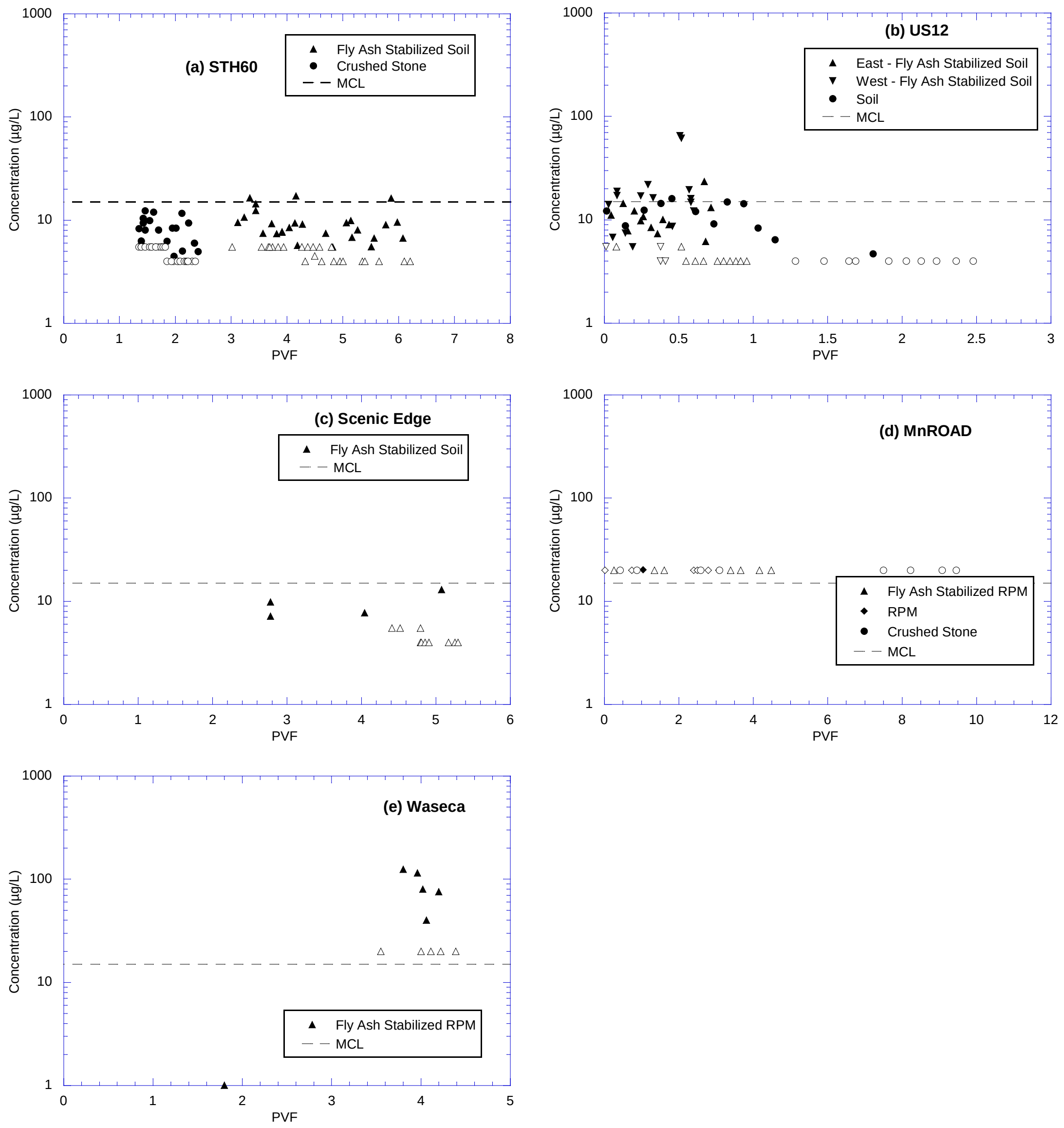


Fig. B-16. Lead (Pb) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

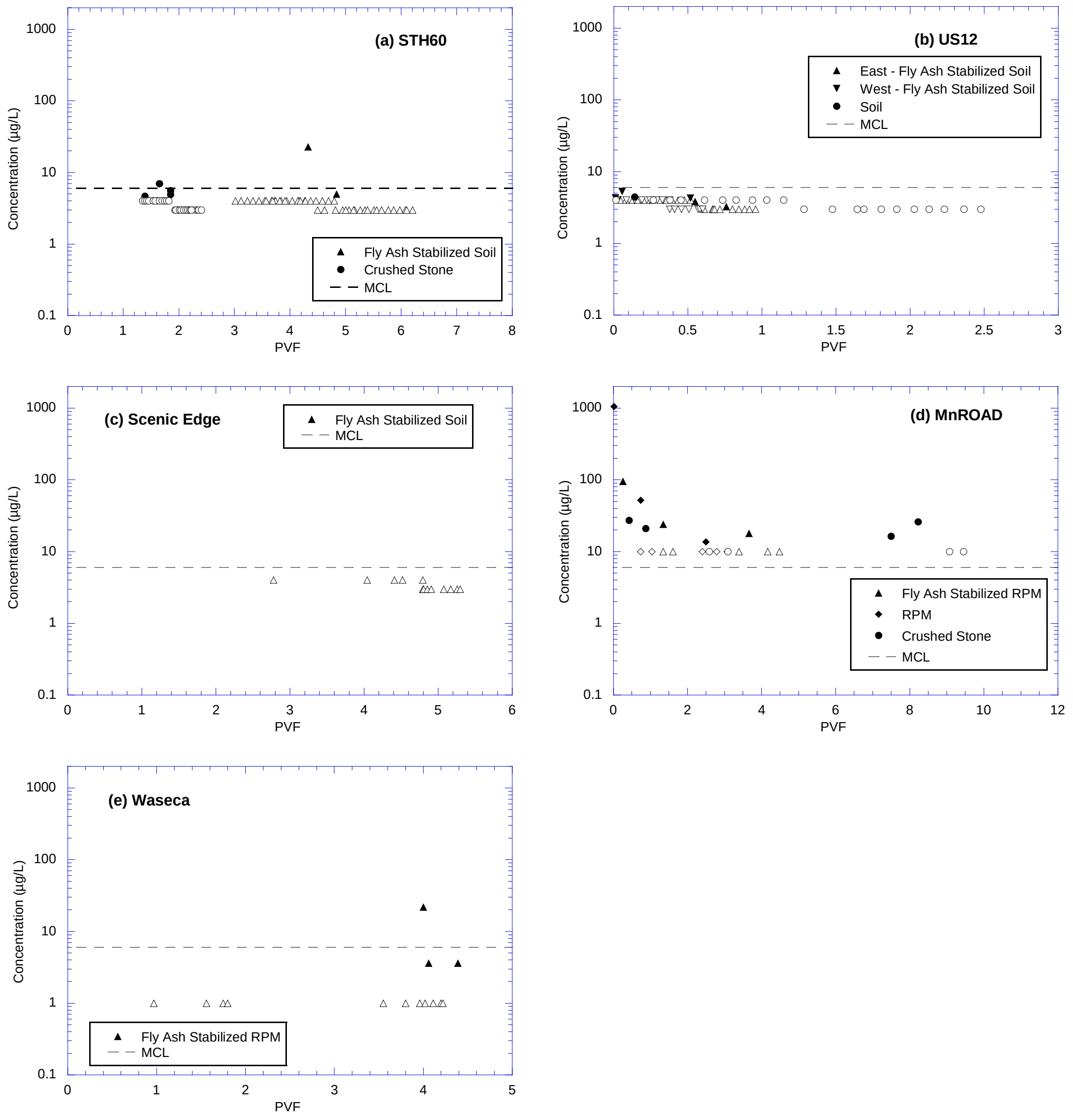


Fig. B-17. Antimony (Sb) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

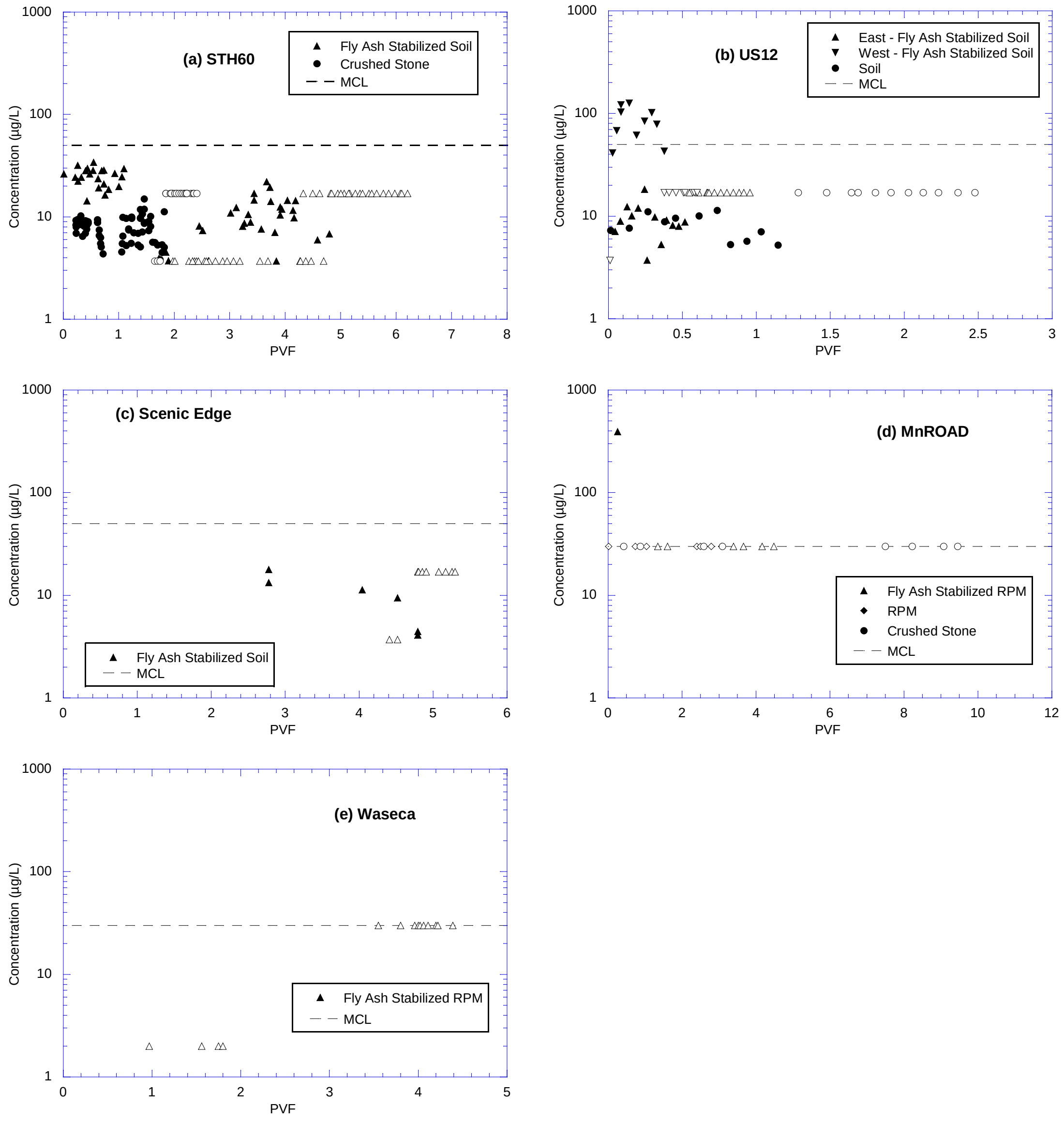


Fig. B-18. Selenium (Se) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

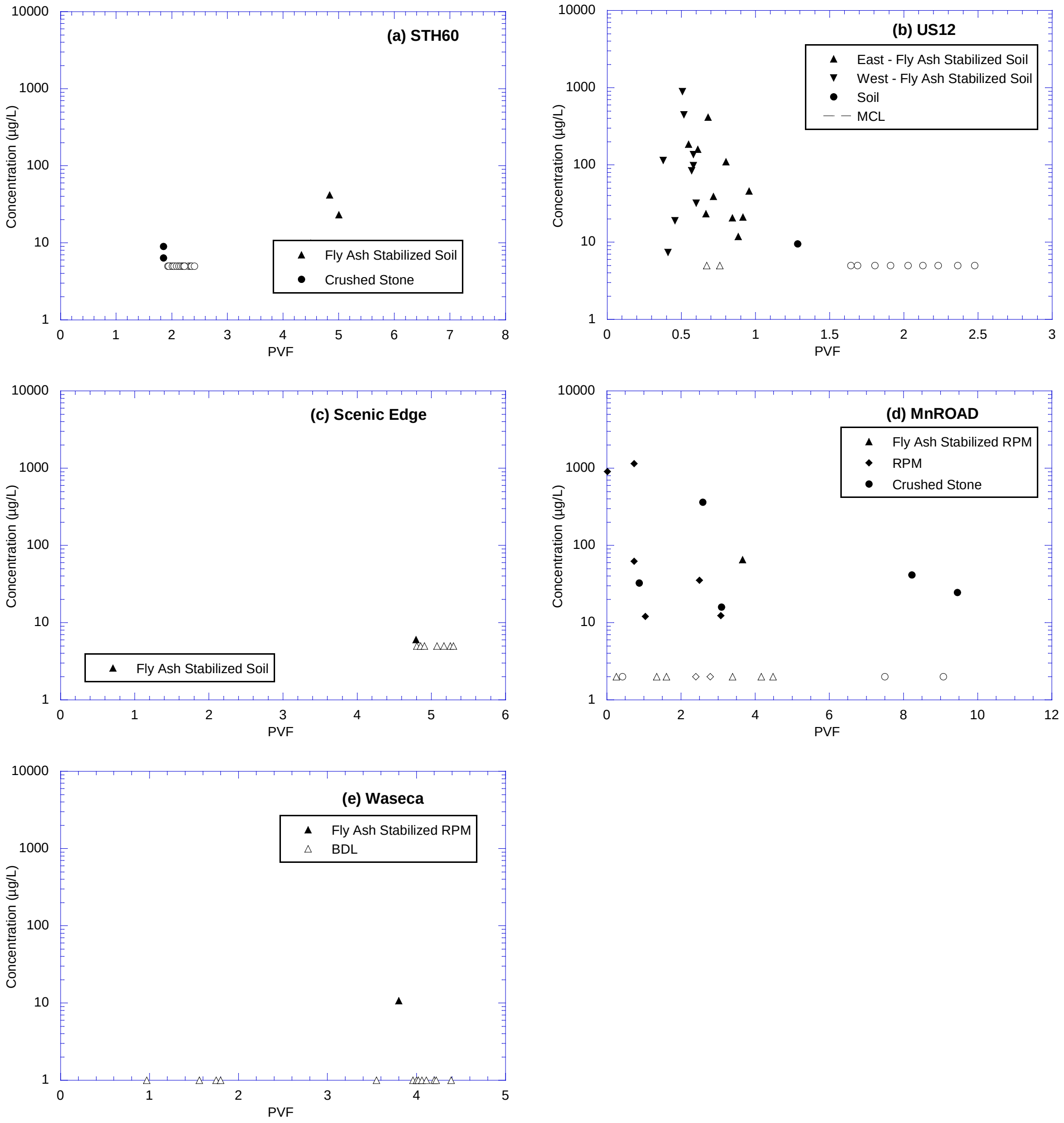


Fig. B-19. Tin (Sn) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

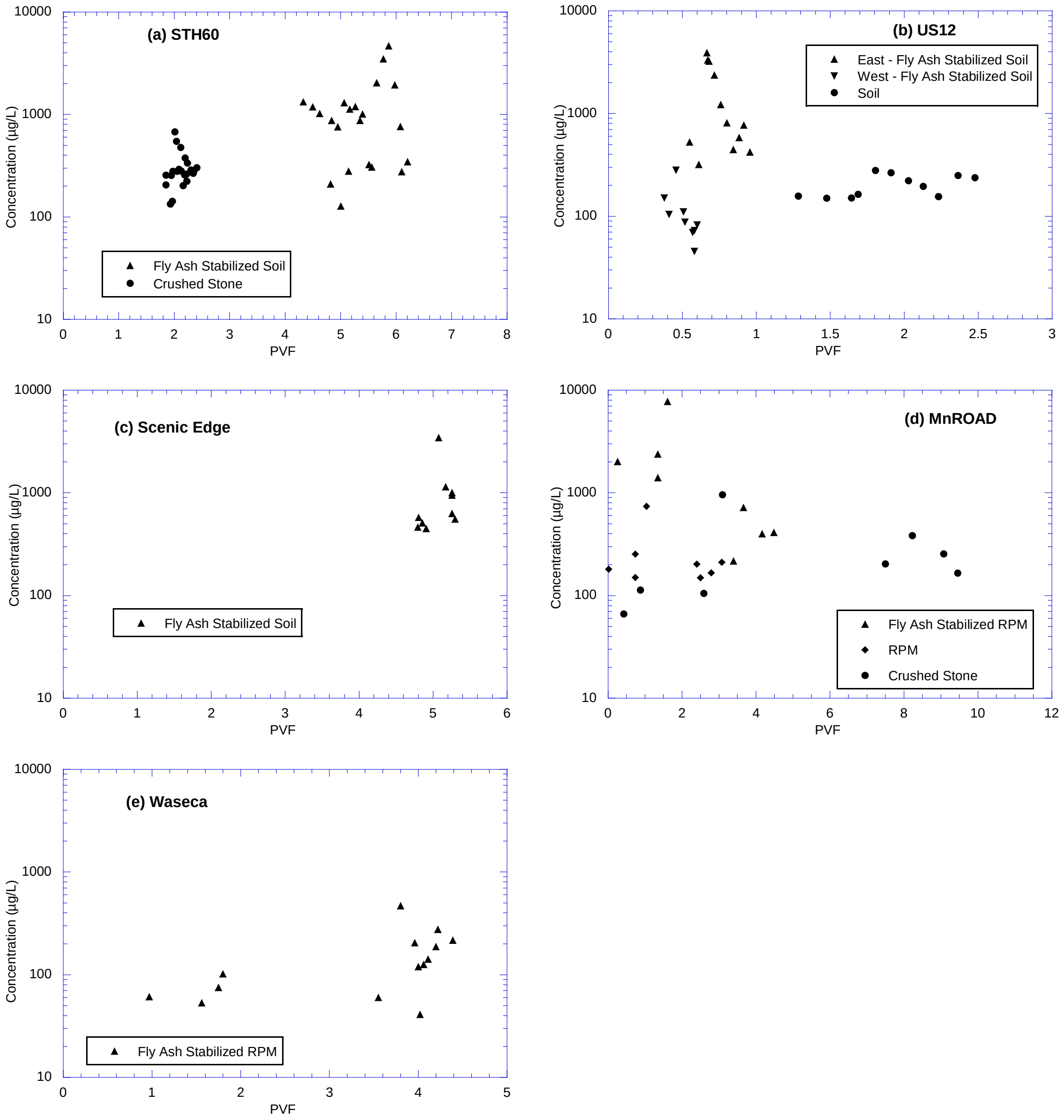


Fig. B-20. Strontium (Sr) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

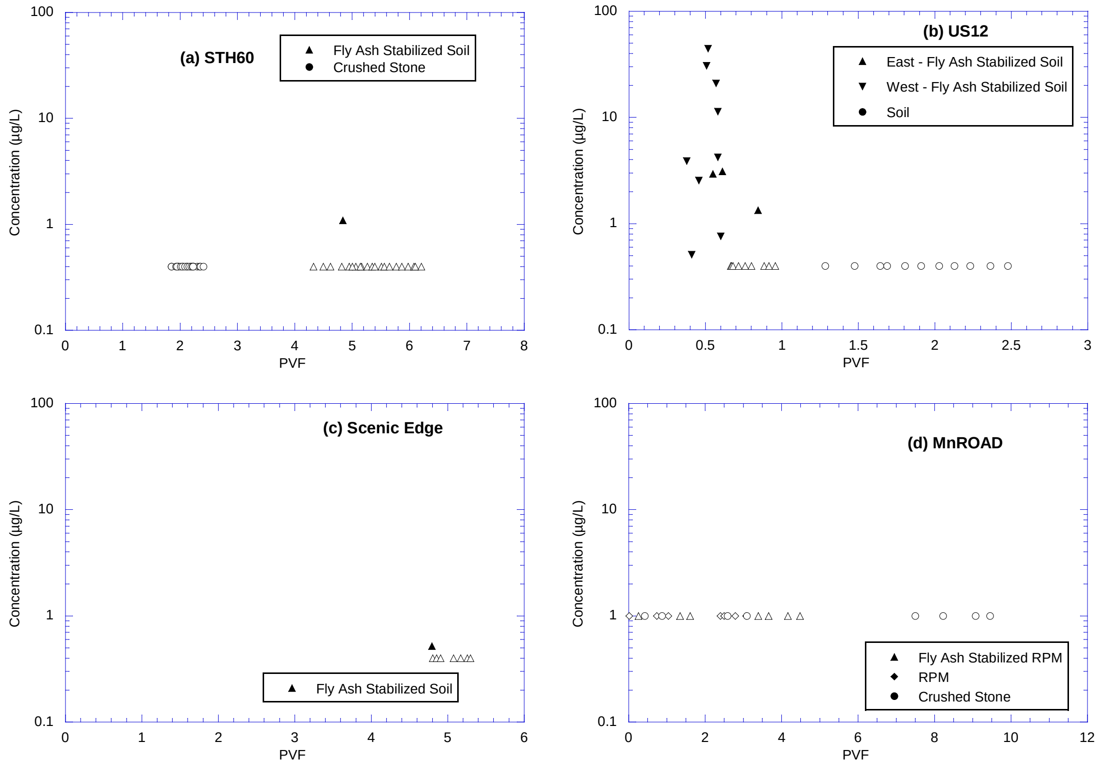


Fig. B-21. Titanium (Ti) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

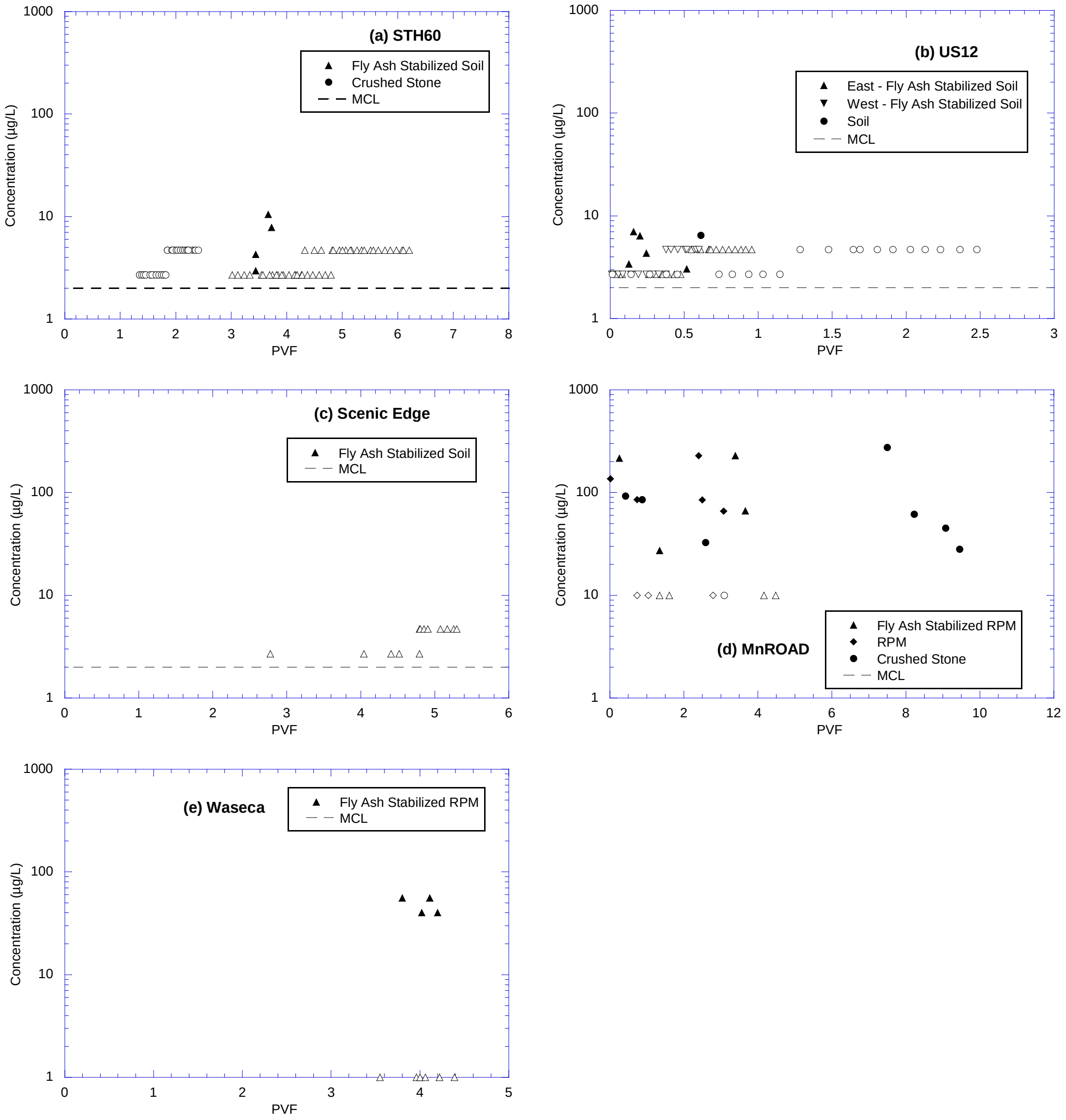


Fig. B-22. Thallium (Tl) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

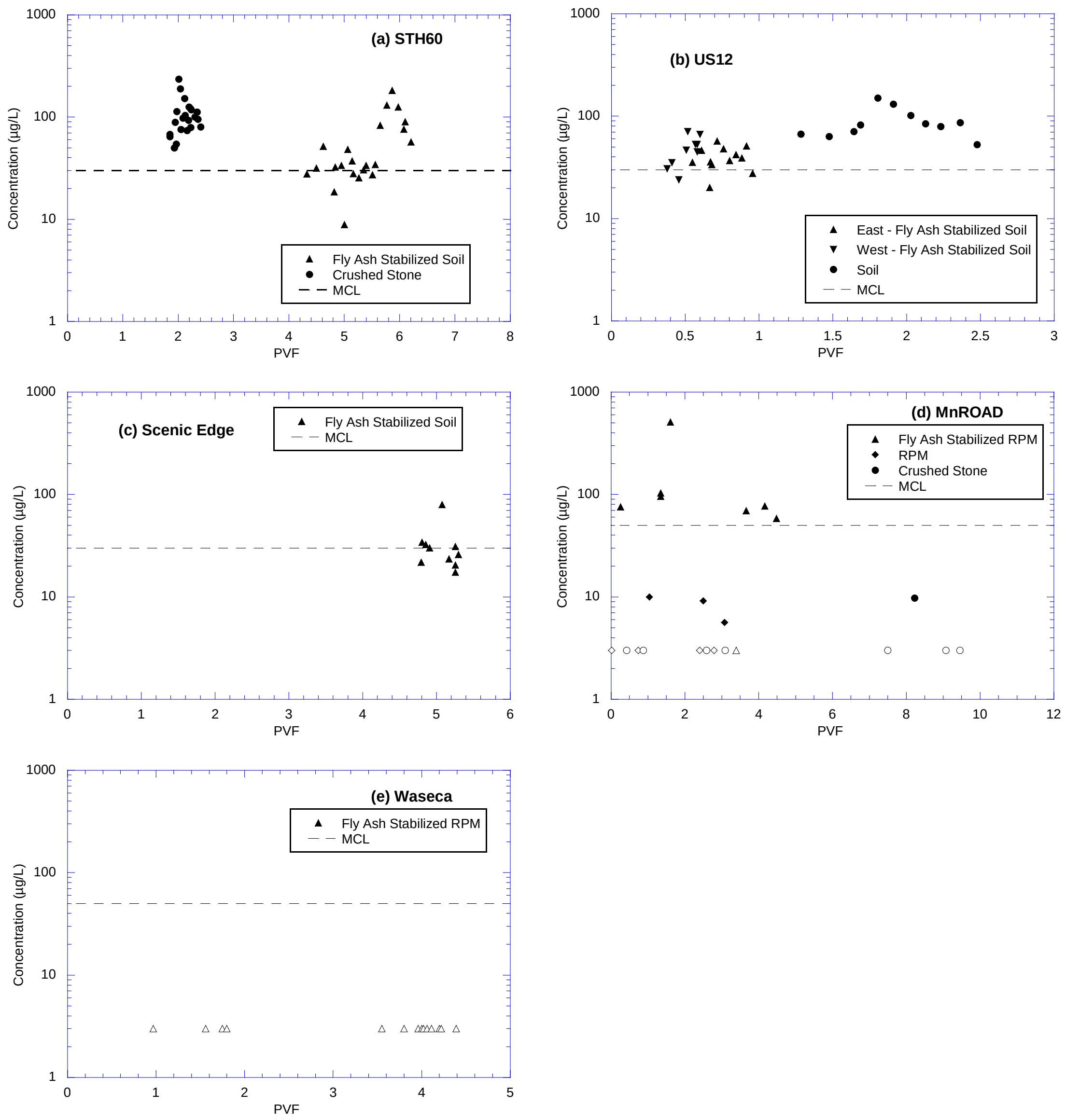


Fig. B-23. Vanadium (V) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

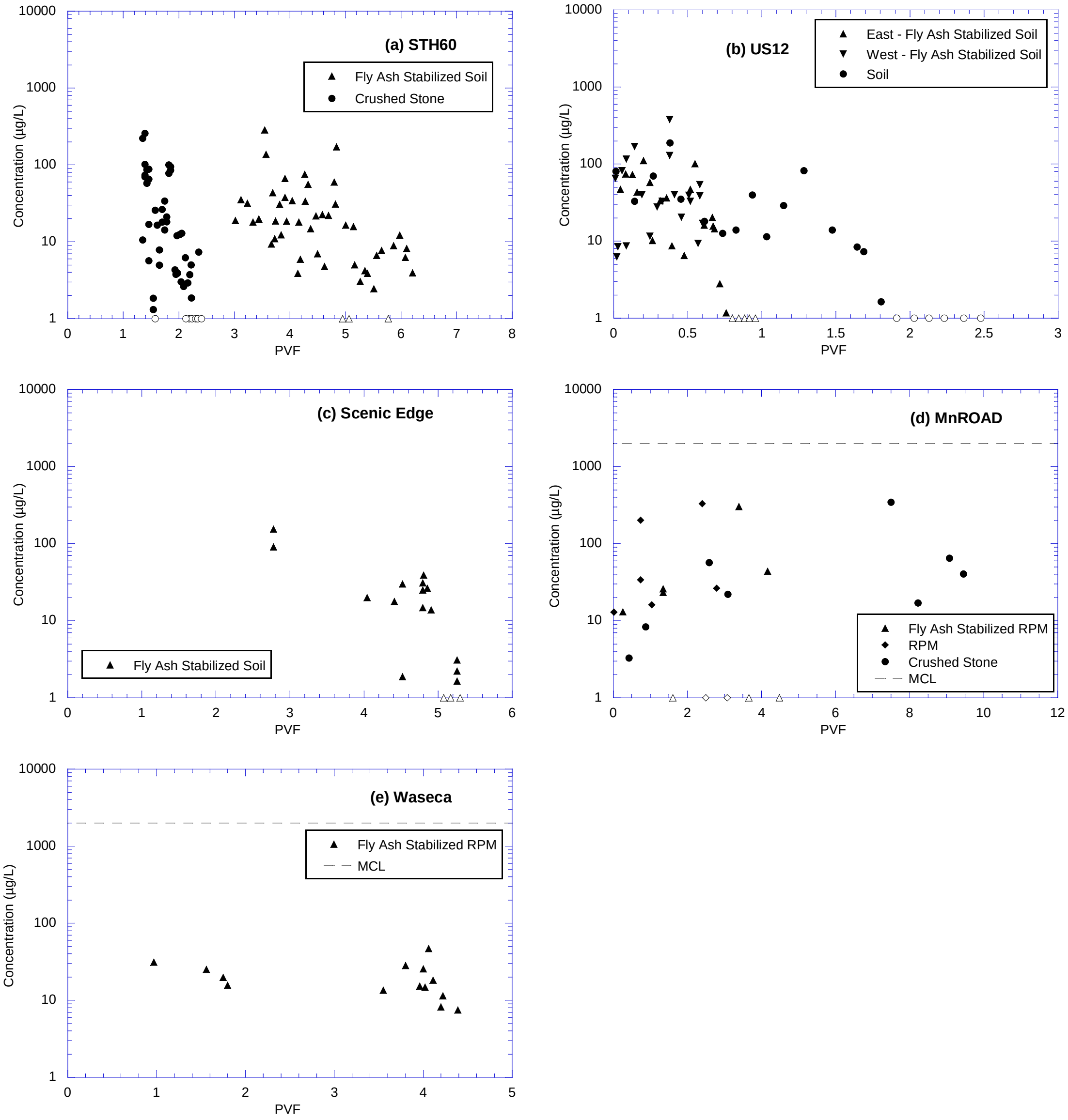


Fig. B-24. Zinc (Zn) concentrations in leachate from field lysimeters. Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

APPENDIX C – LABORATORY CHEMICAL CONCENTRATIONS

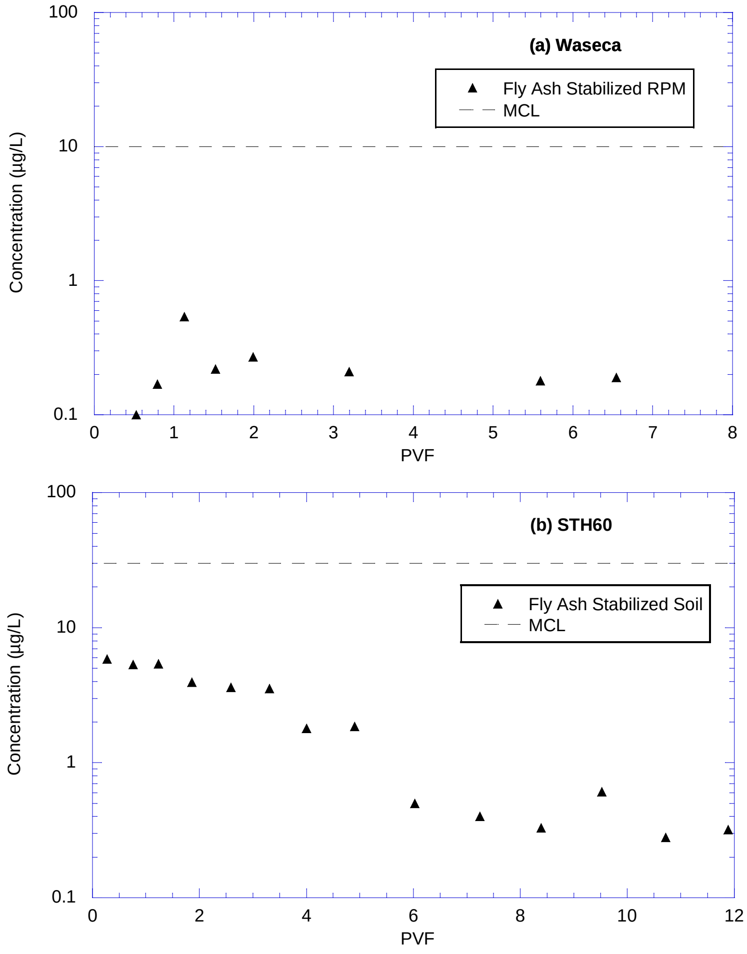


Fig. C-1. Silver (Ag) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

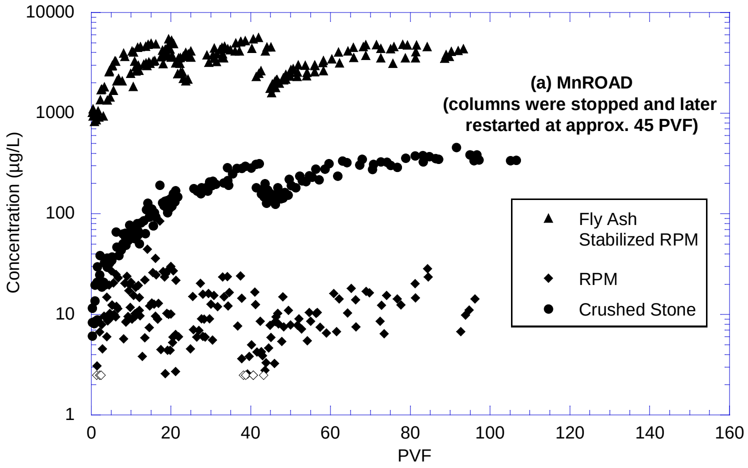


Fig. C-2. Aluminum (Al) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

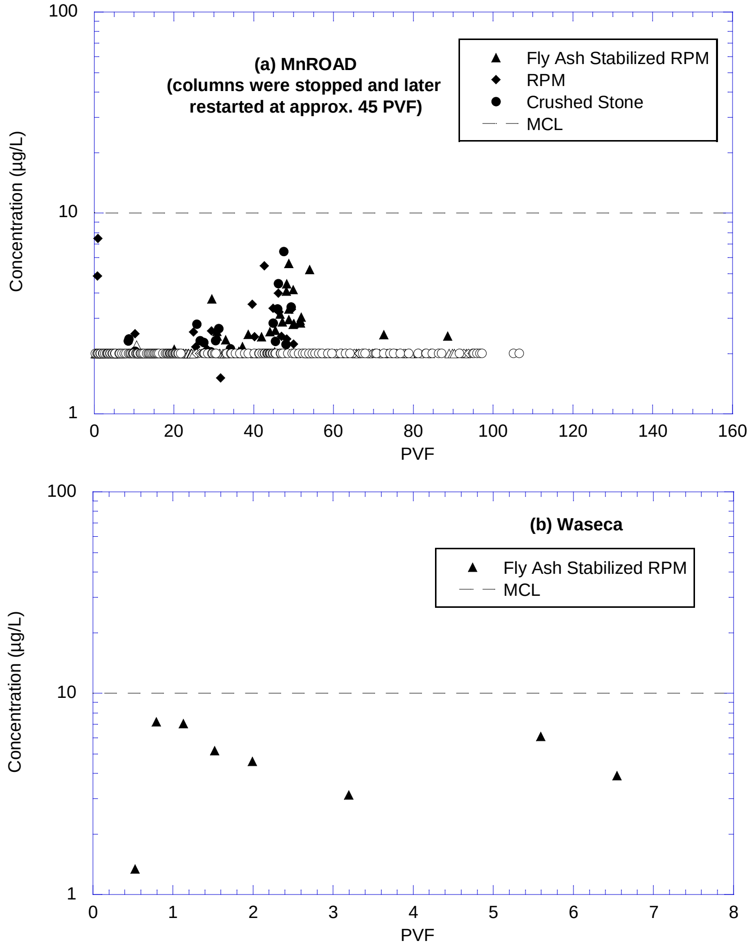


Fig. C-3. Arsenic (As) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

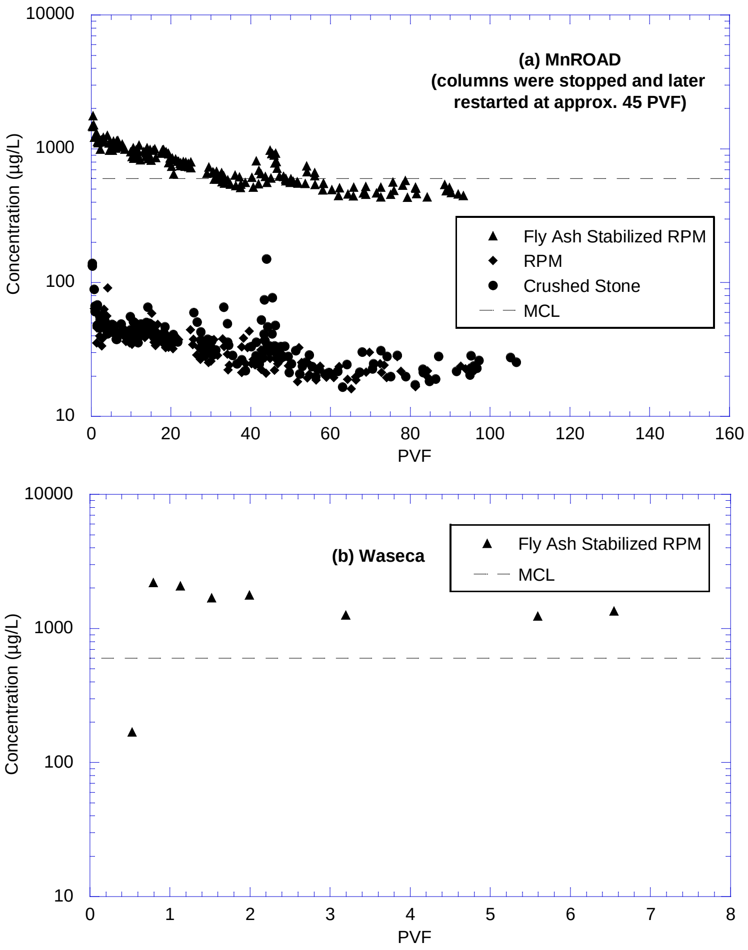


Fig. C-4. Boron (B) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

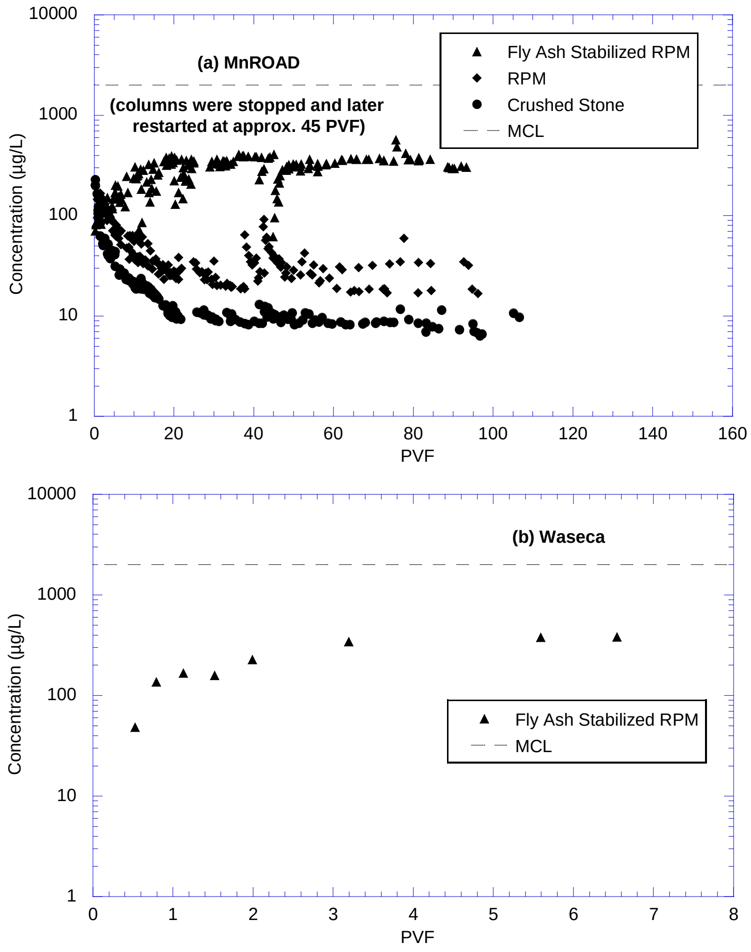


Fig. C-5. Barium (Ba) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

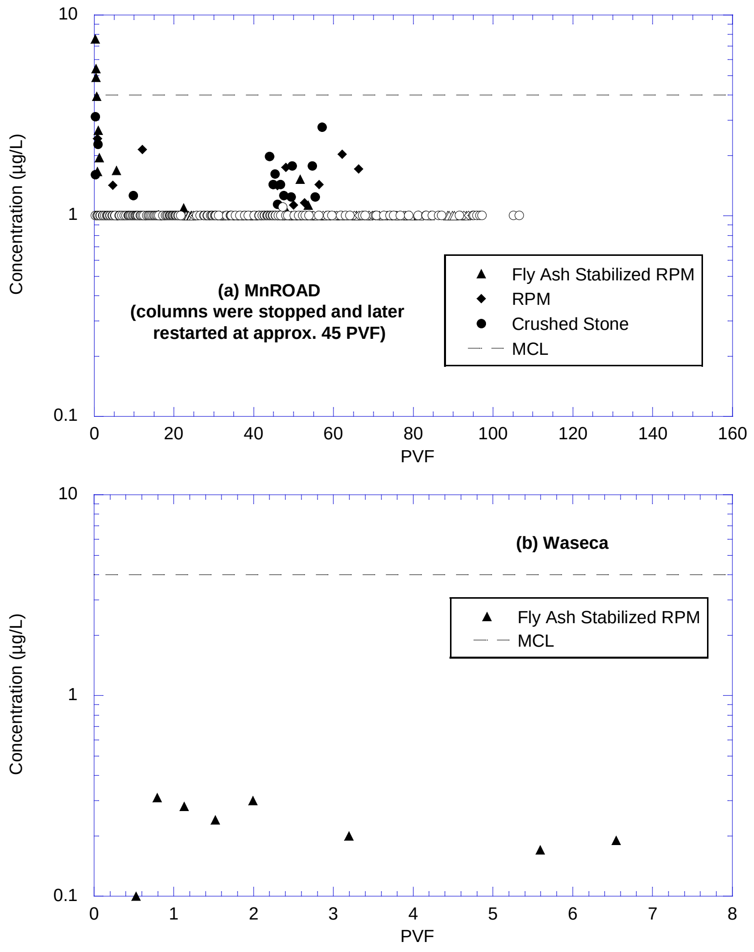


Fig. C-6. Beryllium (Be) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

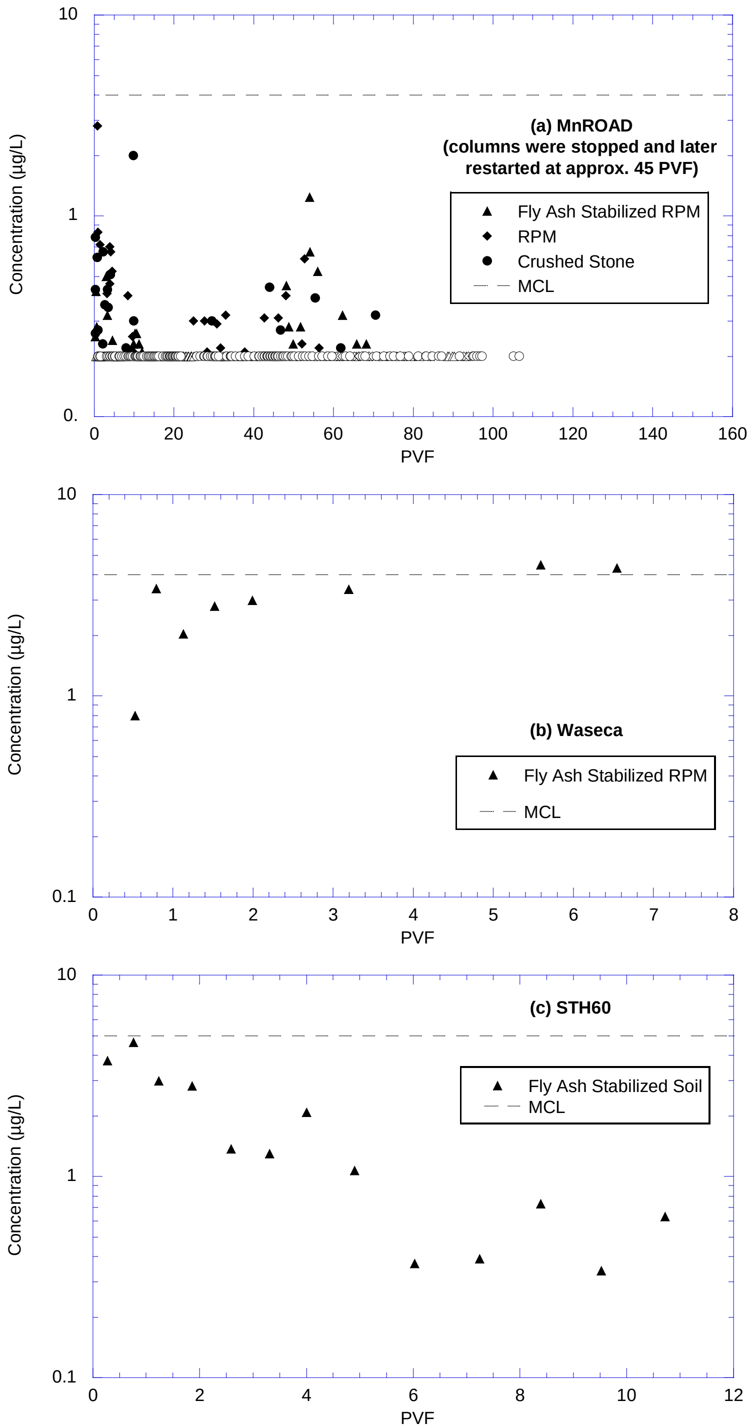


Fig. C-7. Cadmium (Cd) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

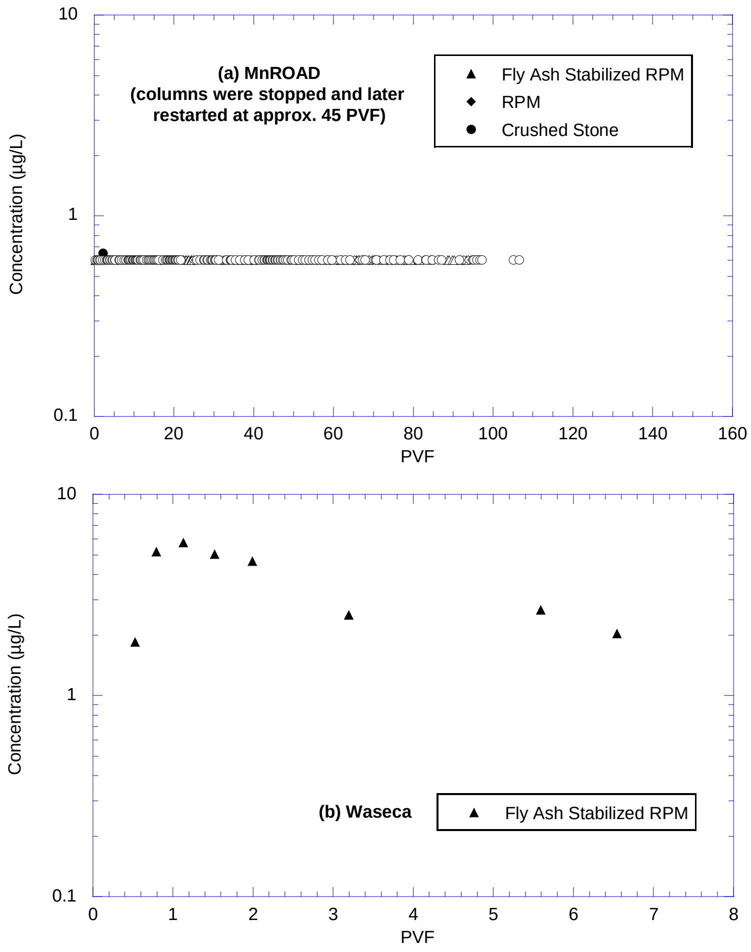
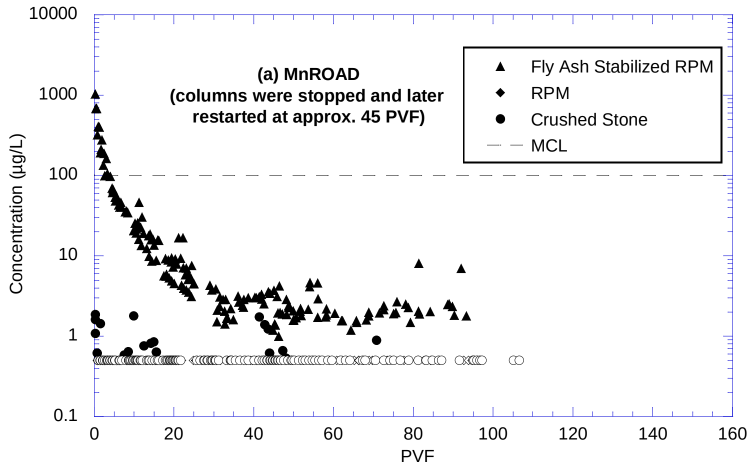
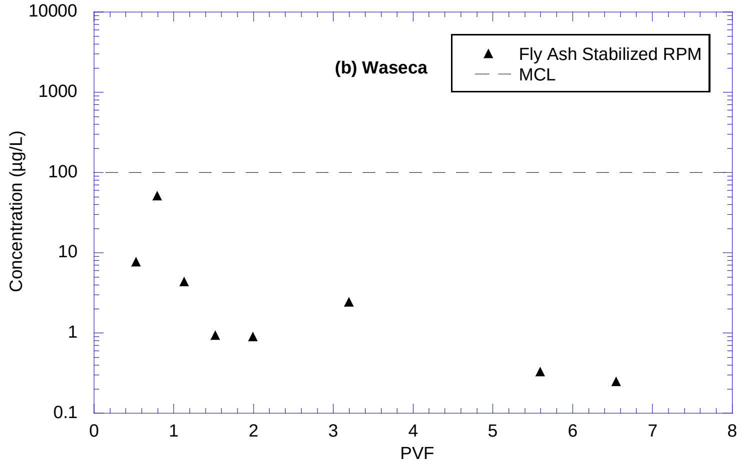


Fig. C-8. Cobalt (Co) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.


(a) MnROAD
(columns were stopped and later restarted at approx. 45 PVF)
Fly Ash Stabilized RPM
RPM
Crushed Stone
MCL
Concentration (µg/L)
10000
1000
100
10
1
0.1
0
20
40
60
80
100
120
140
160
PVF


(b) Waseca
Fly Ash Stabilized RPM
MCL
Concentration (µg/L)
10000
1000
100
10
1
0.1
0
1
2
3
4
5
6
7
8
PVF

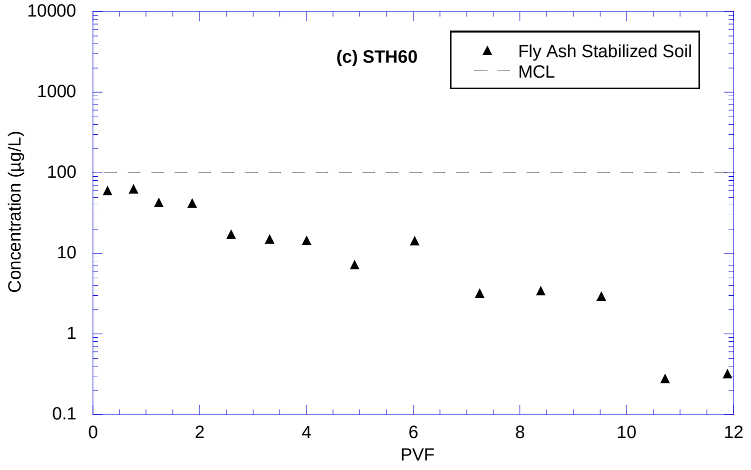

(c) STH60
Fly Ash Stabilized Soil
MCL
Concentration (µg/L)
10000
1000
100
10
1
0.1
0
2
4
6
8
10
12
PVF

Fig. C-9. Chromium (Cr) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

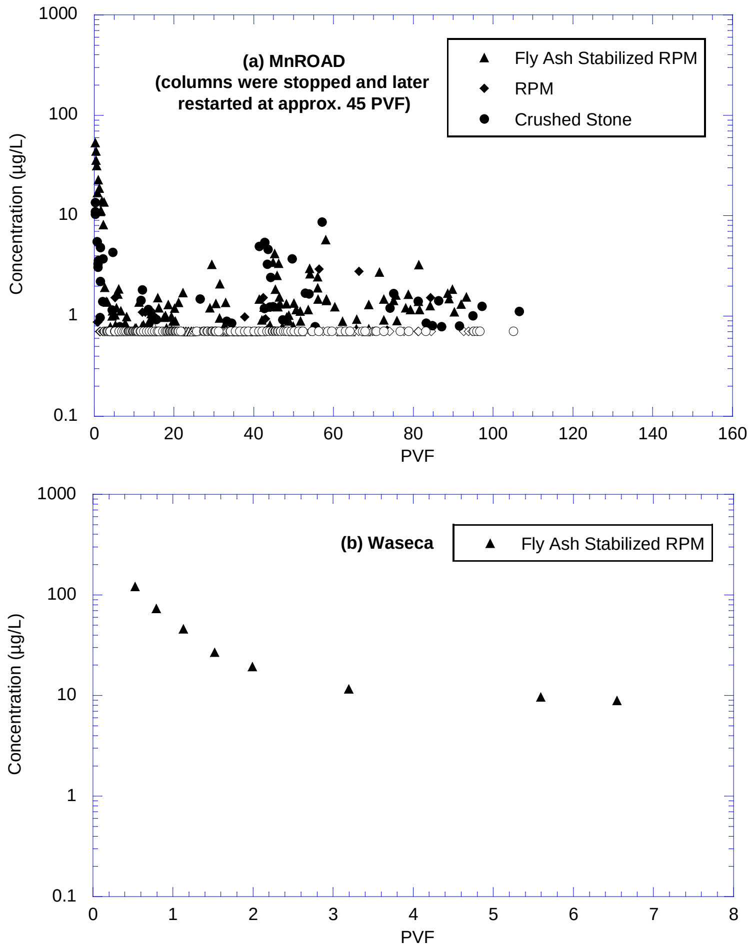


Fig. C-10. Copper (Cu) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

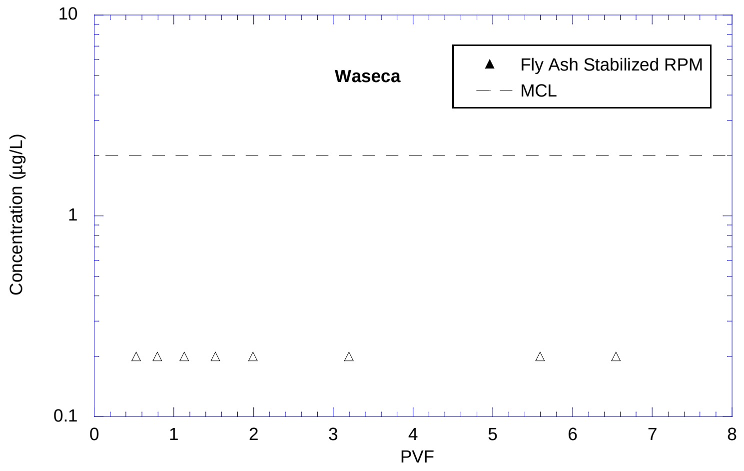


Fig. C-11. Mercury (Hg) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

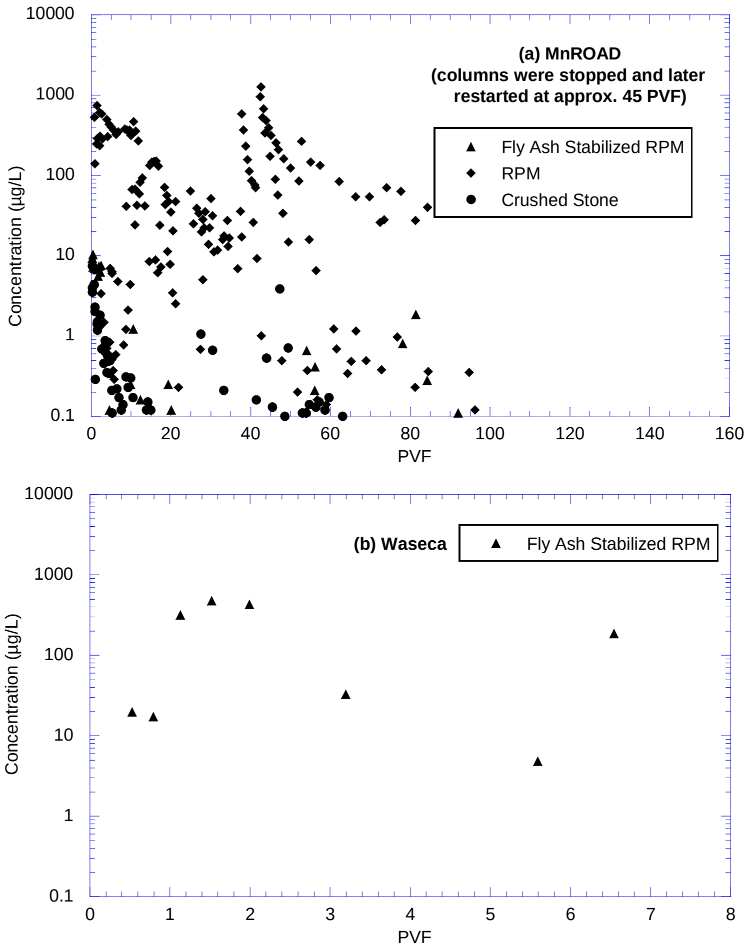


Fig. C-12. Manganese (Mn) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

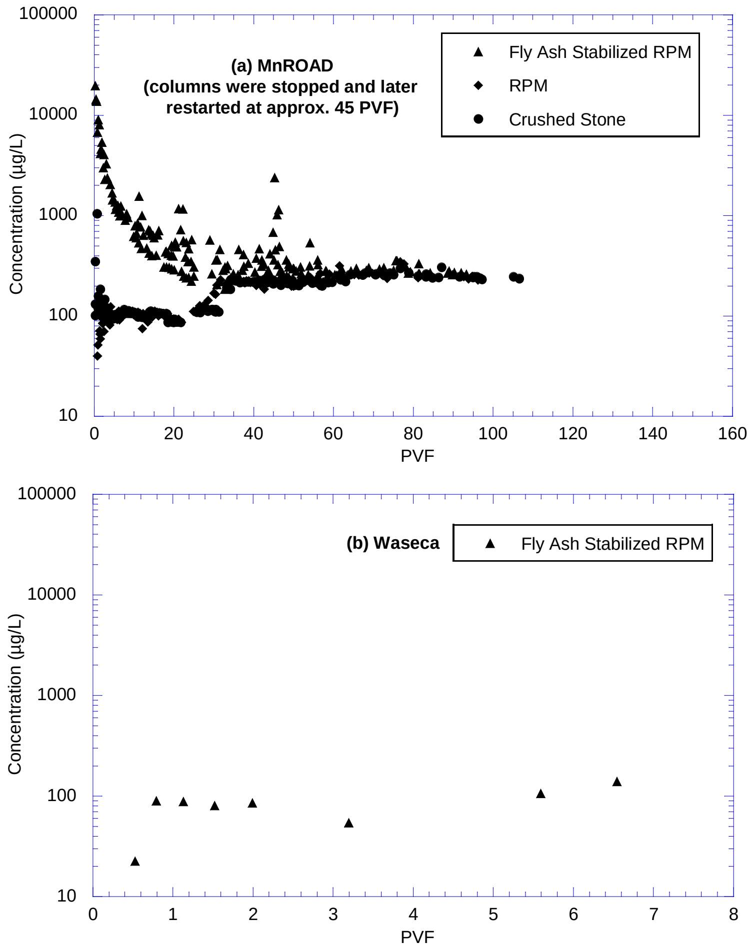


Fig. C-13. Molybdenum (Mo) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

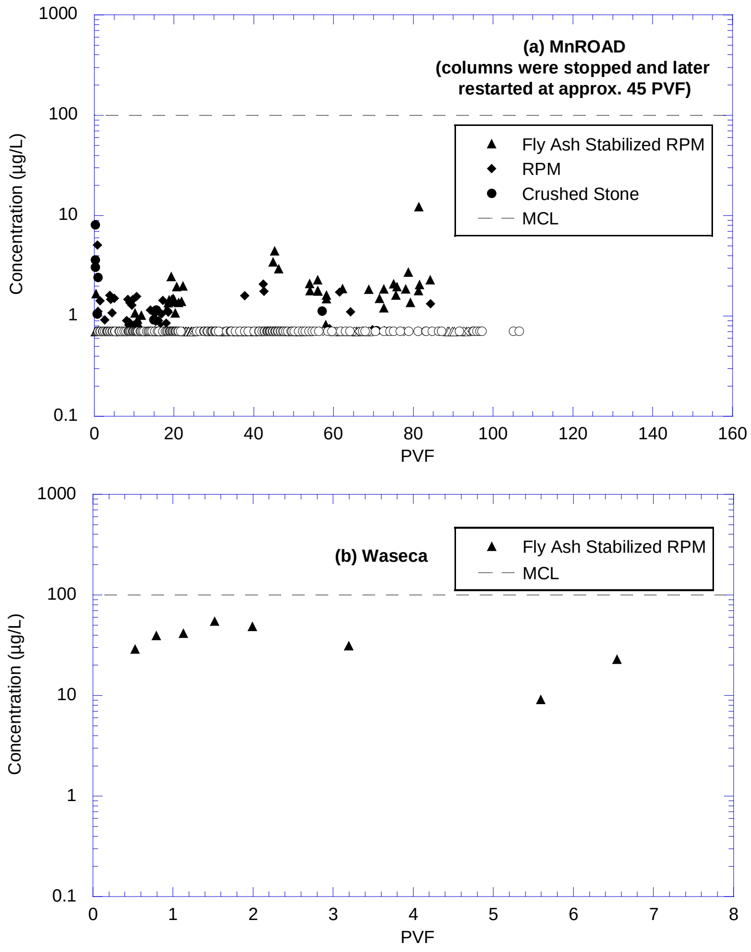


Fig. C-14. Nickel (Ni) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

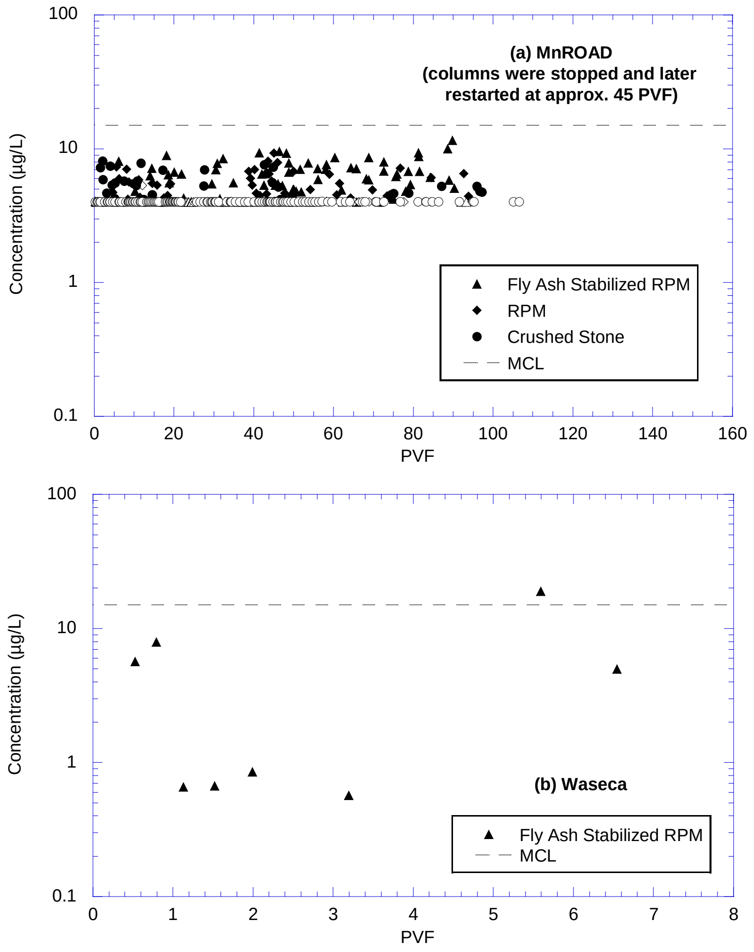


Fig. C-15. Lead (Pb) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

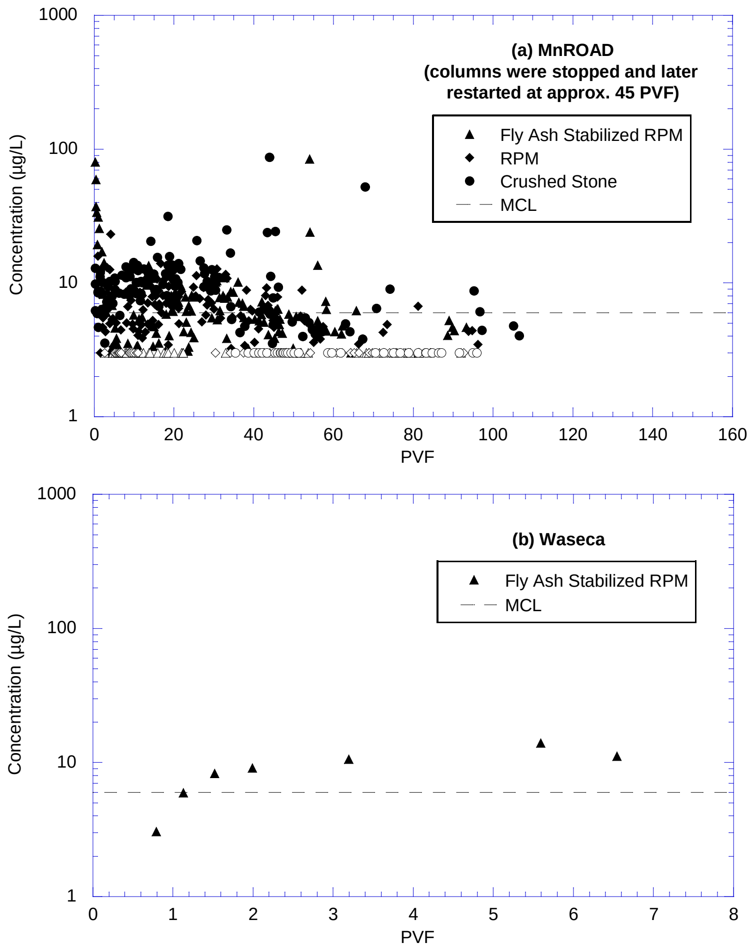


Fig. C-16. Antimony (Sb) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

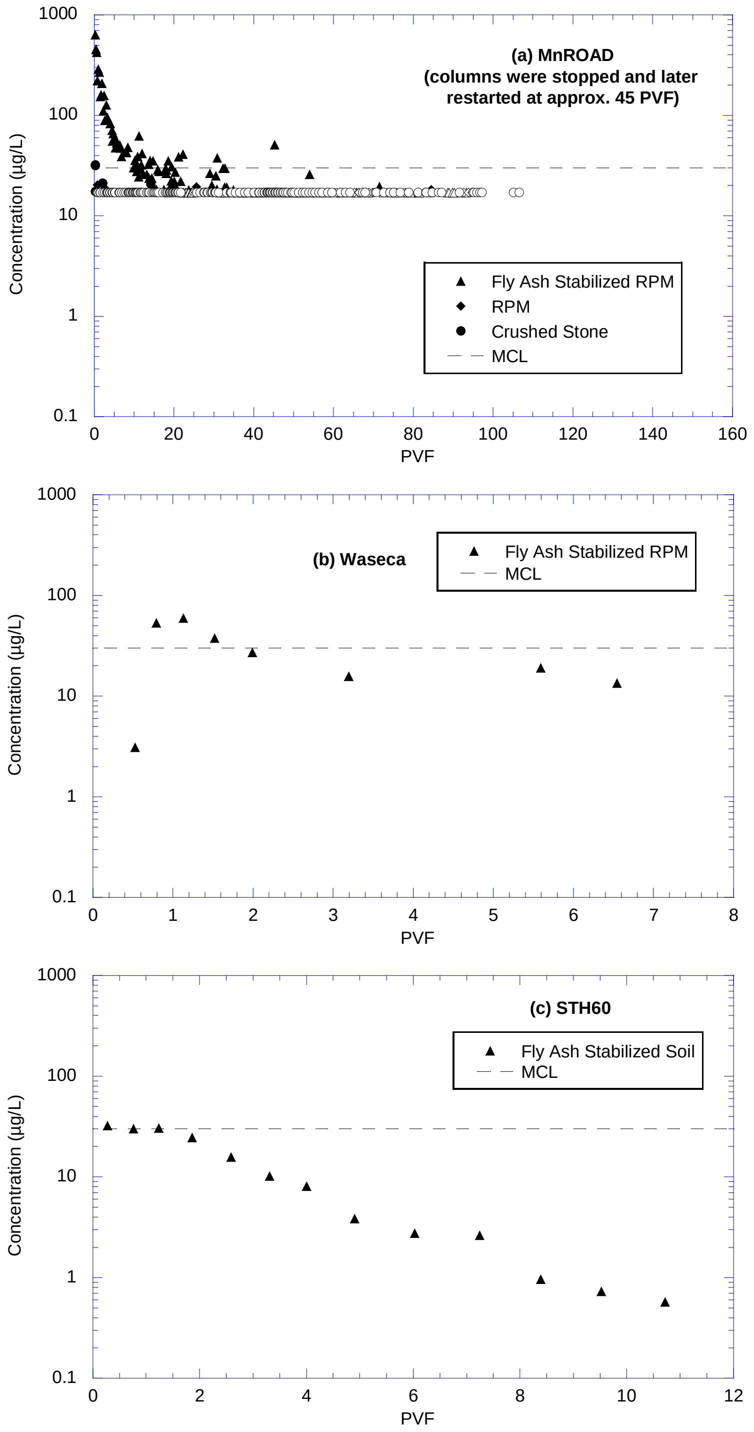

1000
100
10
1
0.1
Concentration (µg/L)
(a) MnROAD
(columns were stopped and later restarted at approx. 45 PVF)
▲ Fly Ash Stabilized RPM
◆ RPM
● Crushed Stone
— — MCL
0
20
40
60
80
100
120
140
160
PVF
1000
100
10
1
0.1
Concentration (µg/L)
(b) Waseca
▲ Fly Ash Stabilized RPM
— — MCL
0
1
2
3
4
5
6
7
8
PVF
1000
100
10
1
0.1
Concentration (µg/L)
(c) STH60
▲ Fly Ash Stabilized Soil
— — MCL
0
2
4
6
8
10
12
PVF

Fig. C-17. Selenium (Se) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

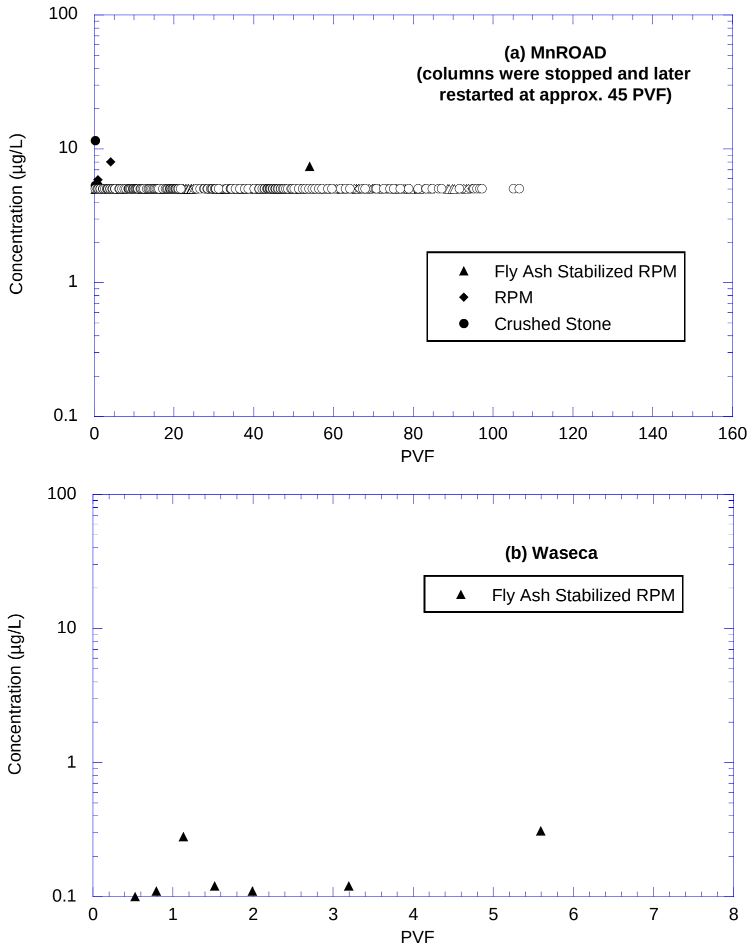


Fig. C-18. Tin (Sn) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

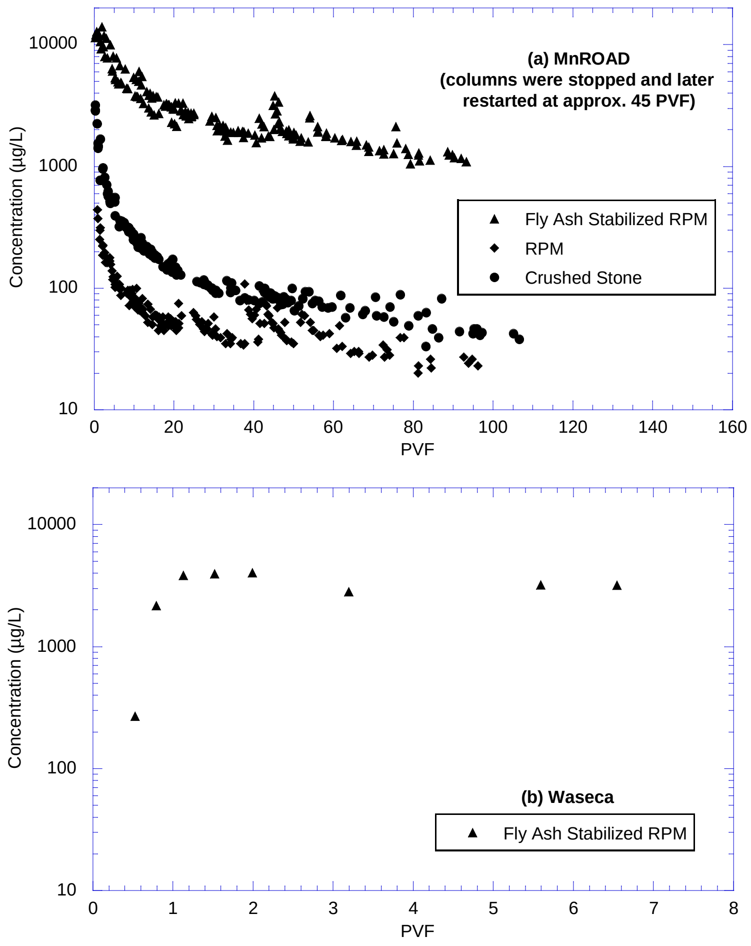


Fig. C-19. Strontium (Sr) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

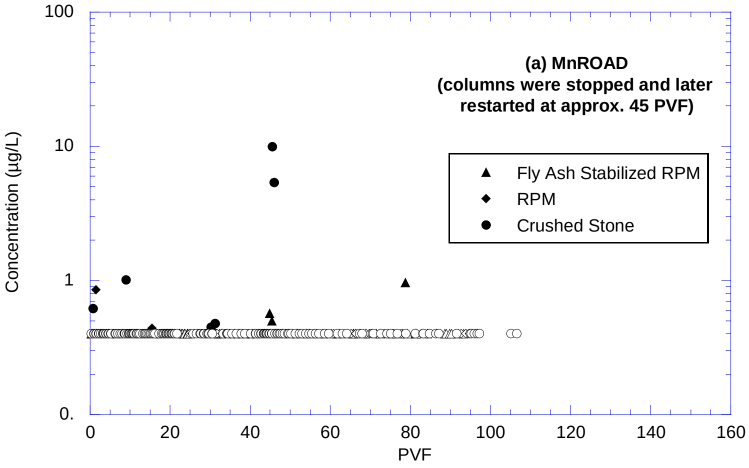


Fig. C-20. Titanium (Ti) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

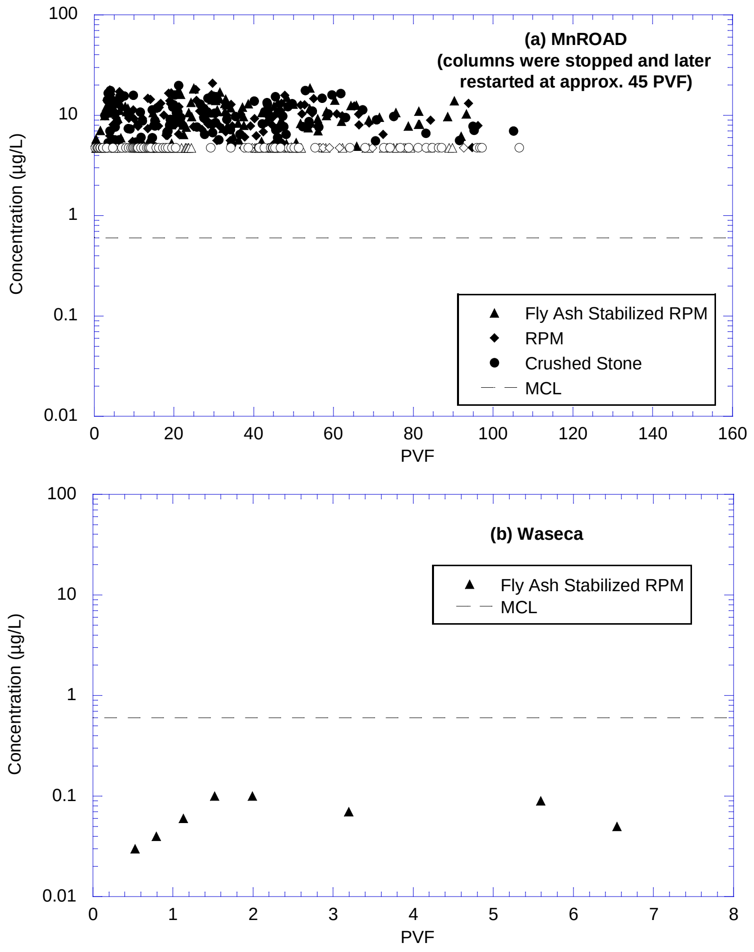


Fig. C-21. Thallium (Tl) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

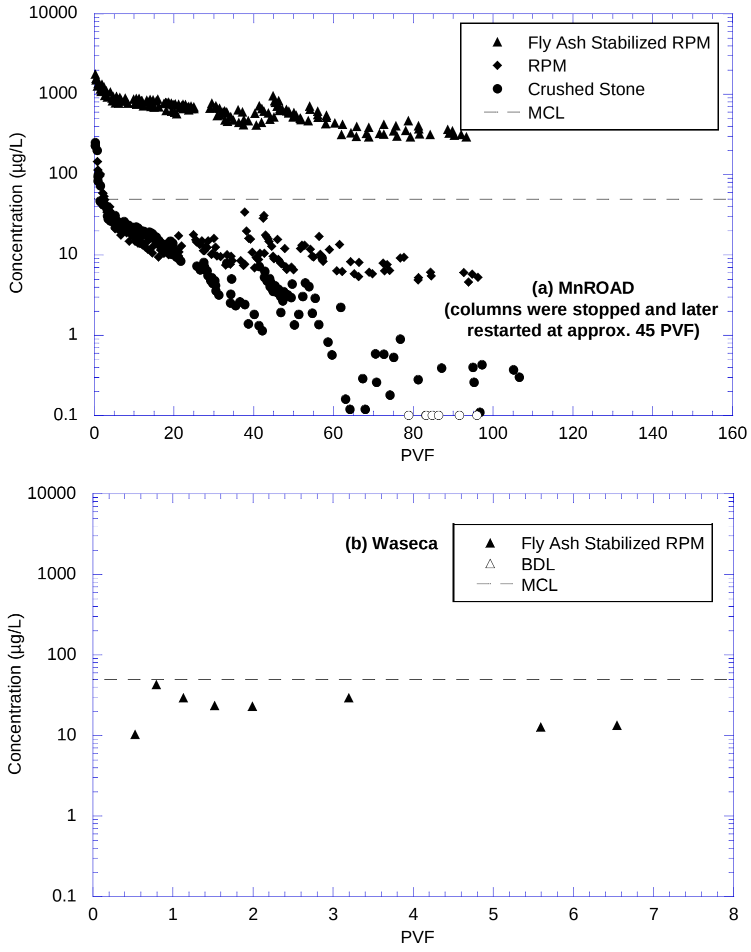


Fig. C-22. Vanadium (V) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

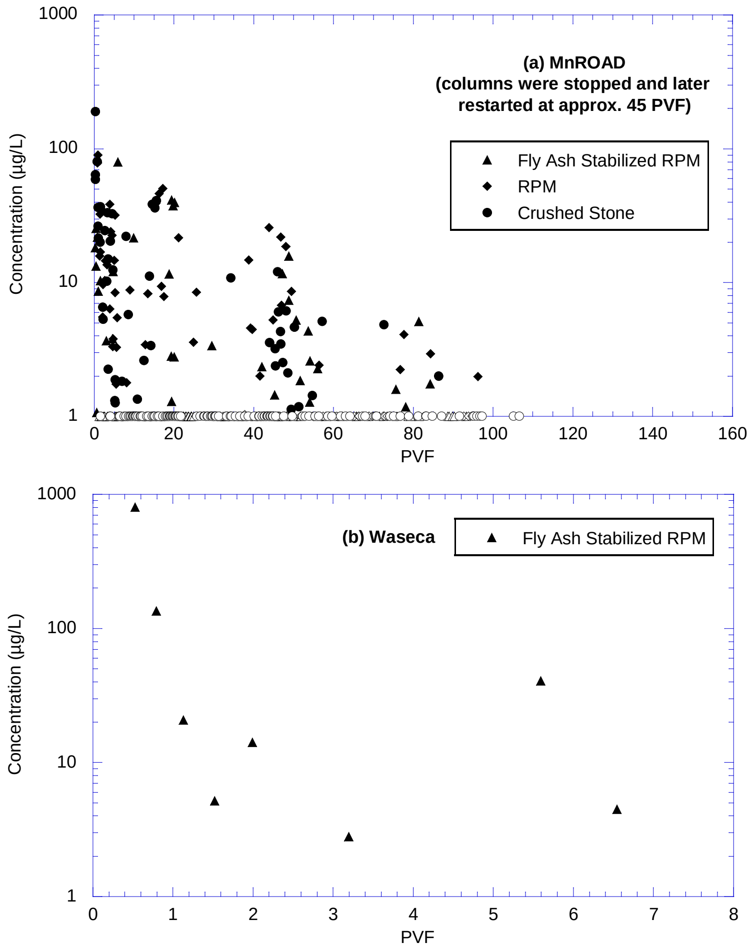


Fig. C-23. Zinc (Zn) concentrations in leachate from column leach tests (CLTs). Concentrations below minimum detection limits are plotted at the limit, and represented with an open symbol.

Table C-1. MnROAD Water Leach Test Results

Sample	Ag	Al	As	B	Be	Cd	Co	Cr	Cu	F
Material and L:S Ratio	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	pp
Crushed Stone - 3:1	3	56.6	<30	<20	<1	<4	<3	<1	<5	23
Crushed Stone - 5:1	<1	128.4	<30	<20	<1	<4	<3	1.1	<5	20
Crushed Stone - 10:1	3	167.2	<30	<20	<1	<4	<3	<1	<5	5
Crushed Stone - 20:1	<1	61.9	<30	<20	<1	<4	<3	<1	<5	
RPM - 3:1	<1	<50	<30	<20	<1	<4	<3	<1	<5	
RPM - 5:1	<1	<50	50	<20	<1	<4	<3	1.9	<5	
RPM - 10:1	<1	<50	<30	<20	<1	<4	<3	<1	<5	
RPM - 20:1	<1	<50	<30	<20	<1	<4	<3	<1	<5	1
Fly-ash-stabilized RPM - 3:1	<1	554.9	110	755.7	<1	<4	<3	127.0	6.6	
Fly-ash-stabilized RPM - 5:1	<1	1263.6	70	739.8	<1	<4	<3	98.4	6.6	
Fly-ash-stabilized RPM - 10:1	<1	3395.1	40	608.1	<1	<4	<3	42.9	<5	
Fly-ash-stabilized RPM - 20:1	<1	7667.8	40	557.8	<1	<4	<3	20.5	<5	

Sample	Ni	Pb	Sb	Se	Sn	Sr	Ti	Tl	V	Z
ID	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	pp
Crushed Stone - 3:1	<3	<20	<10	<30	<5	24	<1	<10	<3	
Crushed Stone - 5:1	<3	24.4	<10	<30	<5	24	<1	<10	<3	
Crushed Stone - 10:1	<3	<20	<10	<30	26	24	<1	<10	<3	
Crushed Stone - 20:1	<3	<20	<10	<30	<5	21	<1	<10	<3	
RPM - 3:1	<3	<20	<10	<30	<5	41	<1	<10	<3	
RPM - 5:1	<3	<20	<10	<30	14	31	<1	<10	<3	
RPM - 10:1	<3	<20	<10	<30	<5	22	<1	<10	<3	1
RPM - 20:1	<3	<20	<10	<30	<5	15	<1	<10	<3	4
Fly-ash-stabilized RPM - 3:1	5.9	<20	<10	<30	<5	10258	<1	<10	990	
Fly-ash-stabilized RPM - 5:1	<3	37.8	<10	<30	<5	8293	<1	<10	900	
Fly-ash-stabilized RPM - 10:1	<3	<20	<10	<30	<5	4566	<1	<10	590	
Fly-ash-stabilized RPM - 20:1	<3	<20	<10	<30	<5	2978	<1	<10	410	

Table C-2. STH60 Water Leach Test Results

Material	**WLT pH and Concentration (µg/L)**				
	Cd	**Cr**	**Se**	**Ag**	**pH**
Fly-Ash-Stabilized Soil	0.6	46	16.2	1.8	11
Fly Ash Alone	0.7	95	26	2.2	11.8

APPENDIX D – STATE REGULATIONS REGARDING FLY ASH USE

Limitations placed by states on the use of fly ash focus on the potential toxicity of the ash (US DOE NETL 2009). Twenty four states in the US have formal regulatory policy regarding the use of fly ash in the production of concrete which then may be used as a road construction material. Twenty states in the US have formal regulatory policy regarding the use of fly ash as a stabilizing additive in construction of roadway layers under certain conditions. Fly Ash usage requirements among states that allow use vary from no requirements, to a requirement to prove non-toxicity by Toxicity Characteristic Leaching Procedure (TCLP), metals analysis, elemental analysis, Water Leach Tests (WLT), or other leaching test results. Thirteen states do not have any formal policy regarding use of fly ash in road construction, but permit use of fly ash on a case by case basis, and seventeen states do not permit fly ash to be used in road construction (US DOE NETL 2009).

Table D-1. Fly ash regulatory status in US states

State	Haz. Waste Status	Status	Use in PCC Specifically Authorized	Road/Soil STable Use Specifically Authorized	If No, Use Possible on case by case basis?
Alabama	Exempt	Special Waste	No	No	Yes
Alaska	Exempt	Indust. Solid or Inert	No	No	Yes, with TCLP and metals, meet requirements
Arizona	Exempt	None	No	No	No
Arkansas	Exempt	Recovered Materials	No	No	Yes, if not "disposal"
California	NOT Exempt	Haz. Waste unless proven not by TCLP	No	No	No
Colorado	Exempt	None	No	No	No
Connecticut	Exempt	Special or Regulated	No	No	Yes
Delaware	Exempt	Nonhaz. Indust.	No	No	Yes, TCLP required

State	Haz. Waste Status	Status	Use in PCC Specifically Authorized	Road/Soil STable Use Specifically Authorized	If No, Use Possible on case by case basis?
Florida	Exempt	Solid or Indust. Byproduct	Yes	No	Yes
Georgia	Exempt	Indust. Solid	No	No	No
Hawaii	Exempt	None	No	No	Yes, with metals
Idaho	Exempt	Indust. Solid	No	No	No
Illinois	Exempt	CCW or CCB	Yes	Yes	-
Indiana	Exempt	Indust. Solid	Yes	Yes	-
Iowa	Exempt	None	Yes	Yes	-
Kansas	Exempt	Indust. Solid	No	No	No
Kentucky	Exempt	Special	Yes	Yes	-
Louisiana	Exempt	Indust. Solid	No	No	Yes
Maine	Exempt	Haz. Waste unless proven not	Yes	No	No
Maryland	Exempt	Pozzolan	No	Yes	-
Massachusetts	Exempt	Solid unless beneficial reuse	Yes	Yes	-
Michigan	Exempt	Low Hazard Indust.	Yes	Yes	-
Minnesota	Exempt	None	No	No	Yes
Mississippi	Exempt	Indust. Solid	No	No	Yes
Missouri	Exempt	None	Yes	No	Yes
Montana	Exempt	Indust. Solid	Yes	No	Yes
Nebraska	Exempt	Special	Yes	Yes	-
Nevada	Exempt	None	No	No	No
New Hampshire	Exempt	waste derived product	Yes	Yes	-
New Jersey	Exempt	Solid unless beneficial reuse	Yes	Yes	-
New Mexico	Exempt	Indust. Solid	No	No	Yes
New York	Exempt	None	Yes	Yes	-
North Carolina	Exempt	None	Yes	Yes	-
North Dakota	Exempt	None	No	No	Yes
Ohio	Exempt	None	Yes	Yes	-
Oklahoma	Exempt	None	Yes	Yes	-
Oregon	Exempt	None	No	No	No
Pennsylvania	Exempt	None	Yes	Yes	-

State	Haz. Waste Status	Status	Use in PCC Specifically Authorized	Road/Soil STable Use Specifically Authorized	If No, Use Possible on case by case basis?
Rhode Island	NOT Exempt	Haz. Waste unless proven not by TCLP	No	No	No
South Carolina	Exempt	Indust. Solid	No	No	Yes
South Dakota	Exempt	Solid or Indust. Byproduct	No	No	Yes
Tennessee	NOT Exempt	Haz. Waste unless proven not by TCLP	Yes	No	No
Texas	Exempt	Indust. Solid	Yes	Yes	-
Utah	Exempt	None	Yes	Yes	-
Vermont	Exempt	None	No	No	No
Virginia	Exempt	None	Yes	Yes	-
Washington	NOT Exempt	Haz. Waste unless proven not by TCLP	No	No	No
West Virginia	Exempt	None	Yes	Yes	-
Wisconsin	Exempt	Indust. Byproduct	Yes	Yes	-
Wyoming	Exempt	Indust. Solid	No	No	No

From US DOE (2009)