Metals Leaching from Highway Test Sections Constructed with Industrial Byproducts

by

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with Industrial Byproducts

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EXECUTIVE SUMMARY

Metals leaching from industrial byproducts used in highway construction was assessed in the field and laboratory. Four byproducts were evaluated: foundry sand and foundry slag from a gray-iron foundry and bottom ash and fly ash from a coal-fired power plant. Field leaching behavior was evaluated by analyzing samples from lysimeters installed beneath highway test sections constructed with the byproducts. Batch water leach tests (WLTs) and column leach tests (CLTs) were conducted in the laboratory. All leachates were analyzed for concentrations of cadmium (Cd), chromium (Cr), selenium (Se), and silver (Ag). Concentrations from the WLTs and CLTs were compared with concentrations measured in the leachate collected in the field and with groundwater quality standards stipulated in the *Wisconsin Administrative Code*.

Leachate collected in the lysimeters commonly had Cd, Se, and Ag concentrations exceeding Wisconsin groundwater quality standards. However, application of dilution factors to account for the reduction in concentration expected between the bottom of the pavement structure and the groundwater table showed that concentrations exceeding groundwater quality standards would not occur if the byproducts layer is at least 5 m above the groundwater table. For a separation distance of 1 m, only Cd would modestly (30%) exceed the groundwater quality standard directly beneath the centerline of the pavement.

Peak concentrations from the lysimeters were 4-160 times larger than the WLT concentrations. Dilution caused by the large liquid-solid ratio used in the WLTs is largely responsible for the disparity between the lysimeter and WLT concentrations. Peak concentrations from the CLTs typically were within a factor of 10 of peak concentrations from the CLTs, although peak CLT concentrations were as much as 45 times higher and 131 times lower than the peak field concentrations. The elution patterns in the field and the CLTs generally were similar, although the magnitude of the concentrations differed. An exception is the fly-ash-stabilized soil, for which both concentrations and elution patterns from the field and the CLTs were similar.

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1. INTRODUCTION

Soft soils encountered during road construction often are removed and replaced with crushed rock to form a sturdy working platform for pavement construction. This construction practice can be costly, particularly if the rock needs to he hauled to the construction site. As a result, transportation agencies are seeking less costly methods to stabilize soft soils and construct working platforms. In some cases, industrial byproducts can be used to construct lower cost working platforms that provide equal support as those constructed with crushed rock (Tanyu et al. 2004). Use of industrial byproducts in this manner also facilitates sustainable construction by re-using materials currently being landfilled and reducing the use of virgin natural resources. A concern, however, is that contaminants leached from byproducts may contaminate underlying groundwater.

Five test sections were constructed along a 1.4 km stretch of Wisconsin State Highway (STH) 60 near Lodi, Wisconsin (USA) to evaluate alternative working platforms for highway construction on soft subgrades. For three of the test sections, coarse-grained industrial byproducts (foundry sand, foundry slag, or bottom ash) were being used as a working platform placed between the soft subgrade and the granular base course material. Fly-ash-stabilized subgrade (a mixture of existing subgrade and 10% fly ash by dry weight blended *in situ*) was used as the working platform in the fourth test section. The fifth test section is a control where crushed dolostone, a granular material commonly used in Wisconsin, was used for the working platform.

Profiles of the test sections are shown in Fig. 1. Thicknesses of the byproduct layers were selected so that each test section had equal structural capacity as the control section. Procedures defined in the *Guide for Design of Pavement Structures* published by the American Association of State Highway and Transportation Officials

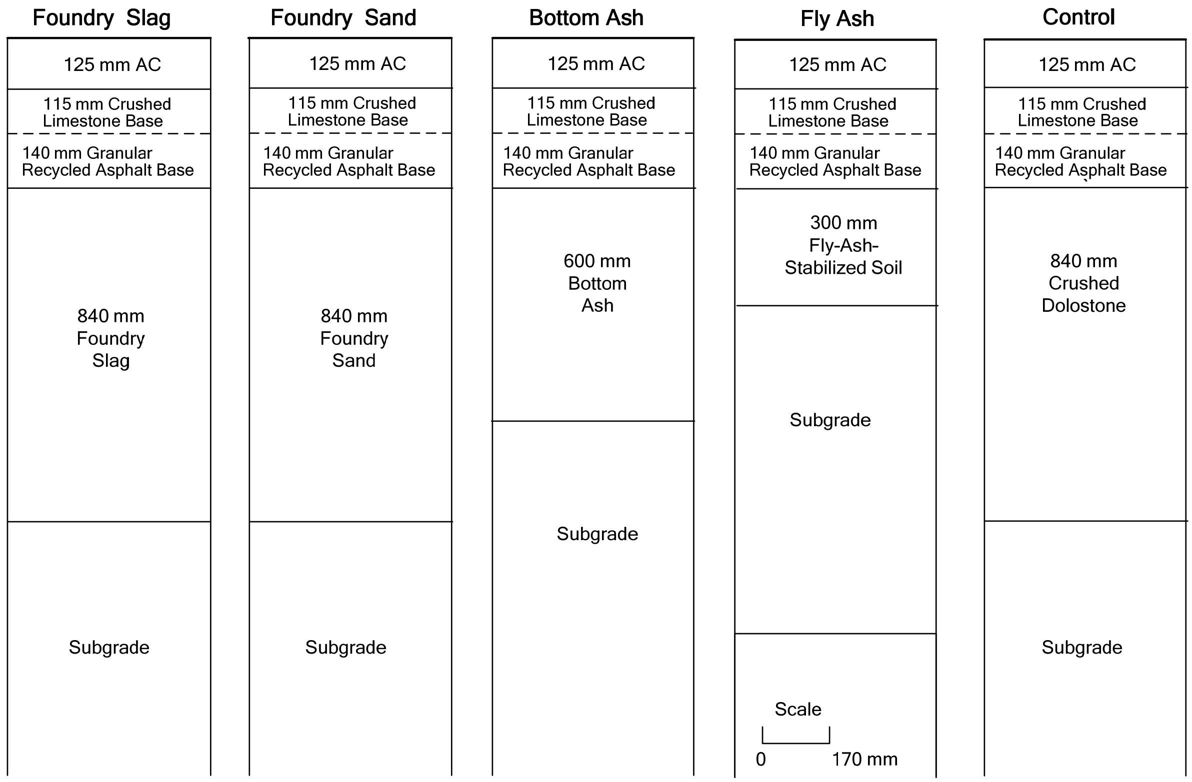

Fig. 1. Profiles of the test sections constructed using foundry slag, foundry sand, bottom ash, fly ash, and crushed rock (control) at STH 60 near Lodi, WI (AC = asphalt concrete).

(AASHTO 1993) were used to determine the structural capacity. Details of the structural design are described in Edil et al. (2002).

During construction, two pan lysimeters were placed beneath each test section to monitor the quality and quantity of water discharged from the base of the pavement. Samples were collected from these lysimeters over a 5-year period and analyzed for concentrations of cadmium (Cd), chromium (Cr), selenium (Se), and silver (Ag). Laboratory tests were also conducted on each of the byproducts using batch water leach tests (WLTs) and column leach tests (CLTs), both of which are commonly used to assess the suitability of byproducts for re-use. This report describes and compares the elution patterns and concentrations observed in field and from the WLTs and CLTs. Peak concentrations observed in the field are also compared with ground water quality standards stipulated by the State of Wisconsin.

2. PAST LEACHING STUDIES ON BYPRODUCTS

2.1 Gray Iron Foundry Sand

Gray-iron foundry sand is a mixture of silica sand, a binding agent (clay or chemical), and other finishing additives that is used to form molds and cores for casting metals. When clay (typically sodium bentonite, calcium bentonite, or kaolinite) is used as the binder, the mixture is referred to as “green sand” (Abichou et al. 2000). A portion of the mixture is discarded after each use (Bastian and Alleman 1998). Some of this waste sand is used in a variety of construction and agricultural applications (Javed and Lovell 1994, Kleven et al. 2000, Abichou et al. 2000, Naik et al. 2001, Goodhue et al. 2001, Tanyu et al. 2004, Lee and Benson 2005). However, most waste foundry sand is landfilled. In Wisconsin, more than 800,000 Mg (1 Mg ≈ 1 US ton) of green sand is landfilled annually (Lee and Benson 2005).

Bastian and Alleman (1998) used Microtox^{TM} microbial bioassay tests to characterize the environmental suitability of foundry sands from iron foundries (11 sands), a steel foundry (1 sand), and an aluminum foundry (1 sand). Thirteen virgin sands (clean sands without any binders or other additives) were also subjected to bioassay testing. Leachate for the bioassays was produced from batch tests conducted with a 2% NaCl solution with a liquid-to-solid (L-S) ratio of 4:1. Leachate from three of the iron foundry sands caused a quantifiable depression in microbial activity (i.e. less light emitted from the bacteria) compared to tests on the virgin sands. Leachate from the other iron foundry sands caused less inhibition of microbial activity than leachate from virgin sands. Leachate from the aluminum and steel foundry sands caused greater inhibition of microbial activity than leachates from the iron foundry sands or the virgin sands.

Partridge et al. (1998) evaluated groundwater samples and leachates from an embankment constructed with foundry sand and an adjacent embankment constructed with natural sand. Chemical analyses (Zn, Ni, Cd, Cr, Pb, and Cu) and Microtox^{TM} and Nitrotox^{TM} bioassays were conducted on the water samples. The foundry sand was from a gray iron foundry that uses organic binders. Samples were collected from 6 groundwater monitoring wells (4 adjacent to a highway embankment constructed using waste foundry sand, 2 near an embankment constructed using natural sand) and from 2 lysimeters (one in the foundry sand embankment, and one in the natural sand embankment). Samples from the lysimeters and monitoring wells in and adjacent to the foundry sand embankment showed negative inhibition relative to leachate and groundwater samples from the natural sand when tested with the Microtox^{TM} bioassays (i.e., the samples enhanced microbial activity). Samples from the monitoring wells and lysimeters did not enhance microbial activity during Nitrotox^{TM} bioassays. However, the bioassay results also showed no differences in microbial growth for samples up-gradient and down-gradient of the foundry sand embankment. Only Cd, Ni, and Zn were detected in any of the leachates, and the metals concentrations observed were generally below USEPA drinking water standards. Samples that exceeded the drinking water standards were below requirements for the use of industrial byproducts as defined in the Indiana Administrative Code.

Lee and Benson (2006) conducted water leach tests (WLTs) and column leach tests (CLTs) on 12 foundry green sands, a sandy silt, and a clean sand using the procedure in ASTM D 3987, which employs a L-S ratio of 20:1 and deionized water. Concentrations of Al, Ag, As, Ba, Be, Cd, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, Tl, and Zn from the WLTs were compared with maximum permissible concentrations specified in the *Wisconsin Administrative Code* for industrial byproducts placed below the water table (Wisconsin 2004). None of the materials, including the sandy silt and the clean sand, met the criteria for use below the water table. Metals concentrations in leachate from the CLTs were higher than concentrations from the WLTs, but in all cases the concentrations were below USEPA maximum contaminant levels (MCLs).

2.2 Gray Iron Foundry Slag

Slag is a byproduct of the metal processing industry that consists of impurities that float to the surface of molten material (Proctor et al. 2000). This floating material is skimmed off and cooled to form the solid referred to as slag. Although the majority of slag is landfilled, some slag is used in civil engineering applications (Shen and Forssberg 2002).

Lind et al. (2001) studied leaching of metals from two roads constructed using a ferrochrome steel slag. One road consisted of an older roadway resurfaced with a 750-mm-thick layer of slag overlain by asphalt pavement. A control section was also included where the older roadway was overlain only with asphalt pavement (no slag layer). The other road was a new road constructed only with a 450-mm-thick layer of slag (no asphalt pavement).

At both sites, groundwater monitoring wells were installed adjacent to the paved and unpaved areas, and adjacent to the asphalt control. The wells were installed 1 m and 4 m from the edge of the road. Groundwater samples were collected 3 times from each location. For the paved road, Cr concentrations in samples collected from the control monitoring wells (area only surfaced with asphalt) were comparable to Cr concentrations in samples collected from monitoring wells near the slag layers (all < 6 μg/L). For the road with an asphalt surface, Cr concentrations in the samples from the monitoring well 4 m from the slag layer typically were one-half of the concentrations in samples from the monitoring well 1 m from the slag layer.

Ham and Boyle (1990) collected groundwater samples collected from monitoring wells at 7 ferrous foundry landfills where a mixture of foundry sand, foundry slag, and dust was disposed. Samples were collected from monitoring wells up-gradient of the landfill and at the down-gradient limit of waste. None of the samples had concentrations of As, Cd, Cr, Pb, Hg, Se, or Ag above USEPA MCLs at the time of the study. Ham and Boyle (1990) also conducted USEPA batch extraction procedure (EP) tests as well as deionized water leach tests (L-S ratio = 5:1) on samples of foundry waste collected from the landfills. Leachate from the EP test on three of the foundry wastes had concentrations exceeding the MCL for Cd. However, Cd was not detected in groundwater at any of the landfills containing these foundry wastes.

2.3 Coal Bottom Ash

Bottom ash is a coarse residual composed of mineral oxides in crystalline or glass form that is collected from dry bottom boilers used at coal-fired power plants (Siddiki et al. 2004). Bottom ash is angular, has a porous surface texture (Seals et al. 1972), and appears similar to well-graded coarse sand (Tanyu et al. 2004). According to the American Coal Ash Association (ACAA), approximately 18 million Mg of bottom ash is produced annually in the United States, and 46% of the ash is re-used in applications such as structural fill and roadway construction.

Thayumanavan et al. (2001) conducted an algal bioassay on leachate from WLTs conducted on bottom ash and bottom ash in an asphalt pavement mixture using distilled water and a L-S ratio of 4:1. Less algal growth was found in tests with bottom ash leachate compared to control tests with water. However, when bottom ash was incorporated as an aggregate in asphalt, algal bioassays on the leachate from the bottom ash produced similar results to control tests.

Goodarzi and Huggins (2001) used a sequential leaching procedure to evaluate leaching of As, Cr, and Ni from coal combustion bottom ash. The bottom ash was exposed to deionized water, ammonium acetate ($NH_4C_2H_3O_2$), and hydrochloric acid (HCl). Concentrations of the $NH_4C_2H_3O_2$ and HCl were not specified. No As was leached from the bottom ash exposed to deionized water and $NH_4C_2H_3O_2$, but 37.5% of the total As was leached after the bottom ash was exposed to HCl. Ni was not leached in water, but 25.7% of total Ni was leached when in $NH_4C_2H_3O_2$. All but the final remaining 0.4% of the Ni was leached in HCl. Cr in the bottom ash was leached by ammonium acetate (4.1%) and hydrochloric acid (95.9%).

2.4 Coal Fly Ash

Fly ash is fine-textured particulate that is removed from the exhaust from coal combustion. Fly ash particles are spherical and have particle sizes ranging between 1 and 150 μm. Most tend to be silt size, between 2 μm and 75 μm (Gutierrez et al. 1993, Bin-Shafique et al. 2006). According to the American Coal Ash Association (ACAA), 70 million Mg of fly ash was produced in 2003 in the United States and 39% was reused in a variety of applications. The remainder was disposed in waste containment facilities such as landfills.

Theis et al. (1977) conducted WLTs on 11 fly ashes at pH 3, 6, 9, and 12 using deionized water at a L-S ratio of 5:1. The batches were shaken for 24 h. pH was controlled with sodium hydroxide and perchloric acid. The leachates were tested for As, Cd, Cr, Cu, Pb, Ni, and Zn. Average concentrations observed for all 11 fly ashes were highest for the tests at pH 3, with the exception of As, which had the highest concentration at pH 12. For instance, Cr release at pH 3 was 3.9 times greater than the Cr release at pH 12, and the Cd release was 6.1 times higher at pH 3 compared to pH 12.

Praharaj et al. (2002) performed WLTs on 4 fly ashes from a power plant burning sub-bituminous coal. The WLTs were conducted using synthetic rainwater (pH 5.6) at L-S ratios of 4, 8, 12, and 16. The leachate was analyzed for Al, Ca, K, Mg, Na, P, S, Si, As, Ba, Fe, Mn, Mo, Ti, V, Pb, Zn, Co, Cr, Cu, Ni, and Cd. Cd, Cr, Co, and Ni did not leach from the ashes at any L-S ratio. As, Mn, and Mo leached at concentrations between 1 and 26 times above drinking water standards recommended by the World Health Organization and As, Fe, and Mn leached at concentrations between 1 and 6 times higher than USEPA MCLs. Concentrations were highest for most of the metals at the lowest L-S ratio, with concentrations decreasing with increasing L-S ratio.

Bin Shafique et al. (2006) performed WLTs and column leach tests (CLTs) on soils mixed with sub-bituminous fly ashes. The CLTs were conducted to evaluate metals leaching under flow-through conditions more typical of that occurring in the field and to provide a comparison to concentrations from the WLTs. WLTs were performed on the soils alone, fly ashes alone, and on mixtures containing 10% and 20% fly ash (by weight). The WLTs were conducted with deionized water at a L-S ratio of 20:1. CLTs were conducted on the soils alone and with mixtures containing 10% and 20% fly ash (by weight). Leachate from the WLTs and CLTs was analyzed for Cd, Cr, Se, and Ag.

Analysis of the CLT data showed that release of Cd, Cr, Se, and Ag was adsorption controlled, with initial concentrations approximately 50 times the WLT concentrations for Cd and Ag and 10 times the WLT concentrations for Cr and Se (Bin Shafique et al. 2006). Metals concentrations in leachate from the WLTs and

CLTs varied with fly ash content, which was attributed to the variation in pH with fly ash content.

3. MATERIALS

A summary of the index and physical properties of the byproducts and the subgrade soil at the field site can be found in Table 1 along with classifications of these materials according to the Unified Soil Classification System (USCS) and the AASHTO classification system. Particle size distribution curves for the materials are shown in Fig. 2. The foundry slag, foundry sand, and bottom ash are coarse-grained materials in the Unified Soil Classification System (USCS), and the fly ash and subgrade soil are fine-grained in the USCS. Additional information on the physical and mechanical properties of the foundry sand, foundry slag, and bottom ash can be found in Tanyu et al. (2004).

Water leach tests (WLTs) were conducted on the foundry sand, foundry slag, bottom ash, fly ash, and on the soil-fly ash mixtures following the procedure in ASTM D 3987. Based on these analyses, all of the byproducts meet the requirements in Section NR 538 of the *Wisconsin Administrative Code* for byproducts used in confined geotechnical applications (e.g., materials covered with asphalt pavement, as in Fig. 1). Results of the WLTs are discussed in Section 5.

3.1 Foundry Sand

Grede Foundries of Reedsburg, WI provided the foundry sand for this study. The foundry produces grey iron castings using a mixture of sand, 10% bentonite, and ≈ 4% sea coal (powdered coal used as a combustible additive). The foundry sand is black in color and classifies as clayey sand (SC) in the USCS and A-2-7 in the AASHTO system. Although the sand is coarse-grained (percent fines = 29%, see Fig. 2), the bentonite gives the material cohesive properties and plasticity (e.g., plasticity index = 9, Table 1).

Table 1. Physical properties and USCS and AASHTO classifications of the foundry sand, foundry slag, bottom ash, fly ash, and soil used in the study.

Material	Specific Gravity	D_{10} (mm)	D_{60} (mm)	C_u	Percent Fines (%)	USCS Symbol	AASHTO Symbol
Foundry Sand	2.55	0.0007	0.25	357	29	SC	A-2-7
Foundry Slag	2.29	0.2	2.5	13	9	SW-SM	A-3
Bottom Ash	2.65	0.2	1.5	8	3	SW	A-3
Fly Ash	2.70	0.001	0.07	70	98	ML	A-4
Subgrade Soil	2.70	0.0006	0.02	33	96	CL	A-6

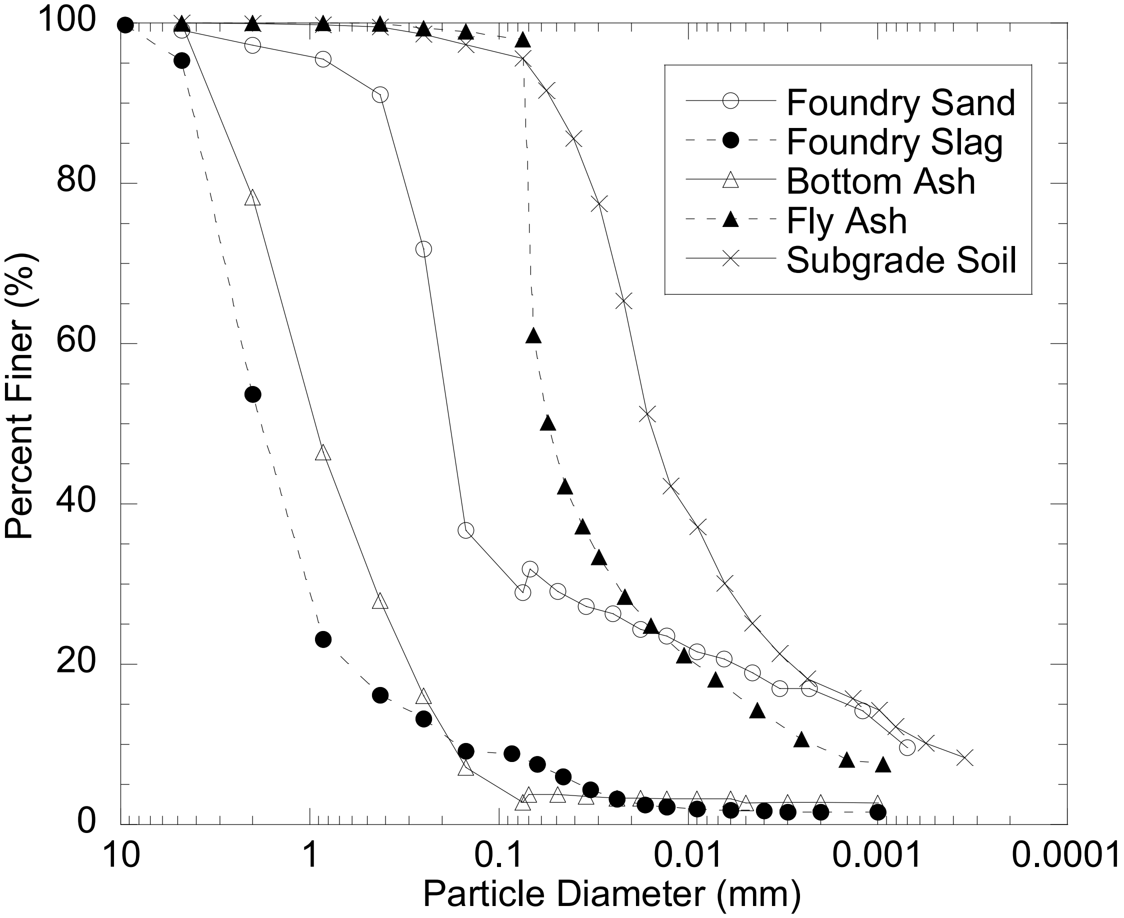

Fig. 2. Particle size distribution curves for foundry sand, foundry slag, bottom ash, fly ash, and subgrade soil used at STH 60 and for the laboratory tests.

3.2 Foundry Slag

The foundry slag is coarse-grained (9% fines) and classifies as well-graded sand with silt (SW-SM) in the USCS and A-3 in the AASHTO soil classification system. The foundry slag was provided by Grede Foundries in Reedsburg, WI, which uses a cupola furnace to prepare molten iron. A cupola furnace is tall cylindrical blast furnace that is typically fed with raw metals and a fluxing agent such as limestone or dolomite (Sun and Sahajwalla 2004). The raw metals fed into the cupola furnace at Grede Foundries come from recycled material, scrap steel, and pig iron. Non-metallic additives used in the melt process include coke, limestone, and coke fines.

3.3 Bottom Ash

The bottom ash used in this study is from a dry bottom furnace at Alliant Energy's Columbia Power Station in Portage, WI that burns sub-bituminous coal from the Wyoming Powder River Basin. The bottom ash is coarse-grained material that classifies as well-graded sand (SW) in the USCS and A-3 in the AASHTO system.

3.4 Fly-Ash-Stabilized Soil

The test section with a fly-ash-stabilized subgrade was constructed with fly ash from Alliant Energy's Columbia Power Station that was blended into the existing subgrade (10% fly ash by dry weight) to a depth of 300 mm using a reclaimer. Immediately after mixing, the mixture was compacted to 15.4 kN/m^3 using a tamping foot, steel drum, and rubber tire compactors. The water content was 21% ± 2% when the mixture was compacted. Details on the construction can be found in Edil et al. (2002).

Columbia Power Station captures the fly ash using electrostatic precipitation and stores the ash in a dry silo. The fly ash contains 98% fines and classifies as elastic silt (ML) in the USCS, A-4 in the AASHTO system, and Class C in ASTM C 618,

The subgrade soil at the STH 60 field site is low plasticity clay (CL) in the USCS and A-6 in AASHTO. The natural water content of the subgrade soil is 23%.

4. METHODS

4.1 Field Lysimeters

Two pan lysimeters (3.75 m x 4.75 m) were installed beneath each section at the STH 60 site to collect leachate draining from the bottom of the profile. A schematic of a typical set of lysimeters is shown in Fig. 3. One lysimeter was located directly under the centerline of the highway and the other was located at the edge, with one-half of the lysimeter under the highway shoulder. The lysimeters were constructed with 1.5-mm-thick textured HDPE geomembrane overlain by a geocomposite drainage layer. Water collected by the lysimeters drains to 120-L HDPE drums located below ground surface adjacent to the highway. Additional information on the lysimeters can be found in Bin Shafique et al. (2002).

Samples were collected from the drums periodically. The sampling frequency depended on the rate of drainage from the lysimeters, which varied seasonally. Sampling was least frequent in the winter when freezing occurred and most frequent in the spring when snowmelt and rainfall are more common. During each sampling event, water contained in each drum was removed with a pump, the total volume of water in the drum was recorded, and samples were collected for chemical analysis. Methods used for filtering, preserving, and storing the samples are described in Section 4.4.

Monitoring wells were also installed adjacent to the sections constructed with fly ash and bottom ash. However, because the fine-grained subgrade soils at the field site have very low hydraulic conductivity, samples could not be collected from the monitoring wells during the monitoring period. A description of the monitoring wells is in the appendix.

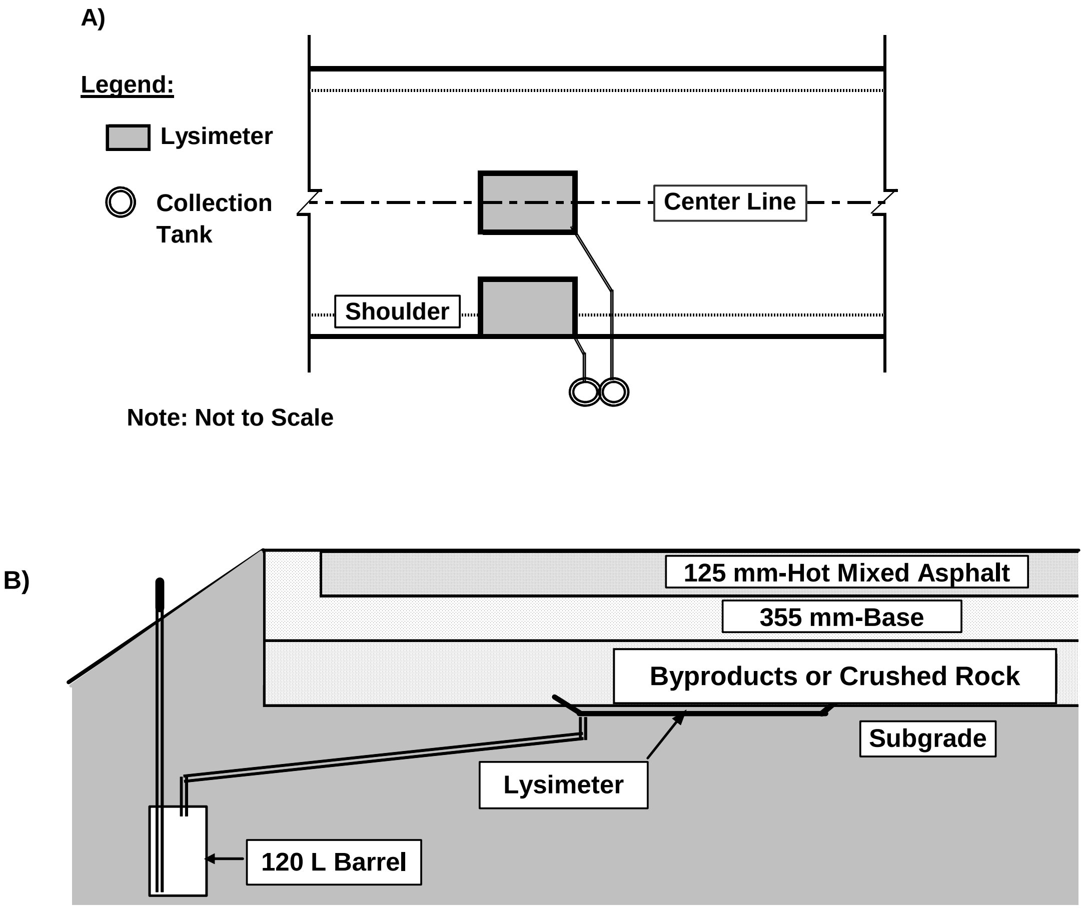

Fig. 3. Plan view (A) and cross-section (B) of typical lysimeter beneath pavement structure.

4.2 Water Leach Tests

Water leach tests (WLTs) were conducted on the byproducts following the methods in ASTM D 3987, where 70 g of dry solid is mixed with 1400 ml of ASTM Type II water (L-S ratio = 20:1) in 2 L HDPE bottles that are rotated continuously for 18 hr at 29 rpm. After rotation, the solution was allowed to settle for 5 min and the supernatant was collected, filtered, and the pH was recorded. Samples of the supernatant were stored in sealed HDPE bottles with no headspace.

4.3 Column Leach Tests

Column leach tests (CLTs) were conducted on each of the industrial byproducts to evaluate leaching under flow-through conditions. CLTs on the cohesionless materials (foundry slag and bottom ash) were conducted using rigid-wall permeameters, whereas flexible-wall permeameters were used for the cohesive materials (foundry sand and fly-ash-stabilized soil).

4.3.1 Columns

The rigid-wall procedure was adapted from the procedure described in Lee and Benson (2006). Specimens were compacted directly into a PVC column having the same size as a standard Proctor mold (102 mm in diameter and 114 mm tall). Non-woven needle-punched geotextiles were placed on the top and bottom of the specimen to ensure uniform flow and to prevent solids from entering the influent and effluent lines. Acrylic end plates with o-rings were used to seal the ends of the column. Upward flow was imposed using a peristaltic pump set at 30 mL/hr (9 mm/d) for the first 1.5 pore volumes of flow (PVF) and 7 mL/hr (2 mm/d) for the remainder of the test. The flow rate was reduced after 1.5 PVF to permit practical sample collection intervals.

The procedure described in Bin Shafique et al. (2002) was used for the flexible-wall tests. Test specimens were placed in the permeameter between acrylic end caps and sealed with a latex membrane. Non-woven needle-punched geotextiles were placed between the ends of the specimen and the end caps to promote uniform flow and to prevent solids from entering the influent and effluent lines. A hydraulic gradient between 7-12 was used to drive the flow in an upflow mode. An effective confining pressure of 15 kPa was applied to simulate the stress existing in the field.

A 0.1 M LiBr solution was used as the influent for all column tests. The solution was prepared by dissolving LiBr salt (99+% pure, from Aldrich Chemical Company) in de-ionized water followed by exposure to the atmosphere until pH 6 was reached. The concentration was selected so that the ionic strength was similar to pore water in pavement layers (Karczewska et al. 1996). Effluent from the columns was collected in sealed Teflon bags that were emptied after approximately 30~60 mL of flow accumulated (≈ 0.1 PVF). Volume and pH of the effluent were recorded each time a bag was emptied and a 45 mL sample was collected for chemical analysis. Methods used to handle, preserve, and store the samples for chemical analysis are described in Section 4.4.

4.3.2 Preparation of Column Test Specimens

Slag and bottom ash used in the rigid-wall CLTs was crushed by hand through a No. 4 sieve (4.8 mm openings) to remove large particles before preparing test specimens. Large particles that could not be crushed though the sieve were discarded (< 5% for slag, 0% for bottom ash). The materials were tamped into the PVC molds in 3 lifts using a standard Proctor hammer until the dry unit weight used in the field was reached (foundry slag: 12.4 kN/m^3 , bottom ash: 17.1 kN/m^3).

The soil-fly ash mixture was prepared using standard Proctor methods (ASTM D 698) at a molding water content approximately 2% dry of optimum water content to simulate conditions that existed during construction of the test sections (Bin Shafique et al. 2002). A mixture containing 90% air-dried soil and 10% fly ash (by weight) was blended by hand until uniform and then sprayed with deionized water until the desired water content (17.3%) was reached. The mixture was compacted one hour after mixing to simulate the delay between mixing and compaction that occurs during construction. After compaction, the specimens were extruded from the compaction molds, sealed in plastic, and cured for 7 days in a 100% humidity environment prior to testing to simulate the condition existing in the field (Edil et al. 2002). The specimen was compacted to a dry unit weight 15.4 kN/m^3, which is the same dry unit weight obtained in the field.

The foundry sand was prepared at a water content of 23% and a dry unit weight of 15 kN/m^3 to simulate the condition existing in the field (Edil et al. 2002). Prior to compaction, the material was dried and crushed through a No. 4 sieve (4.8 mm openings) followed by re-moistening by spraying and blending with tap water until the desired water content was obtained. The foundry sand was placed in 3 lifts, with each lift tamped with a standard Proctor hammer until the target density was reached. After compaction, the specimens were extruded and placed into the flexible-wall permeameter.

4.4 Chemical Analysis of Effluent

Procedures described in Bin Shafique et al. (2002) were followed for sample handling, preservation, analysis, and quality control. All samples were filtered through a 0.45-μm membrane filter as required in ASTM D 3987, acidified to pH < 2 using metals-grade nitric acid, and stored in sealed HDPE bottles at 4°C prior to testing. Blanks were prepared and handled using the same protocol used for the other samples.

All samples from the CLTs and lysimeters were analyzed for Cd, Cr, Se, and Ag. Each of these elements is regulated when foundry sand, foundry slag, fly ash, and bottom ash are reused in Wisconsin. In addition, Cd and Ag more readily sorb to soil solids and are less mobile, whereas Cr and Ag can be less sorptive and more mobile. The samples were analyzed by atomic adsorption (AA) spectrometry or inductively coupled plasma optical emission spectrometry (ICP-OES). AA was used earlier in the study and ICP-OES later in the study. A switch was made to ICP-OES to make testing more efficient.

The AA analyses were conducted using a Varian SpectrAA-800 atomic adsorption (AA) spectrometer equipped with a GTA-100 graphite tube atomizer, an automated sample dispenser, and a Varian SpectAA-800 Data Station. Procedures described in USEPA Standard Methods 213.2, 218.2, 270.2, and 272.2 were followed for the AA analyses. The AA was calibrated using 4 standard dilutions to create a calibration curve. Samples were analyzed using ICP-OES following USEPA Method 6010B using a Perkin Elmer Optima 4300 DV ICP-OES or a Thermo Jarrell Ash ICAP 61E Trace Analyzer. The detection limits for the AA and ICP-OES analyses are in Table 2.

Duplicate tests were conducted on each sample and samples with a relative standard deviation (RSD) > 5% were re-tested. Blanks were included every 10 to 20 analyses and the calibration was verified every 10 analyses. A reagent blank was tested every 20 samples and a spiked sample was analyzed every 10 samples.

Table 2. Limits of detection for ICP-OES and AA analysis.

Element	**Detection Limit (μg/L)**	
	ICP-OES	**AA**
Cd	0.2 or 0.7	0.1
Cr	1.0 or 1.7	2.0
Se	4.0 or 10.0	2.0
Ag	0.8 or 2.5	0.2

Note: Detection limits for the ICP-OES analyses differ depending on the instrument that was used for analysis.

5. RESULTS AND DISCUSSION

5.1 Lysimeters

5.1.1 Hydrologic Data

Volumetric flux in each lysimeter over the 5-year monitoring period is shown in Fig. 4 along with precipitation data from the National Oceanic and Atmospheric Administration (NOAA) station in Prairie du Sac, WI (≈ 16 km from the site). The gap between July 2002 and June 2003 occurred due to a lapse in funding. The volumetric flux from each test section varies seasonally, with higher fluxes typically occurring in spring and summer when precipitation rates are higher and temperatures are above freezing. The lowest volumetric fluxes occur during winter, when frozen ground conditions are common.

Volumetric fluxes from the test sections constructed with the finer grained materials (foundry sand - 0.09 mm/d, fly-ash-stabilized soil - 0.17 mm/d) are lower, on average, than the volumetric fluxes from the test sections constructed with coarser materials (foundry slag - 0.22 mm/d, bottom ash - 0.26 mm/d, and control section - 0.20 mm/d). Liquid did not appear in the collection drums from the foundry sand section for the first 8 months. The lower average flux and the longer time for leachate breakthrough from the foundry sand layer are likely due to the bentonite content (10%) of the foundry sand. Laboratory tests conducted by Abichou et al. (2002) on this foundry sand indicated that the saturated hydraulic conductivity is on the order of 10^{-8} cm/s.

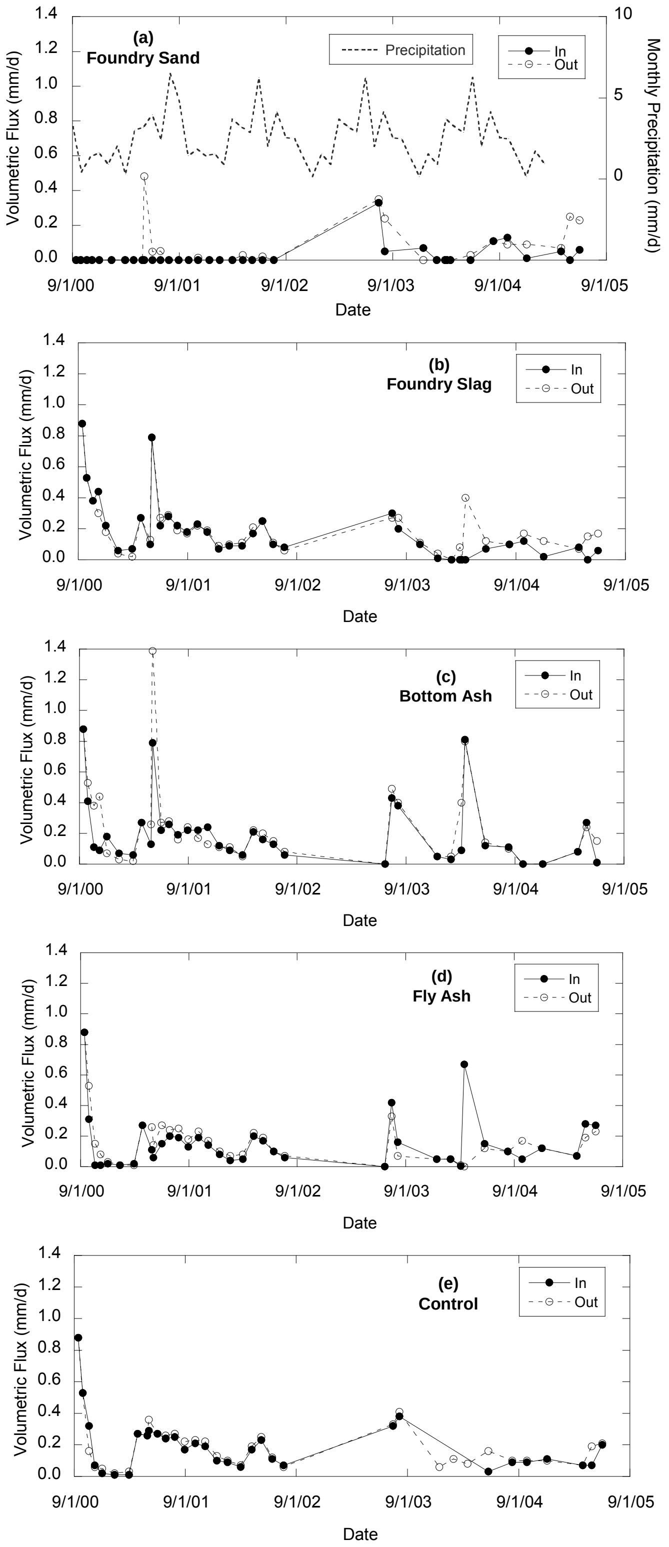

Fig. 4. Precipitation and volumetric flux from (a) foundry sand, (b) foundry slag, (c) bottom ash, (d) fly-ash-stabilized-soil, and (e) control sections.

5.1.2 Metals Concentrations

Metals concentrations in leachate from the lysimeters over the monitoring period are shown in Figs. 5-8. Peak concentrations observed in the lysimeters along with the number of pore volumes of flow to reach the peak concentration are summarized in Table 3. Data for the foundry sand lysimeter are not shown until 6/2002, because too little water was discharged from the foundry sand to permit analysis during the earlier portion of the monitoring period.

Cd and Cr concentrations in leachate (Figs. 5 and 6) generally are highest in the early portion of the monitoring period and then steadily decrease, a pattern referred to as “first-flush” leaching (Edil et al. 1992). Two exceptions are the Cd and Cr elution patterns from the leachate collected from the foundry sand lysimeter, which gradually climbed throughout the monitoring period (“lagged-response” leaching, Edil et al. 1992). Cd concentrations in the foundry sand lysimeters also are very low (< 5 μg/L).

Peak concentrations of Cd and Cr in leachate from the foundry slag, bottom ash, and fly-ash-stabilized-soil sections are higher than the peak concentrations in leachate from the control section (3.4-5.2 times higher for Cd, 6.1-15.0 times higher for Cr). For the foundry sand section, the peak Cr concentration was also 1.8 times higher than the peak concentration in the control section, whereas the peak Cd concentration was 2.2 times lower than that for the control section. After 3 years, the Cd and Cr concentrations are comparable for all test sections (<5 μg/L for Cd, <10 μg/L for Cr). The peak Cd and Cr concentrations occurred between 0.01 and 0.51 PVF (Table 3).

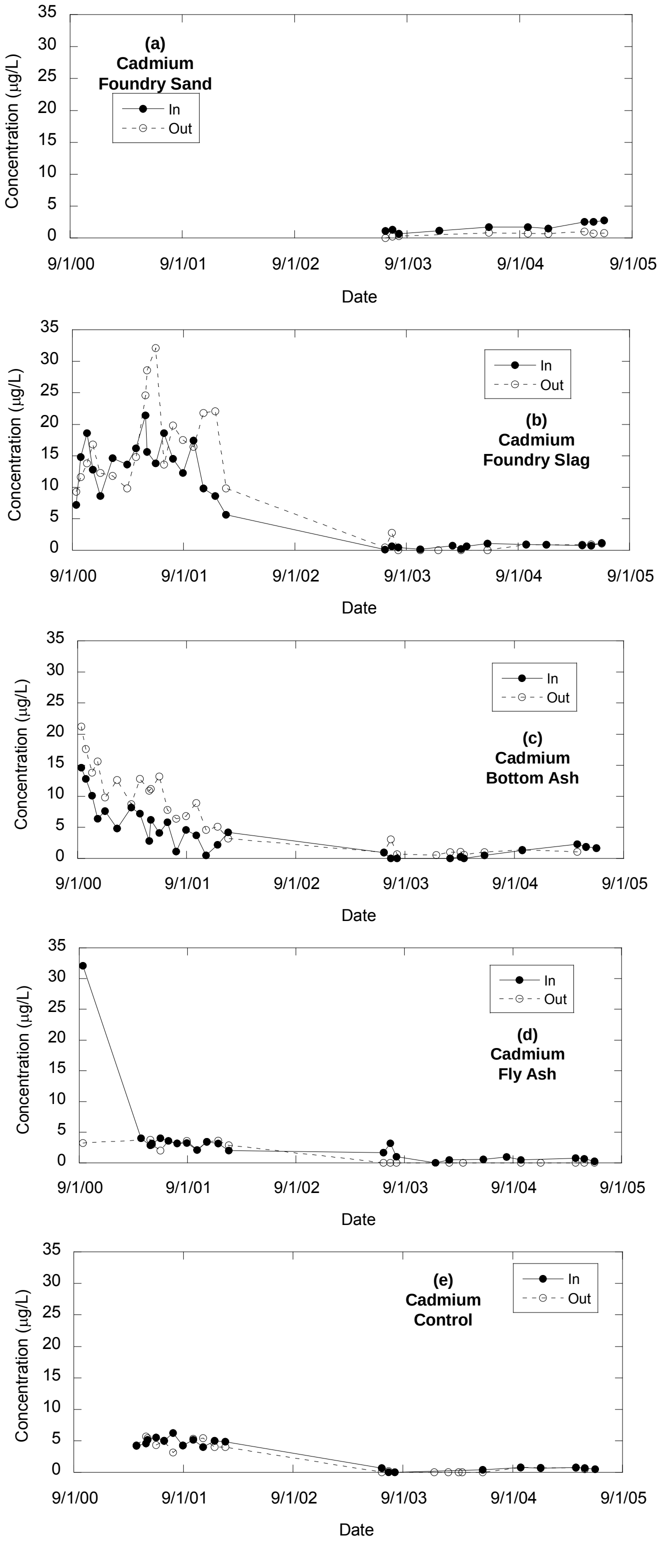

Fig. 5. Cd Concentrations in leachate from lysimeters in (a) foundry sand, (b) foundry slag, (c) bottom ash, (d) fly-ash-stabilized-soil, and (e) control sections.

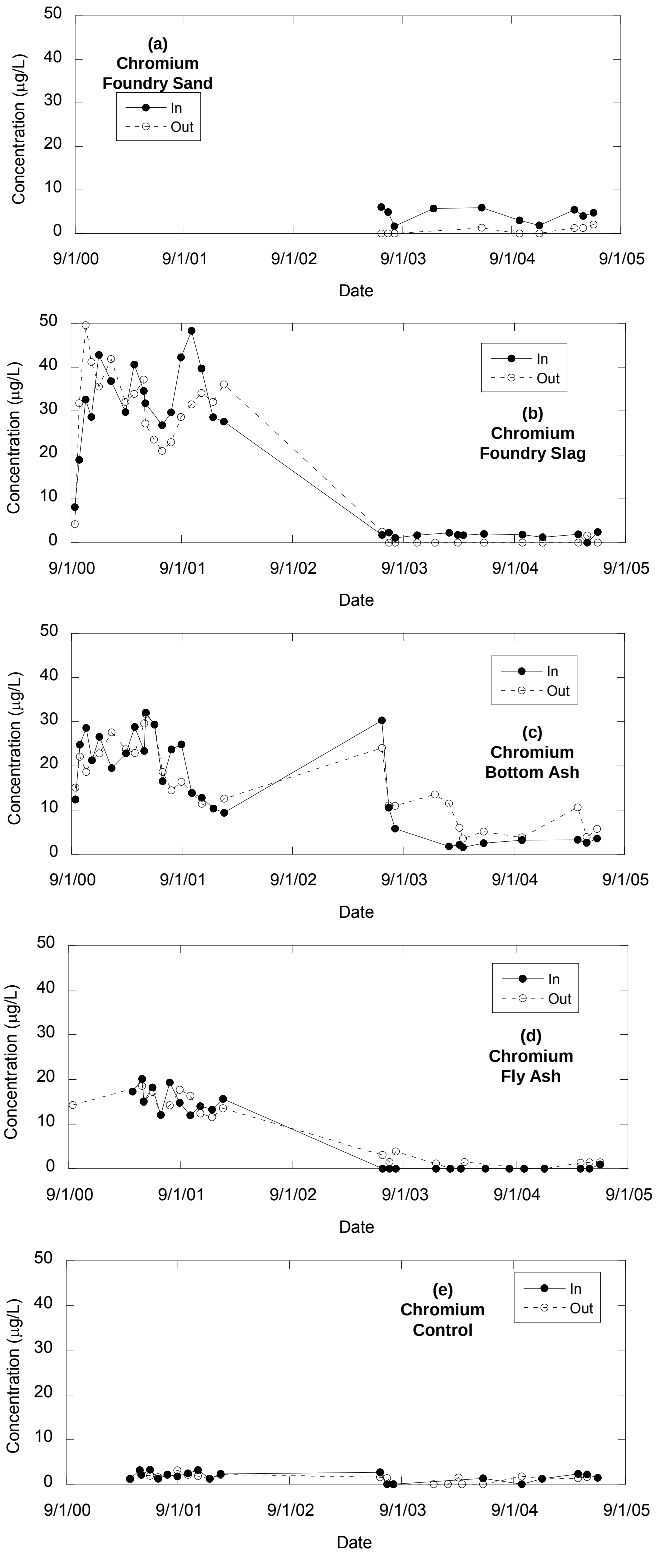

Fig. 6. Cr Concentrations in leachate from lysimeters in (a) foundry sand, (b) foundry slag, (c) bottom ash, (d) fly-ash-stabilized-soil, and (e) control sections.

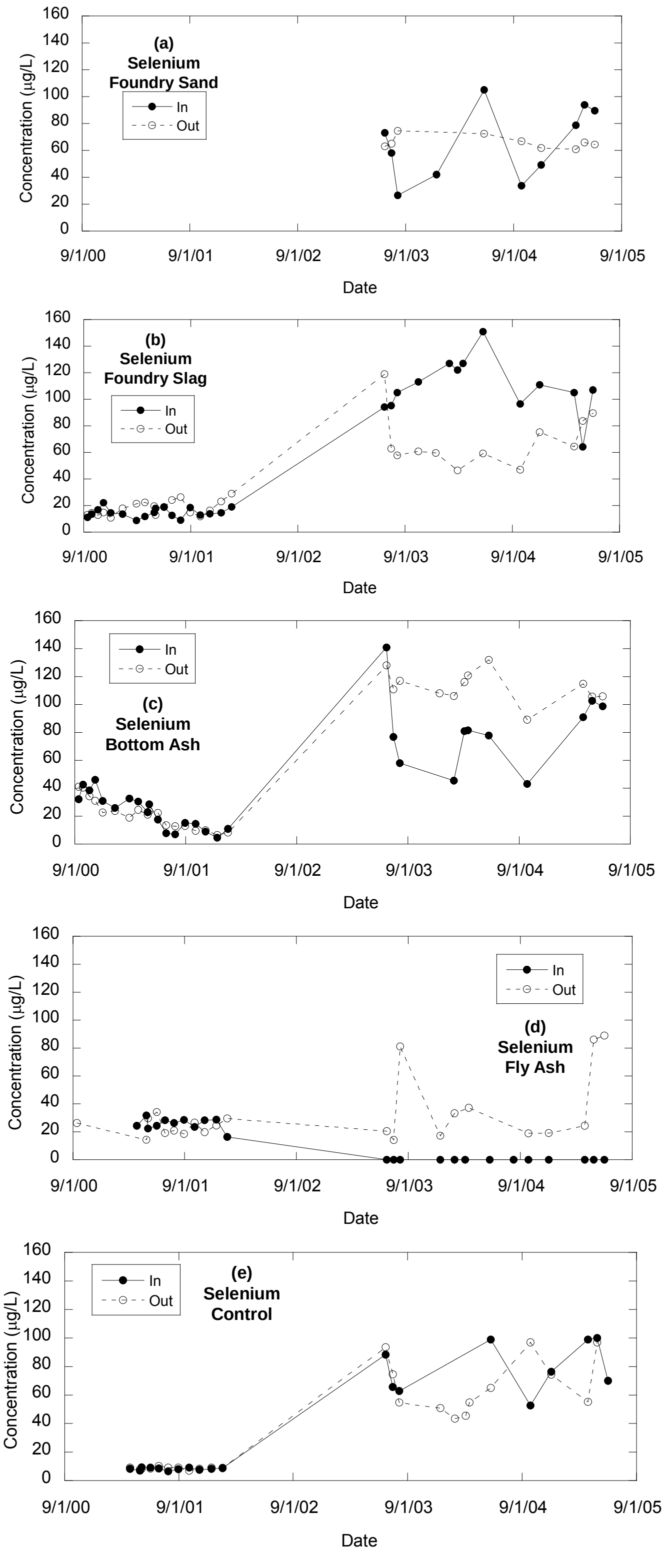

Fig. 7. Se Concentrations in leachate from lysimeters in (a) foundry sand, (b) foundry slag, (c) bottom ash, (d) fly-ash-stabilized-soil, and (e) control sections.

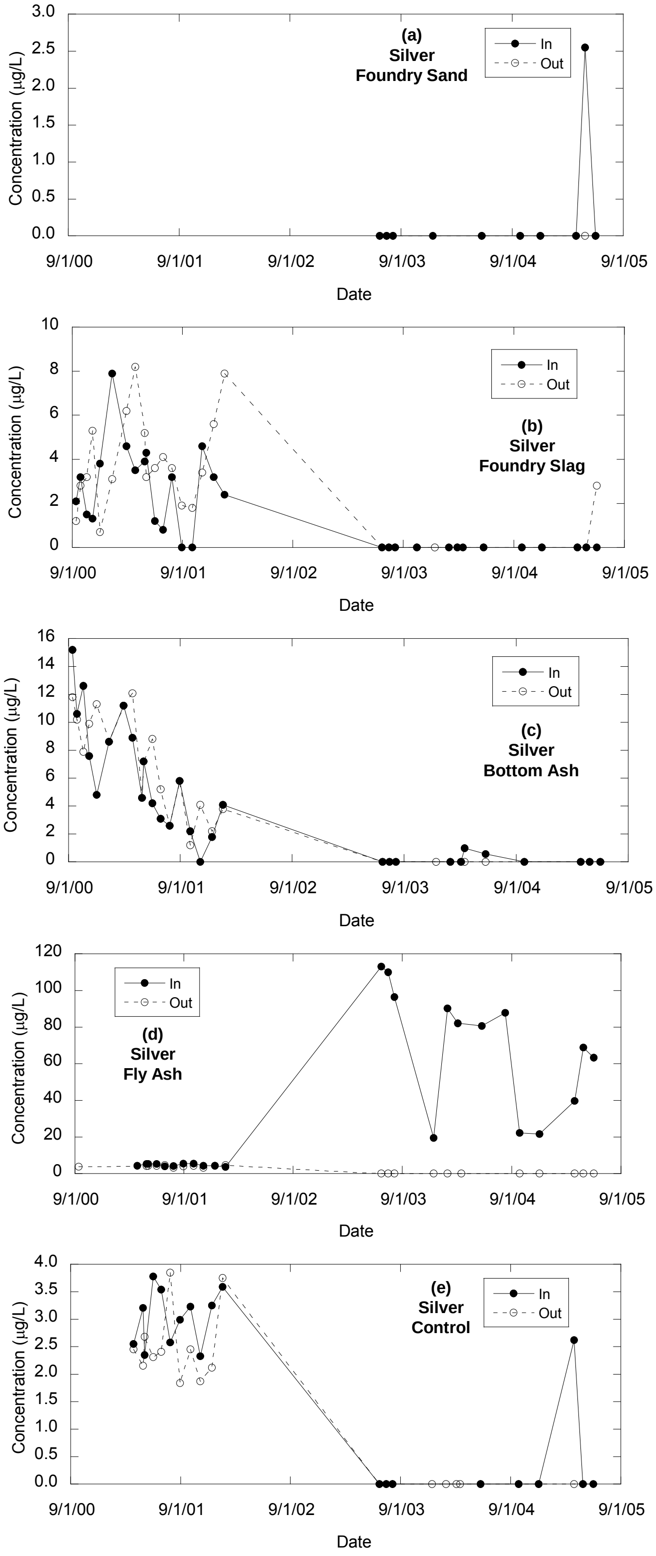

Fig. 8. Ag Concentrations in leachate from lysimeters in (a) foundry sand, (b) foundry slag, (c) bottom ash, (d) fly-ash-stabilized-soil, and (e) control sections.

The elution pattern for Se (Fig. 7) sharply contrasts the patterns for Cd and Cr (Figs. 5 and 6). Se concentrations are low (or are decreasing) during the first 18 mos and much higher during the final 24 mos. The peak concentration typically is reached between 0.9 and 3.4 PVF, and the average PVF at the peak Se concentration is 2.2 times higher than the average PVF at the peak concentration for the other elements studied. The exception is the foundry sand section, where no distinct peak concentration occurred and only 0.05 PVF was transmitted. Peak Se concentrations from each section were similar (89-151 μg/L), although the fly-ash-stabilized-soil test section typically had lower Se concentrations than the other test sections throughout the monitoring period. At the end of the monitoring period, Se concentrations from all sections were comparable (~80 μg/L). The one exception is the Se concentration in the leachate from the inner lysimeter in the fly-ash-stabilized-soil section, which dropped below detection limits (<10 μg/L) after 3 years.

A possible explanation for the elevated Se concentrations in the latter portion of the monitoring period is that another material in the pavement structure is eluting Se. The similarity of the Se elution patterns and concentrations in leachate from each of the test sections during the latter portion of the monitoring period is consistent with this hypothesis. All five test sections used the same base course material (recycled asphalt and crushed limestone), which could be the source of Se. Alternatively, changing redox conditions may be occurring, resulting in transformation of Se(IV) to Se(VI). Se(IV) is cationic, more strongly adsorbed by soil solids, and less mobile, whereas Se(VI) forms anionic complexes that are weakly sorbed and more mobile. However, no tests were conducted to identify the

Se species present in leachate, and the redox conditions present in the field are also unknown.

Ag followed a first-flush elution pattern for the foundry slag, bottom ash, and control sections, with concentrations beginning to drop within 18 mos and 0.5 PVF and decreasing to less than 3 μg/L during the final two years of the monitoring period. The Ag elution pattern from the foundry sand section was not defined because only one sample had a concentration greater than the detection limit (2.5 μg/L, July 2003).

The two lysimeters in the fly-ash-stabilized-soil section yielded remarkably different Ag elution patterns. Ag concentrations in leachate from the outer lysimeter never exceeded 5 μg/L and followed a first-flush pattern. In contrast, Ag concentrations in the inner lysimeter increased to over 100 μg/L after 3 yr, and remained above 20 μg/L for the remainder of the monitoring period. The peak Ag concentration in the leachate from the inner lysimeter in the fly-ash-stabilized soil section occurred after 1.9 PVF.

Peak concentrations in each test section constructed with byproducts were divided by peak concentrations from the control section to define normalized peak concentrations. The normalized concentrations are summarized in Table 3. Three of the sixteen cases (foundry sand – Cd and Ag; fly-ash-stabilized soil – Se) have normalized peak concentrations less than unity (i.e., metals eluted at a lower peak concentration from the byproducts sections than from the control section). In all other cases, the normalized peak concentrations are greater than unity. The normalized peak concentrations typically are highest for Cr and lowest for Se, and tend to be lower for the foundry sand relative to the other byproducts.

Table 3. Peak Cd, Cr, Se and Ag concentrations found in the leachate from lysimeter tests on foundry sand, foundry slag, bottom ash, fly-ash-stabilized soil, and crushed rock (control), along with the PVF to reach the peak concentration.

Material	**Cd**			**Cr**			**Se**			**Ag**		
	Peak Lysimeter Conc. (μg/L)	**Normalized Conc.**	**PVF to Peak Conc.**	**Peak Lysimeter Conc. (μg/L)**	**Normalized Conc.**	**PVF to Peak Conc.**	**Peak Lysimeter Conc. (μg/L)**	**Normalized Conc.**	**PVF to Peak Conc.**	**Peak Lysimeter Conc. (μg/L)**	**Normalized Conc.**	**PVF to Peak Conc.**
Foundry Sand	2.8	0.45	0.16	6.1	1.85	0.01	105	1.05	0.05	2.6	0.67	0.14
Foundry Slag	32.1	5.18	0.29	49.6	15.03	0.17	151	1.51	0.87	8.2	2.10	0.24
Bottom Ash	21.2	3.42	0.17	32.1	9.73	0.33	141	1.41	0.98	15.2	3.90	0.17
Fly-Ash-Stabilized Soil	32.1	5.18	0.01	20.2	6.12	0.26	89	0.89	3.37	96.4	24.72	1.89
Control	6.2	1.00	0.51	3.3	1.00	0.44	100	1.00	1.23	3.9	1.00	0.51

5.2 Comparison of Peak Concentrations in Lysimeters and WLTs

Cd, Cr, Se, and Ag concentrations in the leachate from the WLTs are summarized in Table 4 along with peak concentrations from the lysimeters and CLTs. Concentrations from the WLTs are below detection limits for 8 of the 16 cases, whereas peak concentrations in the leachate collected in the lysimeters are always above detection limits (Table 4). A graph of peak concentrations from the lysimeters vs. corresponding concentrations from the WLTs is shown in Fig. 9. Peak concentrations from the lysimeters generally are higher than those from the WLTs; in only one case is the peak concentration from the WLT higher than the peak concentration from the lysimeters (Cr from fly-ash-stabilized soil).

Differences in liquid-solid ratio may be responsible for the disparity between the peak field concentrations and the concentrations from the WLTs. A dilution calculation based on the PVF at the peak lysimeter concentration indicates that the L-S ratio in the field (at peak concentration) ranges between 0.5-2.2, whereas a L-S ratio of 20 was used in the WLTs (i.e., 9.1 – 40 times larger than the L-S ratio at peak concentration in the field). Many of the peak field concentrations are within a factor of 9-40 of the concentrations measured in the WLTs. Differences in pH and redox conditions may also have contributed to the disparity, but cannot be quantified with the data that are available.

Table 4. Cd, Cr, Se, and Ag concentrations in leachate from lysimeters, CLTs, and WLTs on foundry sand, foundry slag, bottom ash, and fly-ash-stabilized soil.

Material	**Peak Lysimeter Conc. (μg/L)**				**Peak CLT Conc. (μg/L)**				**WLT pH and Concentration (μg/L)**				
	Cd	**Cr**	**Se**	**Ag**	**Cd**	**Cr**	**Se**	**Ag**	**Cd**	**Cr**	**Se**	**Ag**	**pH**
Foundry Sand	2.8	6.1	105	2.6	32.9	<1.7	<4.0	6.7	0.3	<1.0	<10	<2.5	9.0
Foundry Slag	32.1	49.6	151	8.2	<0.7	6530	<4.0	16.8	0.2	<1.0	<10	<2.5	10.7
Bottom Ash	21.2	32.1	141	15.2	10.3	961	24.1	4.4	<0.2	1.1	32.5	<2.5	10.3
Fly-Ash-Stabilized Soil	32.1	20.2	89.0	96.4	4.6	62.9	32.4	5.8	0.6	46	16.2	1.8	11.0
Fly Ash Alone	-	-	-	-	-	-	-	-	0.7	95	26	2.2	11.8

Note: Hyphen indicates that test was not conducted. <X.Y indicates concentration is below the detection limit (X.Y μg/L).

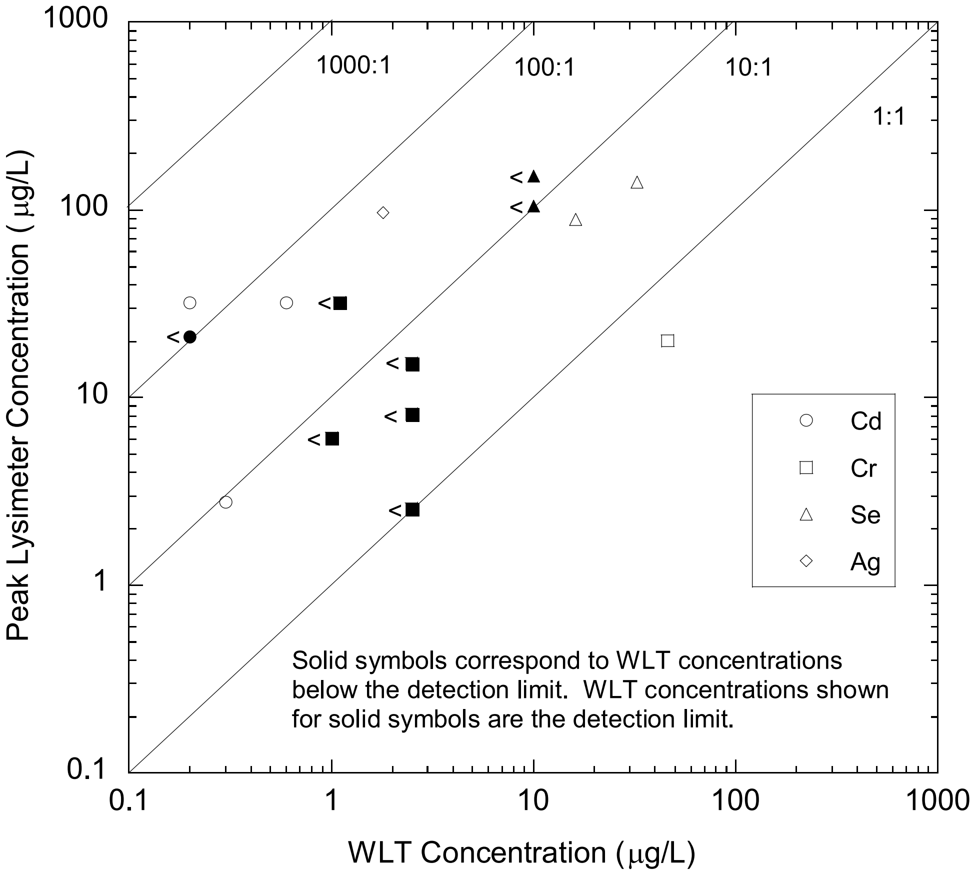

Fig. 9. Comparison peak concentrations found in the leachate from lysimeter tests to Cd, Cr, Se, and Ag concentrations from WLTs.

5.3 Comparison of Elution in Lysimeters and CLTs

Peak concentrations from the CLTs are summarized in Table 5. A comparison of peak concentrations from the lysimeters and peak concentrations from the CLTs is shown in Fig. 10. Many of the peak lysimeter and CLT concentrations differ by less than a factor of 10, but some differ by a factor as large as 131. Peak Se and Cd concentrations in the lysimeters tend to be higher than those from the CLTs, Ag concentrations from the lysimeters and the CLTs tended to be more comparable, and peak Cr concentrations from the lysimeters tend to be lower than those form the CLTs.

Elution curves for Cd from the test sections and CLTs are shown in Fig. 11. Similar elution patterns for Cd were obtained in the field and the CLTs for the test sections constructed with foundry sand (delayed leaching) and fly-ash-stabilized soil (first-flush leaching), except for two outlier points for the CLT on foundry sand. In fact, for the fly-ash-stabilized soil, the Cd elution patterns in the field and CLTs are nearly identical. In contrast, elution of Cd from the foundry slag and bottom ash test sections followed a first-flush pattern, whereas the CLTs yielded concentrations below the detection limits over the same range of PVF. The pH was not measured during the field tests. However, pH at the peak Cd concentration in the leachate from the other CLTs was slightly basic, between 8.4 and 8.6.

Elution curves for Cr from the test sections and CLTs are shown in Fig. 12. The elution curves from the CLTs on foundry slag, bottom ash, and fly-ash-stabilized-soil exhibit a similar pattern as those from the field, although the peak Cr concentrations from the CLTs were 3.1 to 131.7 times larger than those in the field. In contrast, for foundry sand, Cr concentrations from the CLT were always less than the detection limit (1.7 μg/L), whereas concentrations from the lysimeter were as high as 6.1 μg/L. However, only a small volume of water was discharged from the foundry sand test section (< 0.23 PVF), and all of the CLT data are for PVF > 0.14.

Table 5. Peak Cd, Cr, Se, and Ag concentrations, leachate pH, and PVF to peak concentration from CLTs on foundry sand, foundry slag, bottom ash, and fly-ash-stabilized soil.

Material	**Cd**			**Cr**			**Se**			**Ag**		
	Peak CLT Conc. (μg/L)	**pH at Peak Conc.**	**PVF to Peak Conc.**	**Peak CLT Conc. (μg/L)**	**pH at Peak Conc.**	**PVF to Peak Conc.**	**Peak CLT Conc. (μg/L)**	**pH at Peak Conc.**	**PVF to Peak Conc.**	**Peak CLT Conc. (μg/L)**	**pH at Peak Conc.**	**PVF to Peak Conc.**
Foundry Sand	32.9	8.4	0.1	<1.7	-	-	<4	-	-	7.0	8.5	1.6
Foundry Slag	<0.7	-	-	6530	7.4	0.6	<4	-	-	16.8	8.6	28.7
Bottom Ash	10.3	8.5	22.9	961	7.7	0.7	24	9.1	16.5	4.4	8.5	6.9
Fly-Ash-Stabilized Soil	4.6	8.6	0.8	62.9	8.6	0.8	32.4	8.6	0.3	5.8	8.6	0.3

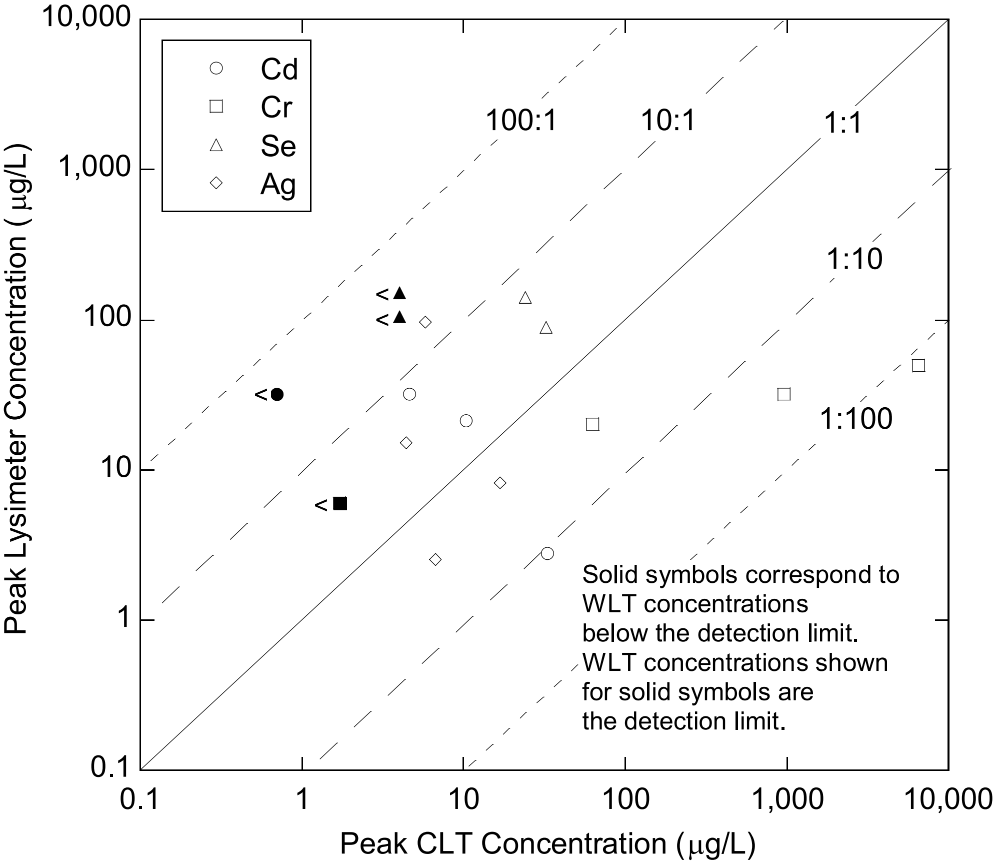

Fig. 10. Comparison of peak Cd, Cr, Se, and Ag concentrations in leachate from lysimeters to peak CLT concentrations.

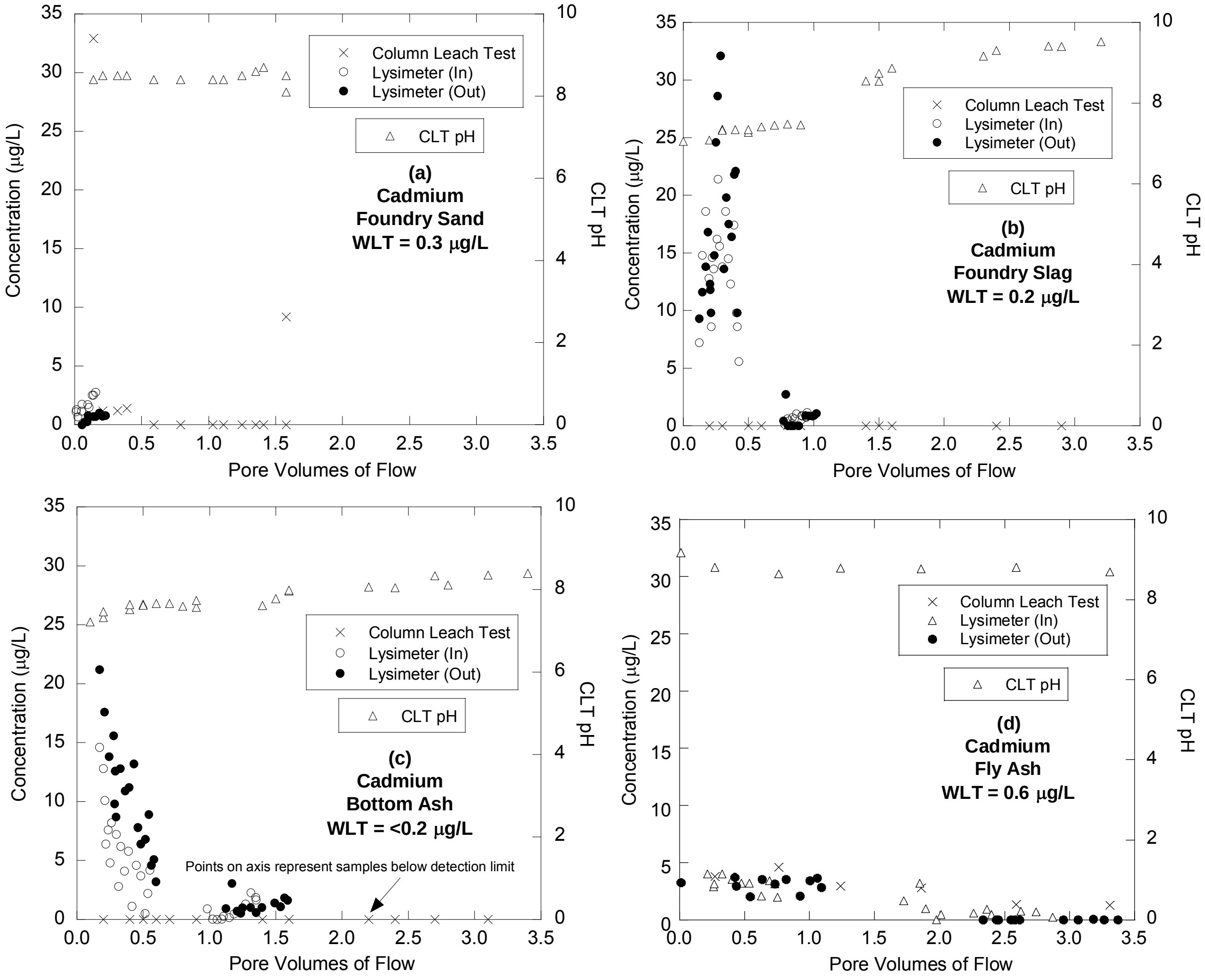

Fig. 11. Cd elution curves from CLTs and lysimeters: (a) foundry sand, (b) foundry slag, (c) bottom ash, and (d) fly ash stabilized soil.

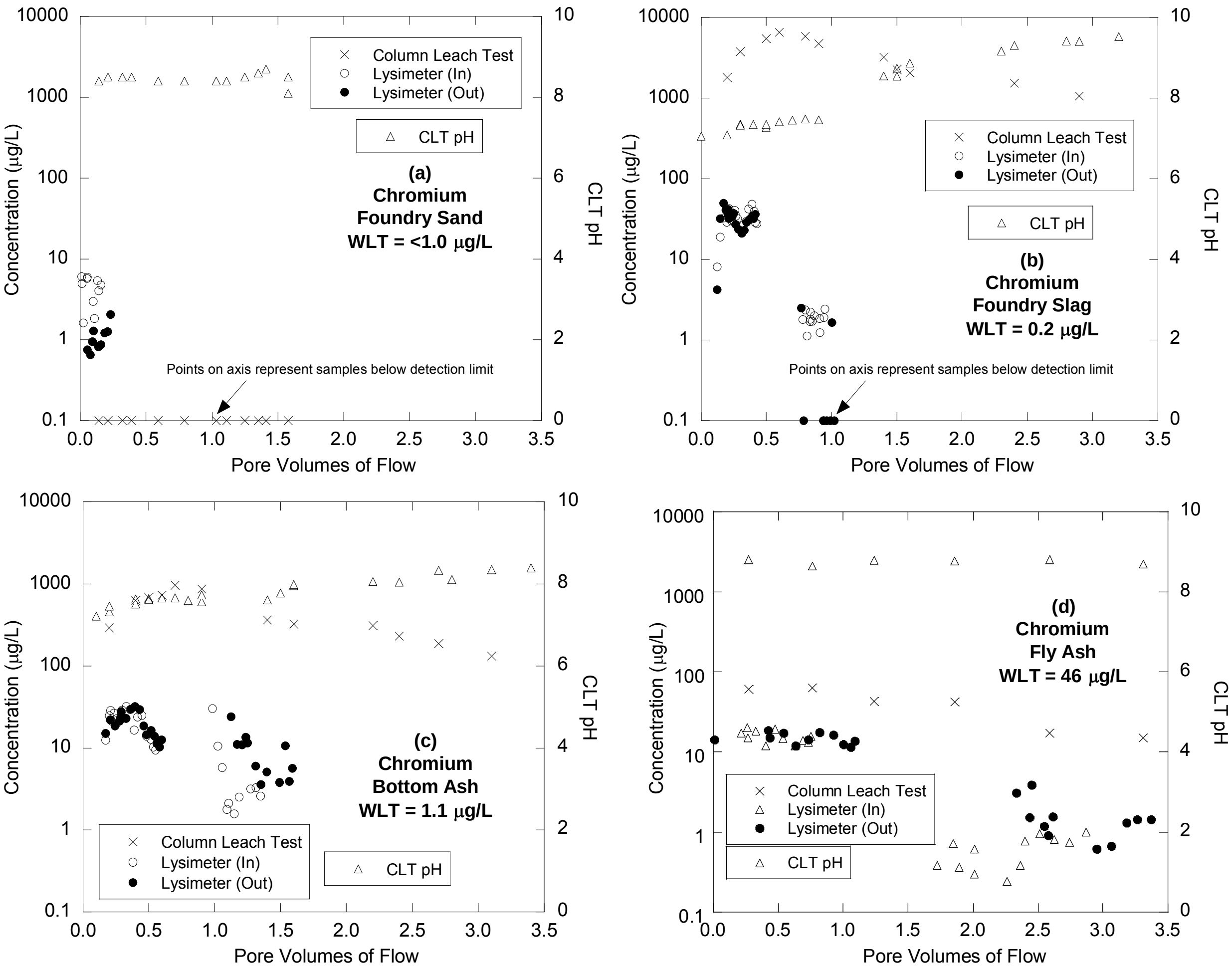

Fig. 12. Cr elution curves from CLTs and lysimeters: (a) foundry sand, (b) foundry slag, (c) bottom ash, and (d) fly ash stabilized soil.

Elution curves for Se from the test sections and CLTs are shown in Fig. 13. Similar curves were obtained from the CLTs and the field only for the fly-ash-stabilized-soil. For the other materials, Se concentrations from the CLTs were nearly always less than the detection limit (4.0 μg/L), whereas peak concentrations of Se in the field ranged from 89 μg/L to 151 μg/L. The large discrepancy between Se concentrations from the CLTs and those measured in the field also supports the hypothesis, proffered in Section 5.1.2, that another material in the pavement structure, which was not tested in the CLTs, is the source of Se.

Elution curves for Ag from the test sections and CLTs are shown in Fig. 14. Similar elution patterns were obtained from the field and CLTs for bottom ash and fly-ash-stabilized soil. For the fly-ash-stabilized soil, however, Ag concentrations increased in one lysimeter and decreased in the other during the latter portion of the monitoring period, whereas the CLT concentrations decreased slightly over the same range of PVF. Concentrations of Ag from the CLT on foundry sand tended to be much higher than those measured in the field, which generally were below the detection limit (2.5 μg/L). However, the one sample from the foundry sand lysimeter that was above the detection limit (2.6 μg/L) was within the range of concentrations obtained from the CLT (1.2-6.7 μg/L). Concentrations of Ag from the foundry slag test section varied considerably and intermittently, ranging from below the detection limit up to 8.2 μg/L. A similar variation in concentration of Ag was observed from the CLT on foundry slag.

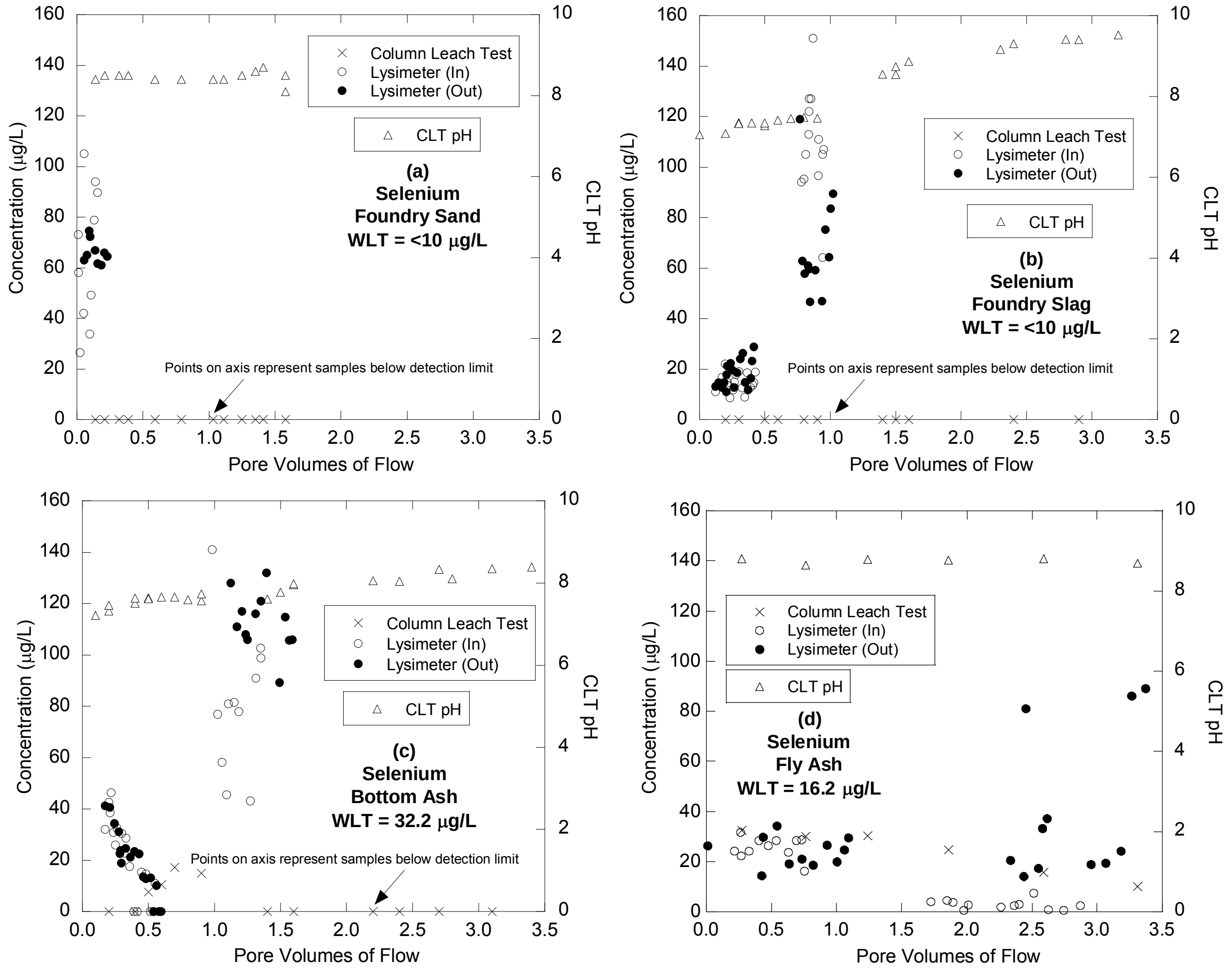

Fig. 13. Se elution curves from CLTs and lysimeters: (a) foundry sand, (b) foundry slag, (c) bottom ash, and (d) fly ash stabilized soil.

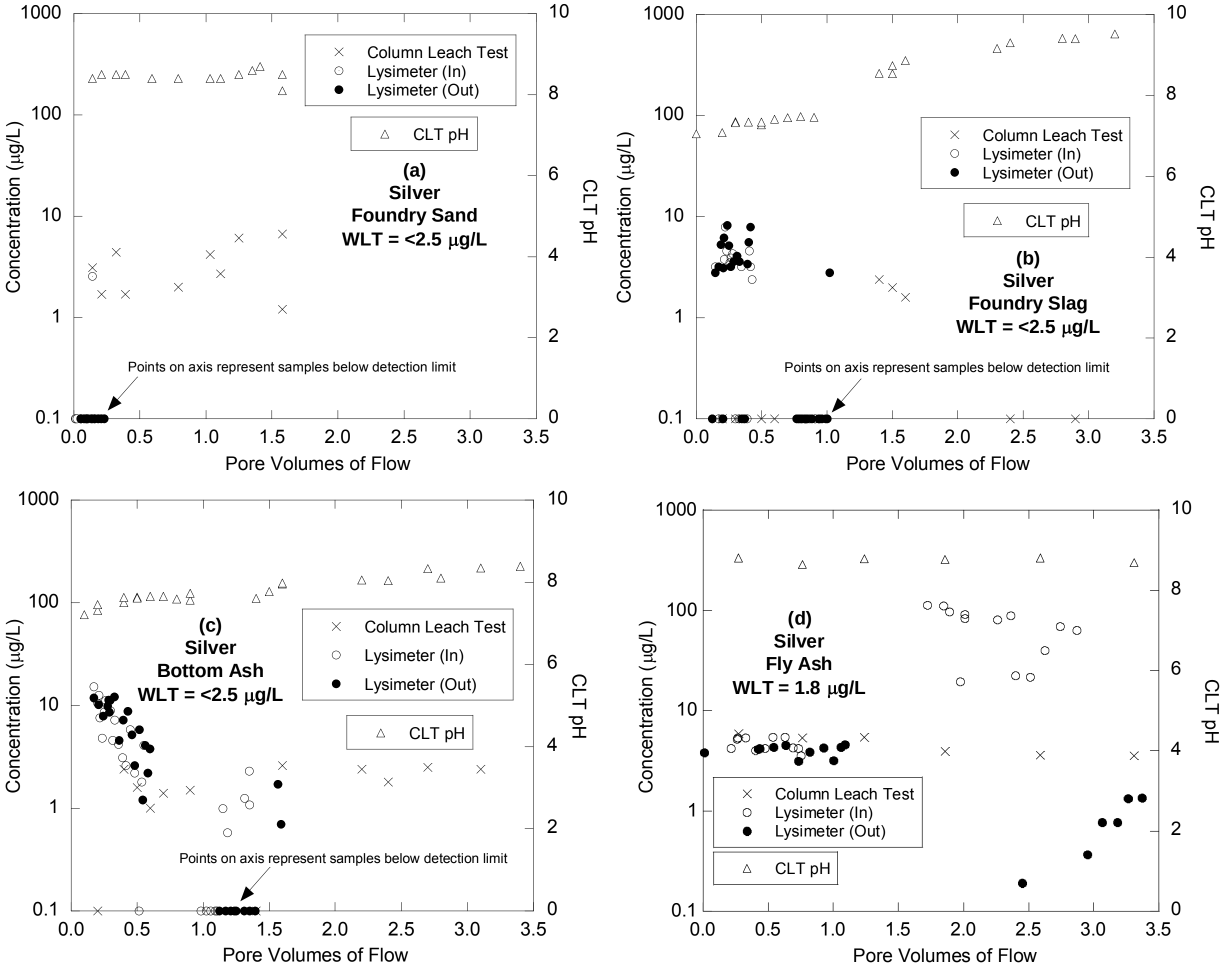

Fig. 14. Ag elution curves from CLTs and lysimeters: (a) foundry sand, (b) foundry slag, (c) bottom ash, and (d) fly ash stabilized soil.

6. IMPLICATIONS FOR GROUNDWATER QUALITY

Groundwater quality standards applicable to the field site are defined in Section NR 140 (Groundwater Quality) of *Wisconsin Administrative Code*. The Wisconsin standards are the same as or lower than USEPA MCLs.

A comparison of the Wisconsin standards for Cd, Cr, Se, and Ag and peak concentrations from the test sections is in Table 6. Cd concentrations in the leachate from the foundry slag, bottom ash, and control sections exceeded the Wisconsin standard (5 μg/L) by a factor of 1.2-6.4 for the first 18 mos of the field test. However, in all cases, the Cd concentrations were below the Wisconsin standard after 16 mos and 0.6 PVF. Se concentrations exceeded the Wisconsin standard (50 μg/L) for all test sections by a factor of 1.8 to 3.0. Moreover, in all cases except for the fly-ash-stabilized soil, the Se concentration increased and then leveled off at a concentration exceeding the Wisconsin standard over the last 24 months of monitoring.

In contrast to Cd and Se, leachate concentrations exceeding the Wisconsin standard for Ag (50 μg/L) were only observed in the fly-ash-stabilized soil section (peak = 96 μg/L). Ag concentrations of this magnitude were only recorded in one lysimeter in the fly-ash-stabilized soil section, and the concentration in this lysimeter fluctuated between 19 and 113 μg/L over the last 24 months of the monitoring period. None of the test sections had Cr concentrations exceeding the Wisconsin standard (100 μg/L).

Leachate collected in the lysimeters is representative of pore fluid at the bottom of the pavement profile and represents water reaching groundwater only if the

Table 6. Peak lysimeter concentrations and estimated concentrations after 1 m and 5 m of migration from the byproduct layers based on analysis reported in Bin Shafique et al. (2002).

Material	**Peak Lysimeter Conc. (μg/L)**				**Conc. after 1 m migration (μg/L)**				**Conc. after 5 m migration (μg/L)**			
	Cd	**Cr**	**Se**	**Ag**	**Cd**	**Cr**	**Se**	**Ag**	**Cd**	**Cr**	**Se**	**Ag**
Foundry Sand	2.8	6.1	105	2.6	0.6	1.2	21.0	0.5	0.3	0.6	10.5	0.3
Foundry Slag	32.1	49.6	151	8.2	6.4	9.9	30.2	1.6	3.2	5.0	15.1	0.8
Bottom Ash	21.2	32.1	141	15.2	4.2	6.4	28.2	3.0	2.1	3.2	14.1	1.5
Fly-Ash-Stabilized-Soil	32.1	20.2	89	96.4	6.4	4.0	17.8	19.3	3.2	2.0	8.9	9.6
Wisconsin Standard	5	100	50	50	5	100	50	50	5	100	50	50

groundwater table is at the base of the pavement profile. In many roadways, the water table will be deeper. Processes such as sorption, diffusion, dispersion, and dilution occurring in soils between the base of the pavement and the groundwater table will result in lower concentrations by the time the groundwater table is reached.

Bin Shafique et al. (2002) conducted a modeling study to simulate the transport of contaminants from working platforms constructed with byproducts to the groundwater table using a variably saturated model of flow and transport that was validated using data from field lysimeter studies. Their findings indicate that the maximum concentration 1 m below the pavement layer is approximately 20% of the peak concentration at base of the byproduct layer. At 5 m, the maximum concentration is approximately 10% of the peak concentration at the base of the byproduct layer.

Concentrations at the groundwater table obtained by applying these “dilution” factors are summarized in Table 6. In all cases, the estimated concentrations of Cd, Cr, Se, and Ag at the water table are below Wisconsin standards when the groundwater table is at least 5 m below the byproduct layer. For cases where the groundwater table is 1 m below the byproduct layer, the Wisconsin standards for Cd, Cr, Se, and Ag would be met for the foundry sand and bottom ash sections. However, for the test sections with foundry slag and fly-ash-stabilized soil, the Cd concentrations are 1.3 times the Wisconsin standard, whereas the Cr, Se, and Ag concentrations are at least 40% lower than the Wisconsin standards.

7. SUMMARY AND CONCLUSIONS

Leaching data from five test sections constructed along a stretch of Wisconsin State Highway 60 near Lodi, WI have been presented and discussed in this report. Four of these test sections were constructed with a layer of industrial byproducts (foundry sand, foundry slag, bottom ash, or fly-ash-stabilized soil) between the existing soft subgrade and the base course layer. One of the test sections was a control and was constructed with a layer of crushed dolostone instead of industrial byproducts. All four byproducts met the criteria in the *Wisconsin Administrative Code* for re-use in confined geotechnical fills.

Leachate draining from the test sections was collected in pan lysimeters and analyzed for concentrations of Cd, Cr, Se, and Ag. Batch water leach tests (WLTs) and column leach tests (CLTs) were also conducted on each of the byproducts using typical procedures used to evaluate the suitability of byproducts for use in earthwork applications. Concentrations of Cd, Cr, Se, and Ag from the WLTs and CLTs were compared with concentrations measured in the leachate collected in the field and with groundwater quality standards in the *Wisconsin Administrative Code*.

Leachate collected in the lysimeters commonly had Cd, Se, and Ag concentrations exceeding Wisconsin groundwater quality standards. However, application of dilution factors to account for the reduction in concentration expected between the bottom of the pavement structure and the groundwater table showed that concentrations exceeding groundwater quality standards would not occur if the byproducts layer is at least 5 m above the groundwater table. For a separation distance of 1 m, only Cd would modestly (30%) exceed the groundwater quality standard directly beneath the centerline of the pavement.

Comparison of peak concentrations from the lysimeters and concentrations obtained from the WLTs indicated that WLTs generally underestimate peak field concentrations by a factor between 4-160, but in most cases the factor is less than 55. Dilution caused by the large liquid-solid ratio used in the WLTs is partly responsible for the disparity between the field and WLT concentrations, although differences in pH and redox conditions may have been important as well.

Peak concentrations from the CLTs were closer to peak concentrations in the field than the concentrations from the WLTs. Peak concentrations from the CLTs typically were within a factor of 10 of peak concentrations from the CLTs, although the peak CLT concentrations were as much as 45 times higher and 131 times lower than the peak field concentrations. The elution patterns in the field and the CLTs (first flush or delayed response) generally were similar, although the magnitude of the concentrations differed. An exception is the fly-ash-stabilized soil, for which both concentrations and elution patterns from the field and the CLTs were similar.

An unusual rise in Se concentration was observed in all of the field lysimeters (including the control) later in the monitoring period, but in none of the CLTs. The presence of elevated Se concentrations in all lysimeters (and at similar concentration) suggests that Se is leaching from another source within the pavement structure, and not the byproducts. One potential source is the crushed rock or recycled asphalt in the base course layer. This observation illustrates that leaching from pavement structures is not limited to byproducts layers, and that other potential sources of contaminants should be considered when evaluating impacts to groundwater attributed to the use of industrial byproducts in highway construction.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

ACAA (2003). "Coal Combustion Product Production and Use Survey." American Coal Ash Association, Aurora, CO.

Abichou, T., Benson, C. H., and Edil, T. B. (2000). "Foundry Green Sands as Hydraulic Barriers: Laboratory Study." *Journal of Geotechnical and Geoenvironmental Engineering*, 126(12), 1174-1183.

Abichou, T., Benson, C. H., and Edil, T. B. (2002). "Foundry Green Sands as Hydraulic Barriers: Field Study." *Journal of Geotechnical and Geoenvironmental Engineering*, 128(3), 206-215.

Acosta, H., Edil, T. B., and Benson, C. H. (2003). "Soil Stabilization and Drying Using Fly Ash," Geo Engineering Report No. 03-03, Dept. of Civil and Environmental Engineering, University of Wisconsin-Madison.

Bastian, K. C., and Alleman, J. E. (1998). "Microtox Characterization of Foundry Sand Residuals." *Waste Management*, 18, 227-234.

Bin Shafique, S., Benson, C. H., and Edil, T. B. (2002). "Leaching of Heavy Metals from Fly Ash Stabilized Soils Used in Highway Pavements." Geo Engineering Report No. 02-14, Dept. of Civil and Environmental Engineering, University of Wisconsin-Madison.

Bin Shafique, S., Benson, C., Edil, T., and Hwang, K. (2006), Leachate Concentrations from Water Leach and Column Leach Tests on Fly-Ash Stabilized Soil, *Environmental Engineering Science*, 23(1), 51-65.

Creek, D. N., and Shackelford, C. D. (1992). "Permeability and Leaching Characteristics of Fly Ash Liner Materials." *Transportation Research Record*, 1345, 74-83.

Ecke, H., Menad, N., and Lagerkvist, A. (2003). "Carbonation of Municipal Solid Waste Incineration Fly Ash and the Impact on Metal Mobility." *Journal of Environmental Engineering*, 129(5), 435-440.

Edil, T. B., Sandstrom, L. K., and Berthouex, P. M. (1992). "Interaction of Inorganic Leachate with Compacted Pozollanic Fly-Ash." *Journal of Geotechnical Engineering,*118(9), 1410-1430.

Edil, T. B., Benson, C. H., Bin Shafique, S., Tanyu, B. F., Kim, W. H., and Senol, A. (2002). "Field Evaluation of Construction Alternatives for Roadway Over Soft Subgrade." Geo Engineering Report No. 02-04, Dept. of Civil and Environmental Engineering, University of Wisconsin-Madison.

Goodarzi, F., and Huggins, F. E. (2001). "Monitoring the Species of Arsenic, Chromium, and Nickel in Milled Coal, Bottom Ash, and Fly Ash from a Pulverized Coal-Fired Power Plant in Western Canada." *Journal of Environmental Monitoring*, 3, 1-6.

Goodhue, M. J., Edil, T. B., and Benson, C. H. (2001). "Interaction of Foundry Sands with Geosynthetics." *Journal of Geotechnical and Geoenvironmental Engineering*, 127(4), 353-362.

Gutierrez, B., Pazos, C., and Coca, J. (1993). “Characterization and Leaching of Coal Fly-Ash.” *Waste Management & Research*, 11(4), 279-286.

Ham, R. K., and Boyle, W. C. (1990). "Research Reveals Characteristics of Ferrous Foundry Wastes." *Modern Casting,* February, 37-41.

Huggins, F. E., Huffman, G. P., Linak, W. P., and Miller, C. A. (2004). “Quantifying Hazardous Species in Particulate Matter Derived From Fossil-Fuel Combustion.” *Environmental Science & Technology*, 38(6), 1836-1842.

Javed, S. and Lovell, C. (1994), Use of Waste Foundry Sand in Highway Construction, Report No. JHRP/INDOT/FHWA-94/2J, Purdue School of Engineering, West Lafayette, IN.

Karczewska, A., Chodak, T., and Kaszubkiewicz, J. (1996). “The Suitability of Brown Coal as Sorbent for Heavy Metals in Polluted Soils,” *Applied Geochemistry*, Vol. 29, 343-349.

Kleven, J. R., Edil, T. B., and Benson, C. H. (2000). “Evaluation of Excess Foundry System Sands for Use as Subbase Material.” *Transportation Research Record*, 1714, 40-48

Kosson, D. S., van der Sloot, H. A., Sanchez, F., and Garrabrants, A. C. (2002). “An Integrated Framework for Evaluating Leaching in Waste Management and Utilization of Secondary Materials.” *Environmental Engineering Science*, 19(3), 159-204.

Lee, T. and Benson, C. (2006), Leaching Behavior of Green Sands from Gray-Iron Foundries Used for Reactive Barrier Applications, *Environmental Engineering Science*, 23(1), 153-167.

Lind, B. B., Fallman, A. M., and Larsson, L. B. (2001). “Environmental Impact of Ferrochrome Slag in Road Construction.” *Waste Management*, 21(3), 255-264.

Meima, J. A., van der Weijden, R. D., Eighmy, T. T., and Comans, R. N. J. (2002). “Carbonation Processes in Municipal Solid Waste Incinerator Bottom Ash and Their Effect on the Leaching of Copper and Molybdenum.” *Applied Geochemistry*, 17, 1503-1513.

Naik, T. R., Singh, S. S., Ramme, B. W., (2001). “Performance and Leaching Assessment of Flowable Slurry.” *Journal of Environmental Engineering*, Vol. 127, No. 4, 359-368.

Partridge, B. K., Alleman, J. E., Fox, P. J., and Mast, D. G. (1998). “Performance Evaluation of Highway Embankment Constructed with Waste Foundry Sand.” *Transportation Research Record,* 1619, 55-63.

Praharaj, T., Powell, M. A., Hart, B. R., and Tripathy, S. (2002). “Leachability of Elements from Sub-Bituminous Coal Fly Ash From India.” *Environment International*, 27(8), 609-615.

Proctor, D. M., Fehling, K. A., Shay, E. C., Wittenborn, J. L., Green, J. J., Avent, C., Bigham, R. D., Connolly, M., Lee, B., Shepker, T. O., and Zak, M. A. (2000). “Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Furnace, and Electric Arc Furnace Steel Industry Slags.” *Environmental Science & Technology*, 34, 1576-1582.

Seals, R. K., Moulton, L. K., and Ruth, B. E. (1972). “Bottom Ash: An Engineering Material.” *Journal of the Soil Mechanics and Foundations Division*, 98(4), 311-325.

Shen, H., Forssberg, E. (2003). “An Overview of Recovery of Metals From Slags.” *Waste Management*, 23(10), 933-949.

Siddiki, N. Z., Kim, D., and Salgado, R. (2004). “Use of Recycled and Waste Materials in Indiana.” *Transportation Research Record,* 1874, 78-85.

Tanyu, B. F., Benson, C. H., Edil, T. B., and Kim, W. H. (2004). “Equivalency of Crushed Rock and Three Industrial By-Products Used for Working Platforms During Pavement Construction.” *Transportation Research Record,* 1874, 58-69.

Thayumanavan, P., Nelson, P. O., Azizian, M. F., Williamson, K. J., and Lundy, J. R. (2001). “Environmental Impact of Construction and Repair Materials on Surface Water and Groundwater - Detailed Evaluation of Waste-Amended Highway Materials.” *Transportation Research Record,* 1743, 25-32.

Theis, T. L., and Wirth, J. L. (1977). “Sorptive Behavior of Trace Metals on Fly Ash in Aqueous Systems.” *Environmental Science and Technology*, 11(12), 1096-1106.

Wisconsin (2004), *Wisconsin Administrative Code*, Revisor of Statutes Bureau, Madison, WI.

APPENDIX

COLUMN LEACH TEST RESULTS

Table A2.1 pH, Cd, Cr, Se, and Ag concentrations from CLT on bottom ash.

Bottom Ash Column Leach Test Results

Est PVF	pH	Influent pH	Concentration (μg/L)			
			Cd	Cr	Se	Ag
0.0						
0.1	7.2	6.8				
0.2	7.3	6.8	ND	292	ND	ND
0.2	7.5	6.8				
0.4	7.5	6.8	ND	625	ND	2.4
0.4	7.6	6.8				
0.5	7.6	6.8	ND	684	7.6	1.6
0.5	7.6	6.8				
0.6	7.7	6.8	ND	730	10.5	1
0.7	7.7	6.8				
0.7	7.7	6.8	ND	961	17.2	1.4
0.8	7.6	6.8				
0.9	7.6	6.8				
0.9	7.7	6.8	ND	863	14.9	1.5
1.4	7.6	6.8	ND	365	ND	ND
1.5	7.8	6.8				
1.6	8.0	6.8				
1.6	8.0	6.8	ND	324	ND	2.6
2.2	8.1	6.8	ND	311	ND	2.4
2.4	8.0	6.8	ND	232	ND	1.8
2.7	8.3	6.9	ND	188	ND	2.5
2.8	8.1	6.9				
3.1	8.4	6.9	ND	131	ND	2.4
3.4	8.4	6.9				
3.6	8.4	6.9	ND	67.3	ND	0.87
3.7	8.2	6.9	ND	45.7	ND	1.2
4.0	8.3	6.9				
4.2	8.4	6.9	ND	7.2	ND	ND
4.6	8.5	6.9				
5.1	8.5	6.9	ND	2.7	ND	2.5
5.6	8.6	6.9				
6.0	8.2	6.9				
6.4	8.4	6.9				
6.9	8.5	6.7	ND	ND	ND	4.4
7.3	8.7	6.6				
7.9	8.7	6.7	ND	3	ND	2.7
8.3	8.8	6.7				
8.7	8.7	6.8	ND	2	ND	3.4
9.2	8.3	6.8				
9.6	8.4	6.7	ND	2.8	ND	3.4
10.2	8.5	6.7				
10.6	8.6	6.7	ND	2	ND	2.4
11.4	8.6	6.7				
12.2	8.8	6.7	ND	1.7	ND	2
12.7	8.9	6.7	ND	0	ND	3.6
13.3	8.9	6.7				

Est PVF	pH	Influent pH	Concentration (μg/L)			
			Cd	Cr	Se	Ag
14.6	9.0	6.7	ND	1.9	ND	0.86
15.2	9.0	6.7	ND	2.8	ND	2.9
15.7	9.1	6.6				
16.5	9.1	6.6	ND	2.8	24.1	3.5
17.1	9.0	6.6				
17.8	8.8	6.8	ND	3.9	ND	1.5
18.6	8.8	6.8	ND	ND	ND	ND
19.2	8.8	6.8	ND	ND	ND	1.7
20.0	8.6	6.8	ND	2.1	ND	2.2
21.0	8.6	6.8	ND	3.2	ND	ND
22.0	8.6	6.8	ND	3.7	ND	1.6
22.9	8.5	6.8	10.3	5.3	ND	1.4
23.7	8.5	6.8	ND	2.1	ND	1.9
24.5	8.5	6.8	ND	ND	ND	2.2
25.1	8.4	7.0	ND	ND	ND	1.1
26.0	8.4	6.9	ND	ND	ND	2.1
26.9	8.4	6.9	ND	ND	ND	1.6
27.8	8.6	6.9	ND	ND	ND	0.9
28.2	9.0	6.9	ND	ND	ND	ND
28.5	8.6	6.9	ND	6.5	ND	1.3
28.6	8.4	6.9	ND	6.3	ND	1.8
28.6	8.6	6.9	ND	5.1	ND	0.92
28.9	9.2	6.9	ND	2.3	ND	1.3
29.7	9.3	6.9	ND	10.2	22	2.5

Table A2.2 Cd, Cr, Se, and Ag concentrations from CLT on fly ash.

Fly Ash Column Leach Test Results				
		Concentration (mg/L)		
PVF	**Cd**	**Cr**	**Se**	**Ag**
0.27338	3.76	60.24	32.38	5.84
0.7605	4.63	62.93	30.07	5.35
1.24	2.99	42.64	30.41	5.39
1.8593	2.81	42.23	24.62	3.95
2.5902	1.37	17.23	15.74	3.61
3.3084	1.3	15.13	10.17	3.54
4.0036	2.08	14.45	8.09	1.8
4.9034	1.07	7.23	3.86	1.86
6.0311	0.37	14.26	2.76	0.5
7.2444	0.39	3.21	2.62	0.4
8.3886	0.73	3.45	0.96	0.33
9.5244	0.34	2.95	0.73	0.61
10.719	0.63	0.28	0.57	0.28
11.887		0.32		0.32

Table A2.3 pH, Cd, Cr, Se, and Ag concentrations from CLT on foundry sand.

Foundry Sand Column Leach Test Results

Est PVF	pH	Concentration (μg/L)			
		Cd	Cr	Se	Ag
0.14	8.4	32.9	ND	ND	3.1
0.21	8.5	1.2	ND	ND	1.7
0.32	8.5	1.2	ND	ND	4.4
0.39	8.5	1.4	ND	ND	1.7
0.59	8.4	ND	ND	ND	ND
0.79	8.4	ND	ND	ND	2
1.03	8.4	ND	ND	ND	4.2
1.11	8.4	ND	ND	ND	2.7
1.25	8.5	ND	ND	ND	6.1
1.35	8.6	ND	ND	ND	ND
1.41	8.7	ND	ND	ND	ND
1.58	8.1	9.2	ND	ND	1.2
1.58	8.5	ND	ND	ND	6.7

Table A2.4 pH, Cd, Cr, Se, and Ag concentrations from CLT on foundry slag.

Foundry Slag Column Leach Test Results

Est PVF	pH	Influent pH	Concentration (μg/L) Cd	Cr	Se	Ag
0.0						
0.0	7.1	6.84				
0.2	7.1	6.84	ND	1790	ND	ND
0.3	7.4	6.84				
0.3	7.3	6.84	ND	3740	ND	ND
0.4	7.3	6.84				
0.5	7.3	6.84	ND	5460	ND	ND
0.5	7.3	6.84				
0.6	7.4	6.84	ND	6530	ND	ND
0.7	7.5	6.84				
0.8	7.5	6.84	ND	5830	ND	ND
0.9	7.5	6.84				
0.9	7.5	6.84	ND	4690	ND	ND
1.4	8.6	6.84	ND	3220	ND	2.4
1.5	8.5	6.84				
1.5	8.7	6.84	ND	2250	ND	2
1.6	8.9	6.84	ND	2050	ND	1.6
2.3	9.2	6.84				
2.4	9.3	6.84	ND	1520	ND	ND
2.8	9.4	6.89				
2.9	9.4	6.89	ND	1060	ND	ND
3.2	9.5	6.87				
3.6	9.6	6.88	ND	640	ND	ND
3.8	9.5	6.9				
3.9	9.2	6.89	ND	525	ND	ND
4.1	9.5	6.91	ND	553	ND	ND
4.4	9.6	6.93				
4.8	9.6	6.93	ND	482	ND	ND
5.3	9.6	6.9	ND	246	ND	ND
5.8	9.7	6.85	ND	165	ND	ND
6.2	9.3	6.93				
6.7	9.4	6.92	ND	161	ND	ND
7.2	9.6	6.68				
7.6	9.7	6.63	ND	118	ND	1.3
8.2	9.6	6.67				
8.6	9.7	6.67	ND	113	ND	ND
9.1	9.7	6.79				
9.6	9.7	6.78	ND	130	ND	ND
10.0	9.7	6.72				
10.5	9.7	6.7	ND	91.1	ND	ND
11.0	9.8	6.68				
11.8	9.8	6.67	ND	93	ND	ND
12.6	9.8	6.7	ND	85.7	ND	ND
13.1	9.8	6.67				
13.8	9.8	6.66	ND	55.7	ND	ND
14.4	9.8	6.66	ND	52.6	ND	ND

Est PVF	pH	Influent pH	Concentration (μg/L)			
			Cd	Cr	Se	Ag
15.7	9.8	6.67	ND	71.6	ND	ND
16.3	9.8	6.64	ND	77.7	ND	ND
17.0	9.9	6.61				
17.6	9.7	6.64	ND	38.3	ND	ND
18.4	9.6	6.83	ND	90	ND	ND
19.2	9.7	6.83				
19.8	9.7	6.83	ND	31.3	ND	ND
20.7	9.7	6.83	ND	45	ND	ND
21.7	9.5	6.83	ND	57.2	ND	ND
22.7	9.4	6.83	ND	52.2	ND	ND
23.6	9.6	6.83	ND	70.7	ND	ND
24.2	9.6	6.83				
25.0	9.6	6.83				
25.6	9.6	6.95	ND	37.9	ND	ND
26.5	9.5	6.88	ND	37.6	ND	ND
27.5	9.5	6.9	ND	46.1	ND	ND
28.5	9.4	6.9	ND	37.5	ND	ND
28.7	8.6	6.94	ND	17.1	ND	16.8
29.0	8.8	6.94	ND	95	ND	ND
29.1	8.5	6.94	ND	89.9	ND	ND
29.1	8.5	6.94	ND	91.5	ND	ND
29.6	9.0	6.87	ND	29.1	ND	ND
30.3	9.4	6.87	ND	177	ND	ND

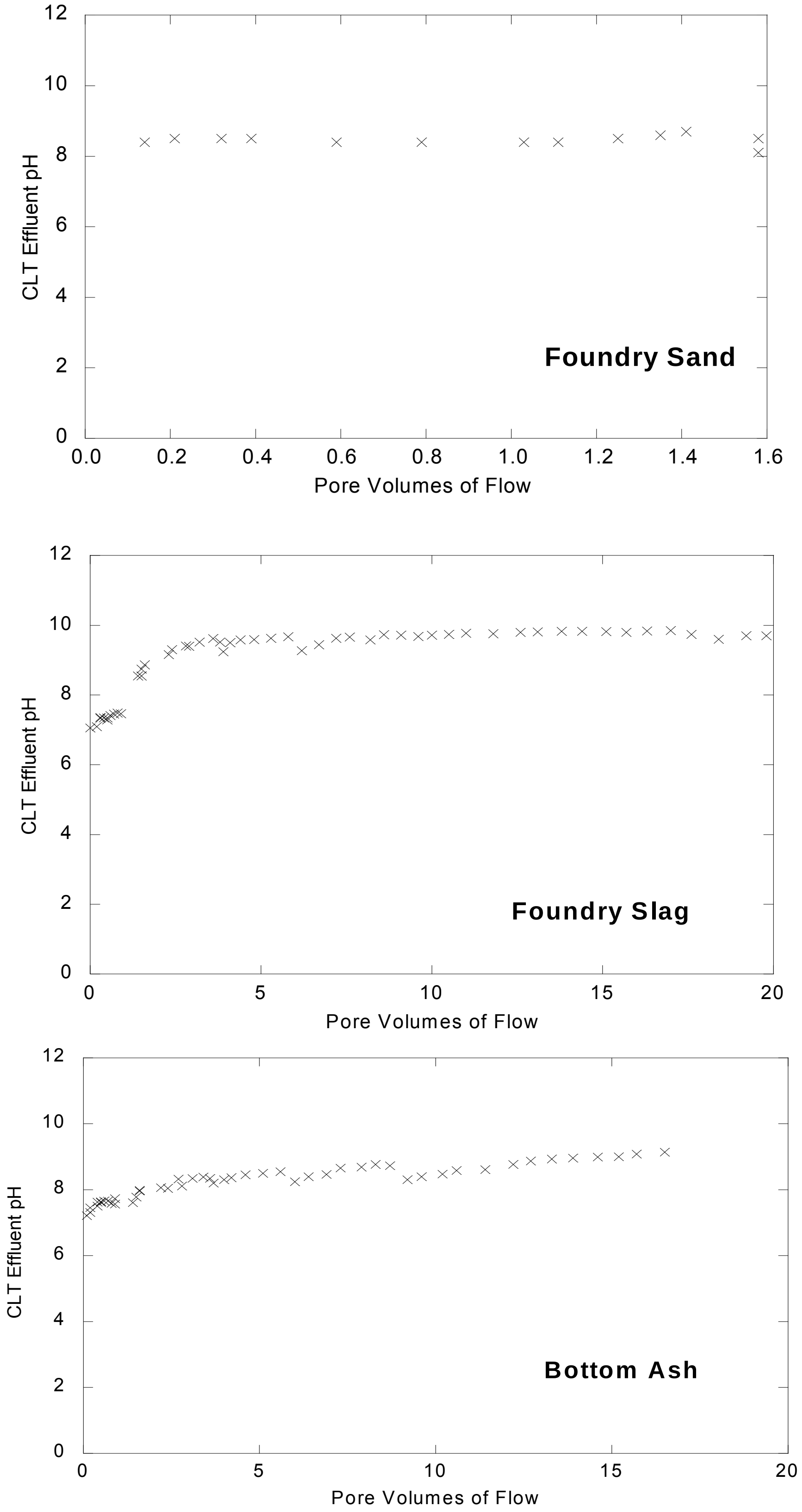

Fig. A2.1 pH versus PVF for CLTs on foundry slag, foundry sand, and bottom ash.

WATER LEACH TEST RESULTS

Table A3.1 **pH, Cd, Cr, Se, Ag, Fe, and Pb concentrations from WLTs on foundry sand, foundry slag, bottom ash, fly ash alone, and fly-ash-stabilized soil.**

Material	WLT pH and Concentration (μg/L)						
	Cd	**Cr**	**Se**	**Ag**	**Fe**	**Pb**	**pH**
Foundry Sand	0.3	<1.0	<10	<2.5	430	8	9.0
Foundry Slag	0.2	<1.0	<10	<2.5	48.3	12	10.7
Bottom Ash	<0.2	1.1	32.5	<2.5	-	-	10.3
Fly-Ash-Stabilized Soil	0.6	46	16.2	1.8	-	-	11.0
Fly Ash Alone	0.7	95	26	2.2	-	-	11.8

MONITORING WELLS

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Well Location: 20 ft South of STH 60, 50 ft West of Dettman Rd
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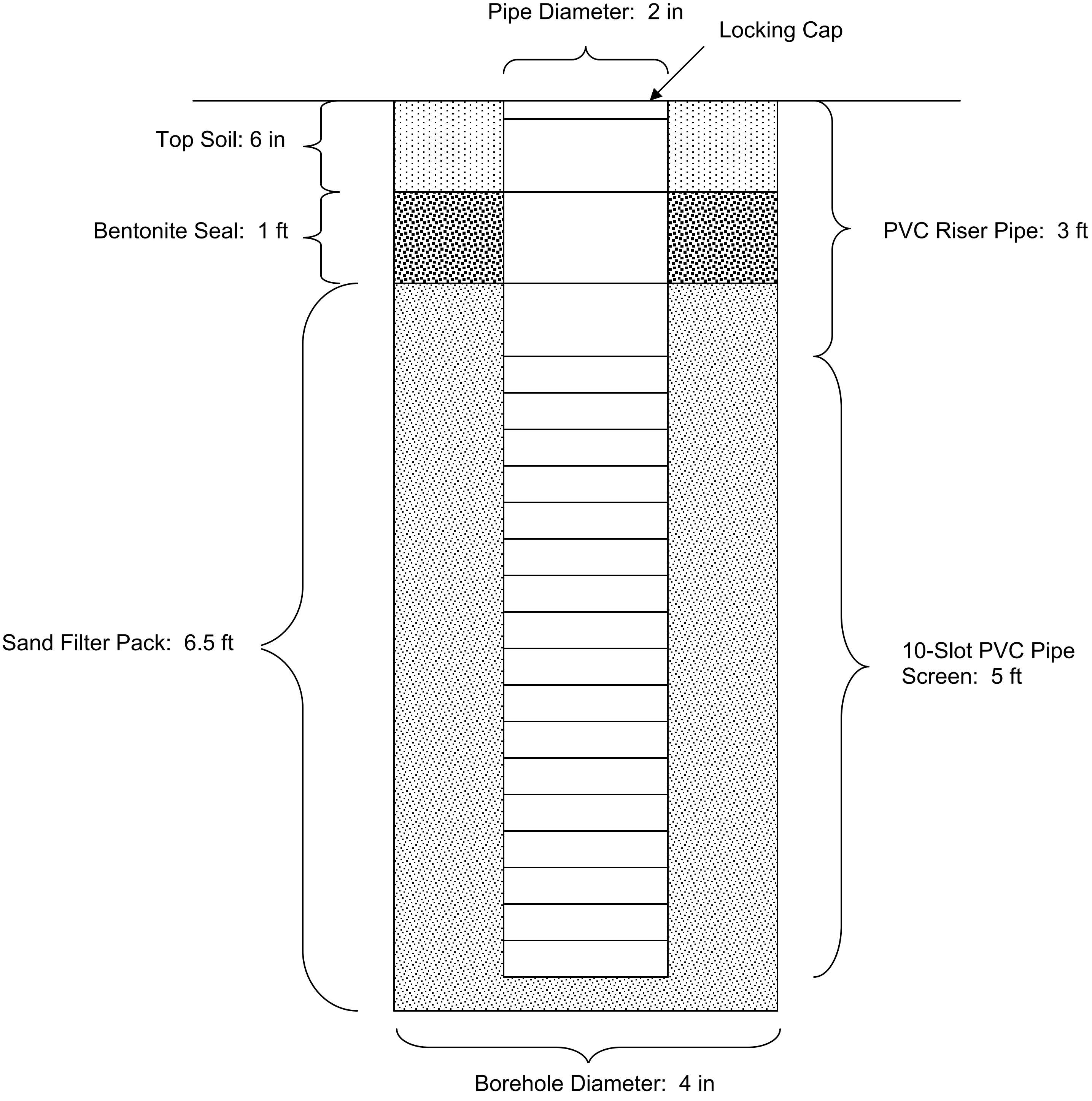
Installation Date: 1/16/04



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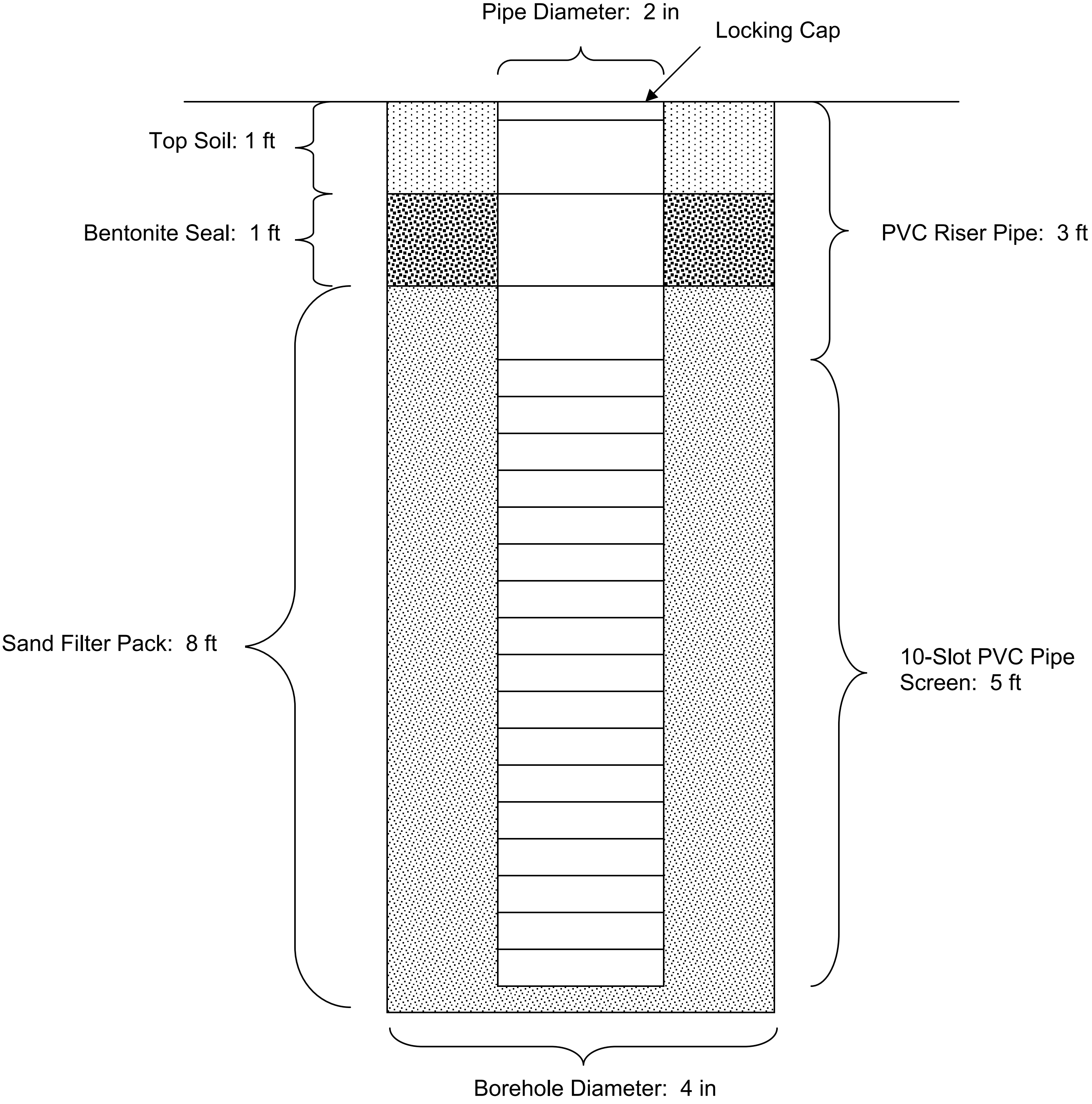

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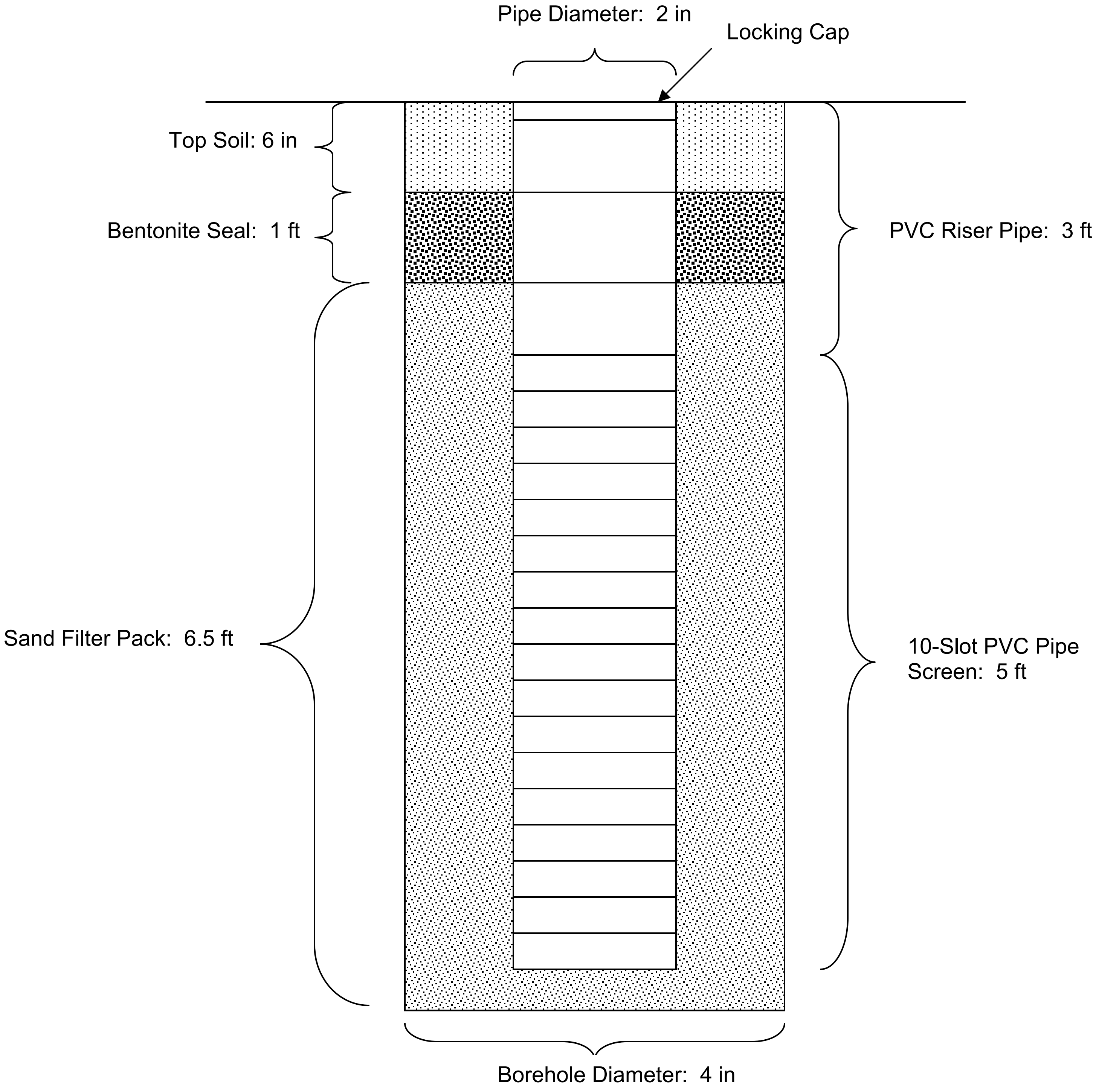

Well Profile:

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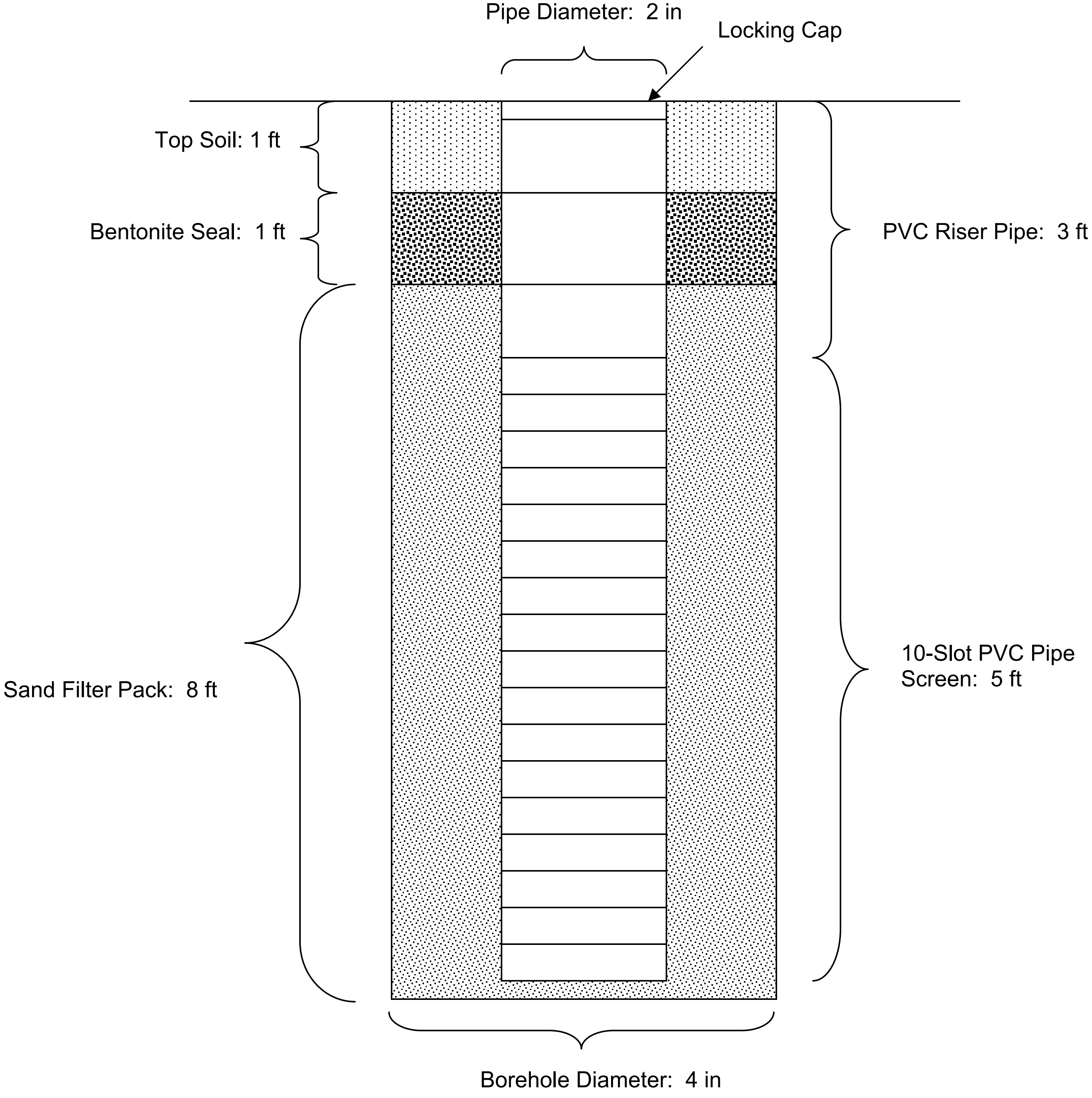

Well Profile:

Well ID: FA #1
Well Location: 20 ft South of STH 60, 350 ft East of Dettman Rd
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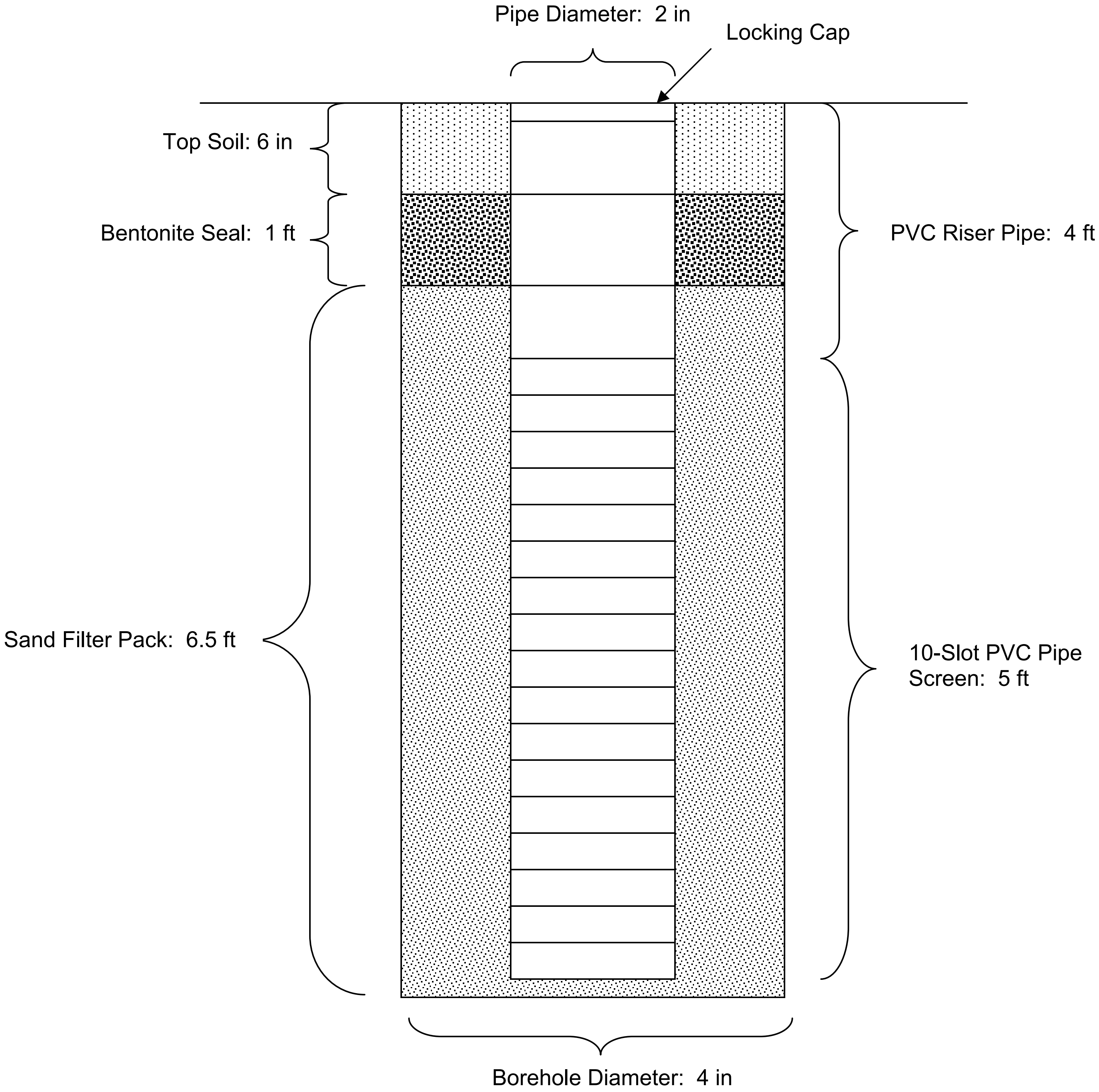
Installation Date: 1/16/04



Well Profile:

Well ID: FA #2
Well Location: 20 ft North of STH 60, 350 ft East of Dettman Rd
UTM Coordinates: INSERT
Installation Date: 10/27/03