Leaching from Roadways Stabilized with Additive Coal Combustion Products (CCPs): Data Assessment and Synthesis

By

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Leaching from Roadways Stabilized with Additive Coal Combustion Products (CCPs): Data Assessment and Synthesis

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ABSTRACT

Approximately 37% of the electrical power used in the United States is generated by coal-fired power plants. Air pollution control systems installed on coal-fired power plants collect solid byproducts of coal combustion, which are commonly referred to as coal combustion products (CCPs). Common CCPs include fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) residuals. Disposing CCPs in landfills or similar waste containment facilities is costly and land intensive, and many CCPs have useful engineering properties. Consequently, CCPs are often used beneficially in other products or applications, most notably as construction materials. Beneficial use of CCPs has many positive benefits in the context of sustainability including an annual reduction in greenhouse gas emissions by 11 million tons, fossil fuel consumption by 17 TJ, and water consumption by 121 GL, amounting to more than $11 billion (US) in total economic benefits.

Field water quality data collected from roadways where fly ash or bottom ash was used as embankment fill or as a stabilizing agent in the base or subgrade was assessed for any potential risk of ground water and surface water trace element contamination. Trace element concentrations (e.g. As, Cd, etc.) were obtained for seven roadways in Minnesota, Wisconsin, Indiana, and Georgia, spanning the applications of fly ash base and subgrade stabilization, fly ash fill, and bottom ash fill.

Direct assessments for field site water quality were conducted to provide a conservative evaluation of the risk of contaminating surface water and ground water with trace elements leached from roadway substructure applications using fly or bottom ash. Field site water quality data was directly compared to federal and state drinking and surface water quality limits. Elements evaluated were categorized as imposing “no risk” when trace element concentration profiles were below water quality limits. When elemental concentrations from a roadway sections constructed with fly ash or bottom ash were not statistically different from concentrations eluted from control sections (constructed without fly ash or bottom ash) the element was categorized as imposing “no additional risk” relative to that imposed by a roadway constructed using conventional materials. Water quality at the Indiana and Georgia sites was characterized as no risk or no additional risk imposed by leached trace elements from fly ash fill in embankments as compared to embankments constructed with conventional fill materials. Only up to 6 of 17 elements required further evaluation at the Minnesota and Wisconsin field sites.

Elements requiring further evaluation were assessed indirectly to conservatively assess predicted field concentrations at a point of compliance (i.e., edge of right-of-way) 20 m away from the centerline of the roadway ($C_{POC@20}$). Predicted trace elemental concentration below water quality limits were categorized as imposing “no predicted risk.” Field concentration data and

other field parameters were inputs for WiscLEACH hydrologic and transport modeling software. Conservative assumptions built in and applied to WiscLEACH included taking the maximum observed field concentration as the input concentration and assuming no reactions (chemical or biological) or sorption takes place. The assumptions are conservative because they create a scenario that results in higher values of $C_{POC@20}$ than are likely to occur. Assumptions are reasonable because simulation with less conservative inputs resulted in $C_{POC@20}$ lower by one order of magnitude, which is significantly low on the scale of observed C_{POC} (1 to 0.1 μg/L). Water quality at the Minnesota and Wisconsin sites requiring further investigation were characterized as no predicted risk, resulting in the characterization of Minnesota and Wisconsin sites as no risk, no additional risk, and no predicted risk imposed by trace elements leached from fly ash stabilization or bottom ash fill roadway substructures, as compared to roadways constructed with conventional construction materials.

The reduction factor for each element at each site was calculated by dividing the initial concentration by the predicted concentration at the point of compliance to provide site specific context for quick estimation of potential concentrations to be realized at a point of compliance given the element concentration at the base of the byproducts layer. The reduction factor can also be used to estimate the allowable initial concentration given a maximum allowable concentration at a point of compliance. (e.g. water quality limits). The minimum RF of all roadways was 46, meaning the initial elemental concentrations expected at the base of the byproducts layer at levels equal to or below 46 times the water quality limit are predicted to impose no additional risk where the groundwater table was at least 1 m below the ground surface. The reduction factor can be applied to similar roadways, however roadways with different field conditions than evaluated in this study (especially those with a thicker stabilized layer or groundwater that is closer to the base of the pavement structure) should be evaluated to ensure eluted trace element concentrations meet the water quality standards at a point of compliance.

Overall, the use of fly ash stabilization, fly ash fill, and bottom ash fill in roadway applications described in this study do not impact ground water and surface water quality making these beneficial reuse applications suitable with respect to trace element leaching based on obtained water quality data. Water quality data used in this study spans seven locations in four states, three substructure applications (fly ash stabilization, fly ash fill, and bottom ash fill) and 19 monitoring points and many years of monitoring (some more than a decade). Thus, it represents a substantial database to make inferences. Conclusions and RF can be applied to similar roadways, however roadways with different field conditions than evaluated in this study (especially those with a thicker stabilized layer or groundwater that is closer to the base of the pavement structure) should be evaluated using the analytical procedure provided herein to ensure eluted trace element concentrations meet the water quality standards at a point of compliance. These applications are indicated to be low risk and should not be prohibited by future regulations regarding the beneficial reuse of CCPs.

Keywords

Coal combustion products, CCP, fly ash, bottom ash, additive roadway applications, roadway substructures, subgrade, subbase, base course, embankment fill, trace element leaching

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CHAPTER 1

Approximately 37% of the electrical power used in the United States is generated by coal-fired power plants [1]. Air pollution control systems installed on coal-fired power plants collect solid byproducts of coal combustion, which are commonly referred to as coal combustion products (CCPs). Common CCPs include fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) residuals. Disposing CCPs in landfills or similar waste containment facilities is costly and land intensive, and many CCPs have useful engineering properties [2, 4, 6, 14, 15, 17]. Consequently, CCPs are often used beneficially in other products or applications, most notably as construction materials [2, 4, 6, 9, 10, 11, 12, 13, 14, 15, 16, 17]. Beneficial use of CCPs has many positive benefits in the context of sustainability including an annual reduction in greenhouse gas emissions by 11 million tons, fossil fuel consumption by 17 TJ, and water consumption by 121 GL, amounting to more than $11 billion (US) in total economic benefits [1, 2, 3, 4, 5, 6].

Fly ash comprises 52% of the CCPs generated today and currently is reused at a non-adjusted rate of 37% (Figure 1-1) [7], and adjusting for missing data the reuse rate increases to 43% [2]. Increasing the rate of fly ash reuse can enhance sustainability while reducing disposal costs. Most fly ash is used in matrix applications as a partial replacement for Portland cement in concrete, and most concrete applications today include fly ash in the mixture [8]. Research has shown that roadway materials stabilized with fly ash have superior mechanical properties and durability [9, 10, 11, 12, 13, 14, 15, 16]. Base, subbase, and subgrade layers incorporating fly ash have increased strength and stiffness, which results in roadways that last longer and need less maintenance, reducing life cycle impacts and costs and consequently increasing sustainability [2, 4, 6, 14, 15, 17]. Moreover, in many roadway cases, construction costs are lower and construction is more expedient when CCPs are employed [16]. However, fly ash use in matrix applications as a partial replacement for Portland cement in concrete, concrete products, and grout is the most common CCP use[8]. Roadway additive applications such as stabilization of subgrade and base course are less common uses for fly ash (i.e. comprise 7% of fly ash end use) [8], and present an opportunity for increasing reuse of CCPs.

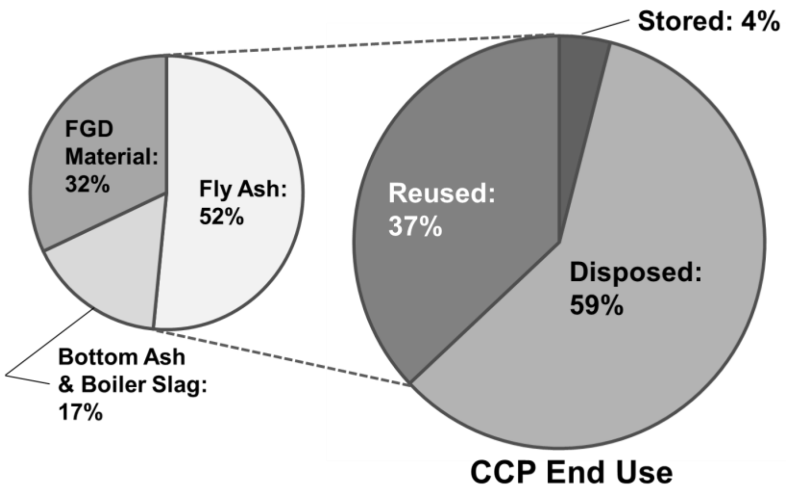


Figure 1-1
Uses of CCPs as identified by EIA [7].

This study assesses the potential risk of contaminating ground water and surface water by trace elements constituents leaching from fly ash and bottom ash used in additive roadway applications. Field water quality data was evaluated from roadways where these fly ash and bottom ash were used in bases, subbases, subgrades, and as fill. Trace element concentrations from the leachate of these roadways were compared directly to federal and state water quality standards to provide a conservative evaluation of the risk of contaminating surface water and ground water when using fly ash or bottom ash in roadway substructure applications. Assessments of the impacts on groundwater quality were also conducted by predicting trace element concentrations at a point of compliance (POC) using field conditions as inputs to hydrologic modeling software.

Background

Fly ash is a residual powdery material created through the combustion of coal and collected from the flue gas of coal-fired electric generating plants. Fly ash is comprised of silt-size spherical particles composed primarily of silica and contains some trace elements (e.g., heavy metals) [18,19].

Standards such as AASHTO M and ASTM C 618 are often used to classify fly ash into Class C and Class F ashes. Class C fly ashes contain at least 50% oxides, are produced form sub-bituminous coal, and are typically brown and tan in color [18, 20, 22, 23]. Class F fly ashes contain at least 70% oxides, are from bituminous and lignite coal, and are typically grey and black in color [20, 23, 24]. Class F fly ash is more common than Class C fly ash because use of sub-bituminous coal has been encouraged by the 1990 Amendments to the Clean Air Act to help meet more stringent sulfur emission standards [5]. Class C fly ashes often are self-cementing whereas Class F fly ashes generally are not self-cementing. There are also fly ashes not conforming to these specifications that are self-cementing [25].

Class F fly ash is a pozzolan that becomes cementitious when combined with water and an activator (e.g., lime, Portland cement, or kiln dust) [18, 20, 21]. Class C fly ashes are self-cementing when hydrated. Therefore fly ash is used in many applications such as: feed stock for production of Portland cement, cementing agent for concrete in lieu of (or in addition to) Portland cement, mineral filler for hot-mix asphalt, structural and embankment fill, stabilizing or solidifying agent for soft soils, cementing and flow agent for flowable fill, and stabilizing agent for roadway bases, subbases, and subgrades [18].

Bottom ash is comprised of particles too large to be carried in the flue gas during the combustion of coal. Most bottom ash is comprised of broadly graded angular particles ranging in size from fine sand to fine gravel. Many bottom ashes have a porous surface structure, which results in lower specific gravity that can be beneficial in lightweight concrete applications. The porous surface can make bottom ash less durable than conventional mineral aggregates [18].

Bottom ash is commonly employed as: structural and embankment fill, aggregate in roadway bases and subbases, feedstock in production of Portland cement, aggregate in lightweight concrete products, and as traction control material in regions with snow and ice [18].

Field Sites

Water quality data for seven roadways employing fly ash or bottom ash in additive roadway applications came from the Indiana (56^{th} Street Overpass) and Georgia (Southwest Rome Bypass) state Department of Transportation (DOT) as well from the Recycled Materials Resource Center (RMRC) at the University of Wisconsin-Madison, which had data for roadways in Minnesota (MnROAD and Waseca) and Wisconsin (STH60, US12, and Scenic Edge). Characteristics of these sites are summarized in Table 1-1 and locations of the sites are shown in Figure 1-2. Trace elements monitored at each field site is summarized in Table 1-2. Roadways employed fly ash for stabilization of subgrade (US12, Scenic Edge, STH60), stabilization of recycled pavement material (RPM) subbase (MnROAD and Waseca), or for embankment fill (56^{th} Street Overpass and Southwest Rome Bypass) (Table 1-1). The roadway at STH60 also had a separate road section constructed with bottom ash as subbase and there were control sections at some field sites where no fly ash or bottom ash was used (Table 1).

Roadways employed either pan lysimeters located at the base of the stabilized layer (STH60, US12, Scenic Edge, MnROAD, and Waseca) or monitoring wells located near the roadway (Southwest Rome Bypass), and sometimes a combination (56^{th} Street Overpass) to obtain water quality data (Table 1-1). Additionally, some sites had multiple water monitoring points, including control sections where only conventional material was used.

Figure 1-2
Locations of roadways were field data were available for use in this study [26, 27, 28, 29].

Table 1-1
Characteristics of roadways using fly ash and bottom ash.

CCP	Application	Field Site	Water Monitoring Device	Stabilized Layer Thickness	Ash Percentage & Source	Ash Classification	Control	Construction End Date	Monitoring Period
Fly Ash	Subgrade Stabilization	STH60	Lysimeter	0.3 m	12% Columbia Plant	Class C in ASTM C 618 and AASHTO M 295	Dolostone Subbase	August 2000	9/14/00 to 8/20/12
		US12	Lysimeter	0.3 m	12% Columbia Plant	Class C in ASTM C 618 and AASHTO M 295	Un-Stabilized Subgrade	October 2004	11/10/05 to 8/20/12
		Scenic Edge	Lysimeter	0.3 m	10% Columbia Plant	Class C in ASTM C 618 and AASHTO M 295	None	October 2000	02/27/06 to 03/12/10
	RPM Base Stabilization	MnROAD	Lysimeter	0.2 m	14% Riverside 8 Plant	Off-specification ash (>5% carbon content)	RPM Base	August 2007	09/11/07 to 06/30/12
		Waseca	Lysimeter	0.15 m	10% Riverside 7 Plant	Class C in ASTM C 618 and AASHTO M 295	None	August 2004	07/07/05 to 06/20/08
	Embankment Fill	Southwest Rome Bypass	Monitoring well	3.0 – 3.7 m	Fly Ash 100% Yates Plant	AASHTO Soils Classification A-4	Sand, silt, clay, and large rock fill material	June 2009	09/01/09 to 07/26/11
		56^{th} Street Overpass	Monitoring Well and Lysimeter	5 m**	100% E.W. Stout Generating Station	Indiana Environmental Type III Material	None	June 1995	*06/01/95 to 3/05/96
Bottom Ash	Subbase Fill	STH60	Lysimeter	0.6 m	100% Columbia Plant	USCS: = SW; AASHTO = A-3	Dolostone Subbase	August 2000	9/14/00 to 8/20/12

*Date reflects samples taken post embankment construction
**Maximum thickness of embankment

Table 1-2
Trace elements monitored at each field site.

CCP	Fly Ash							Bottom Ash
Application	Subgrade Stabilization			RPM Base Stabilization		Embankment Fill		Subbase Fill
Elements	STH60-FA	US12	Scenic Edge	MnROAD	Waseca	SWRB	56^{th} St. Overpass	STH60-BA
Ag	■	■	■	■	■	■		■
Al	■	■	■	■			■	■
As	■	■	■	■	■	■		■
B	■	■	■	■	■		■	■
Ba	■	■	■	■	■	■		■
Be	■	■	■	■	■	■		■
Cd	■	■	■	■	■	■	■	■
Co	■	■	■	■	■		■	■
Cr	■	■	■	■	■	■	■	■
Cu	■	■	■	■	■	■	■	■
F				■		■		
Fe	■	■	■	■			■	■
Hg					■	■		
Mn	■	■	■	■	■		■	■
Mo	■	■	■	■	■		■	■
Ni	■	■	■	■	■	■	■	■
Pb	■	■	■	■	■	■	■	■
Sb	■	■	■	■	■	■		■
Se	■	■	■	■	■	■		■
Sn	■	■	■	■	■			■
Sr	■	■	■	■	■			■
Ti	■	■	■	■				■
Tl	■	■	■	■	■	■		■
V	■	■	■	■	■	■		■
Zn	■	■	■	■	■	■	■	■

Key: Grey cells denote elements monitoring data was collected for at roadways.

Roadway Subgrades Stabilized with Fly Ash

The STH60 field site is located along a 0.1-km stretch of State Trunk Highway 60 (STH60) near Lodi, WI (Figure 1-2). The site contained several test sections employing industrial byproducts in lieu of earthen construction materials. The section evaluated in this study employed subgrade stabilized in place with fly ash (STH60-FA) and subbase constructed with bottom ash (STH60-BA) [17, 20]. The US12 site is located along a 0.6-km section of US Highway 12 near Cambridge, Wisconsin (Figure 1-2). At the US12 field site one lysimeter was located at the west end (US12-W) and the other at the east end (US12-E) of the site [27, 28, 30]. The Scenic Edge field site is located along a 200-m stretch of residential street in the Scenic Edge neighborhood in Cross Plains, Wisconsin [9, 20, 27, 28, 30, 31].

Soft soil subgrade was stabilized to a depth of 0.3 m at all Wisconsin roadways (STH60, US12, and Scenic Edge) with 10% to 12% class C fly ash by weight obtained from Alliant Energy's Columbia Power Station in Portage, WI. Pan lysimeters ranging in size from 3.50 m x 4.75 m to 3.00 m x 3.00 m were installed beneath each stabilized roadway section [9, 17, 20 , 26, 27, 28, 30, 31, 32, 33, 34]. A typical lysimeter profile is provided in Figure 1-3. Lysimeters were lined with textured linear low density polyethylene geomembrane and overlain by a geocomposite drainage layer comprised of a geonet sandwiched between two non-woven geotextiles. Water collecting in the drainage layer in each lysimeter was routed to a 120-L collection tank via PVC pipe [26, 32].

Control lysimeters installed with conventional construction methods and materials (i.e., no fly ash) were constructed at most roadways (STH60, US12, and MnROAD). The STH60 field site contained a control section composed of an 0.84-m-thick layer of crushed dolostone subbase on top of the subgrade to ensure adequate support for the pavement (STH60-C). A control lysimeter was also installed beneath the centerline of the road near the west end of US12, where unstabilized subgrade was used in lieu of subgrade stabilized with fly ash (US12-C). Construction details for the roadways are provided in Figure 1-5 and the analytical and field sampling methods are summarized in Appendix A.

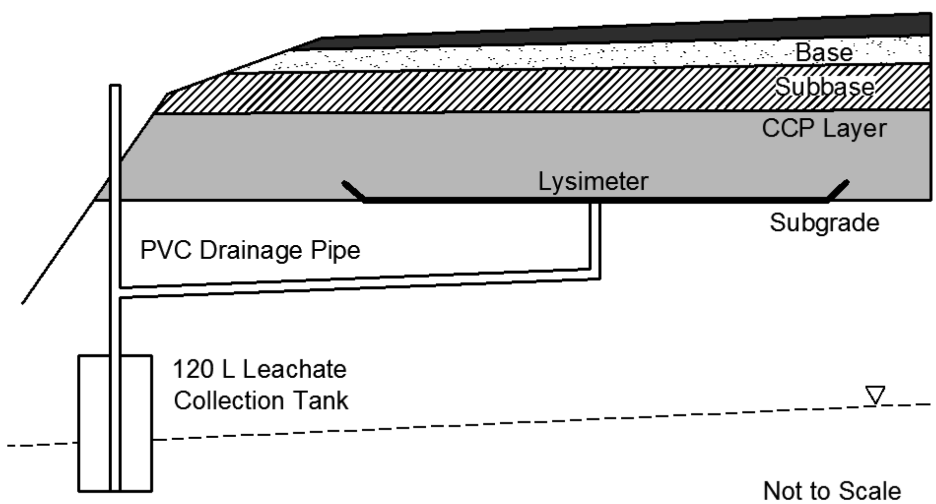


Figure 1-3
Typical lysimeter detail based on designs reported in O'Donnell [26] and Wen et al. [32].

RPM Roadway Bases Stabilized with Fly Ash

RPM base at both Minnesota roadways was stabilized to a depth of 0.15 m and 0.2 m with 10% to 14% fly ash by weight obtained from Excel Energy's Riverside Power Plant. At both sites the RPM was reclaimed on site and blended with fly ash using a road reclaimer. The MnROAD field site is located along a low-volume loop at the Minnesota Department of Transportation highway testing laboratory located adjacent to Interstate 94 between Albertville and Monticello, Minnesota and employed an off specification fly ash [27,28, 32, 33]. The Waseca field site is located at the intersection at 7th Street and 7th Avenue in Waseca, Minnesota and employed class C fly ash [34].

Pan lysimeters were installed directly beneath the stabilized roadways in a similar fashion as the Wisconsin sites (Figure 1-3). Two control lysimeters were installed at the MnROAD field site: one beneath an identical roadway profile but without fly ash stabilization (MnROAD-C1) and another beneath a conventional control where Class 5 crushed stone replaced RPM as base course (MnROAD-C2). The conventional control was not considered for this study since the potential leaching from RPM compared to conventional materials was beyond the scope of this study, but its field data is included in the database. Construction details for the roadways are provided in Figure 1-5 and analytical and field sampling methods are summarized in Appendix A.

Roadway Embankment Fills Employing Fly Ash

Both the Georgia and Indiana sites employed fly ash in embankment fill applications. The Georgia Southwest Rome Bypass (SWRB) site is a structural fill constructed with 31,000 Mg of fly ash from Georgia Power's Yates Plant in Newnan, GA (Table 1-1). The fill extends over a 70 m by 70 m section along the Southwest Rome Bypass located in Floyd County, Georgia and is 3-4 m thick. Earthen fill was placed around and over the fly ash, with 1.5 m placed on the surface and 1.5 m beneath a pavement placed over the fill (Figure 1-4). Details of the project site can be found in Southern Company Services, Inc. 2012 [35].

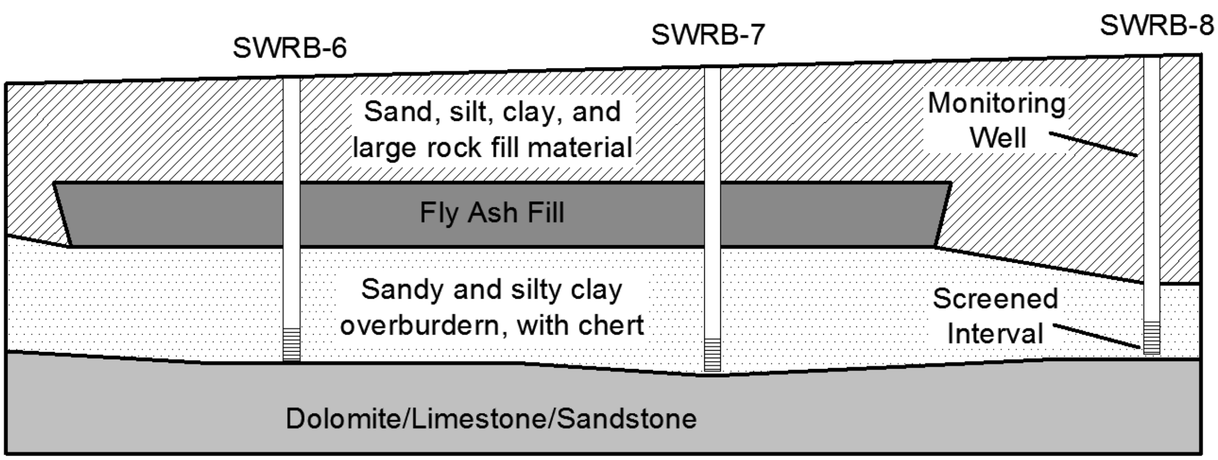


Figure 1-4
Southwest Rome Bypass construction details as reported in Southern Company Services, Inc. 2002 [35].

Twelve monitoring wells were installed to evaluate the potential impact of the fly ash on ground water. Four wells (SWRB-1 through SWRB-4) were sampled prior to construction to document background concentrations. SWRB-1 through SWRB-3 were abandoned after background conditions were defined. SWRB-6 and SWRB-7 are located beneath the footprint of the fly ash fill. The remaining monitoring wells (SWRB-5 and SWRB-8 through SWRB-12) are located around the perimeter of the fill. SWRB-5 was designated as the control because the well is located upstream of groundwater flow relative to the fly ash embankment. Construction details for the roadways are provided in Figure 1-6 and the analytical and field sampling methods are summarized in Appendix A.

Indiana's 56th Street Overpass is a reconstructed overpass across I-465W in Indianapolis, IN. The reconstruction involved renovating two existing earth embankments using Indiana Environmental Type III material Fly Ash (ponded) sourced from the E.W. Stout Generating Station, Ash Pont No. 1, in Indianapolis [29]. A lysimeter was constructed under the entire span of the west embankment to analyze water quality (56th St. Overpass-L). A 0.3 m thick layer of sand was placed above the bottom clay encasement, along the 22.9 m length of the west embankment, which created a drainage layer for the collection of leachate [29]. This sand layer was sloped at 2% and connected to a 4 in. PVC SDR-35 perforated pipe with filter wrap. A 2082 liter underground storage tank was used to collect the leachate, of which the excess was allowed to overflow into the adjacent soil. The western embankment has a maximum ash thickness of 5 m, near the overpass bridge. Figure 1-5 depicts the embankment fill and the leachate collection system.

Monitoring wells were also installed, one in the west embankment (56th St. Overpass-W) and one in the east embankment (56th St. Overpass-E). No control lysimeter was constructed; however two pre-construction water samples were collected from each monitoring well. Construction details for the field site is provided in Figure 1-7 and the analytical and field sampling methods are summarized in Appendix A.

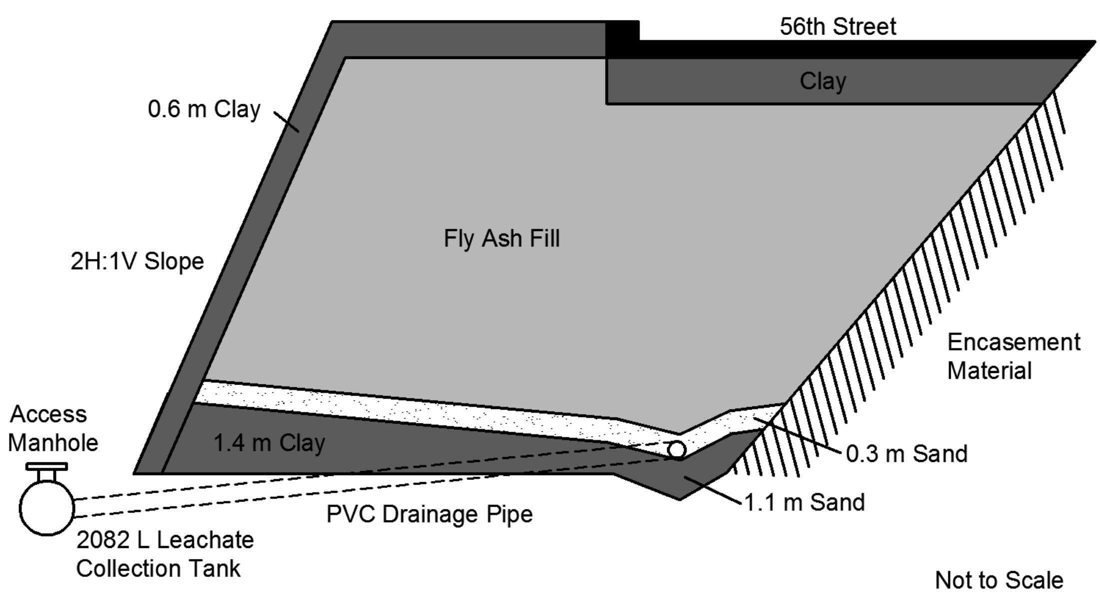


Figure 1-5
56th Street Overpass lysimeter detail based on designs reported in Alleman et al.[29].

Subbase Fill Employing Bottom Ash

The STH60 field site described in the Fly Ash section also contained one pan lysimeter beneath a section of the road where 0.6 m of bottom ash from a dry bottom furnace at Alliant Energy's Columbia Power Station was used as a subbase working platform between the soft subgrade and granular base course material. The control lysimeter described for STH60 in the Fly Ash section is also the control lysimeter that the STH60 bottom ash data was analyzed against (Figure 1-6). Construction and sampling details are the same for the STH60 bottom ash lysimeter as they are for the STH60 fly ash lysimeter. Construction details for STH60-BA sites are provided in Figure 1-7 and the analytical and field sampling methods are summarized in Appendix A.

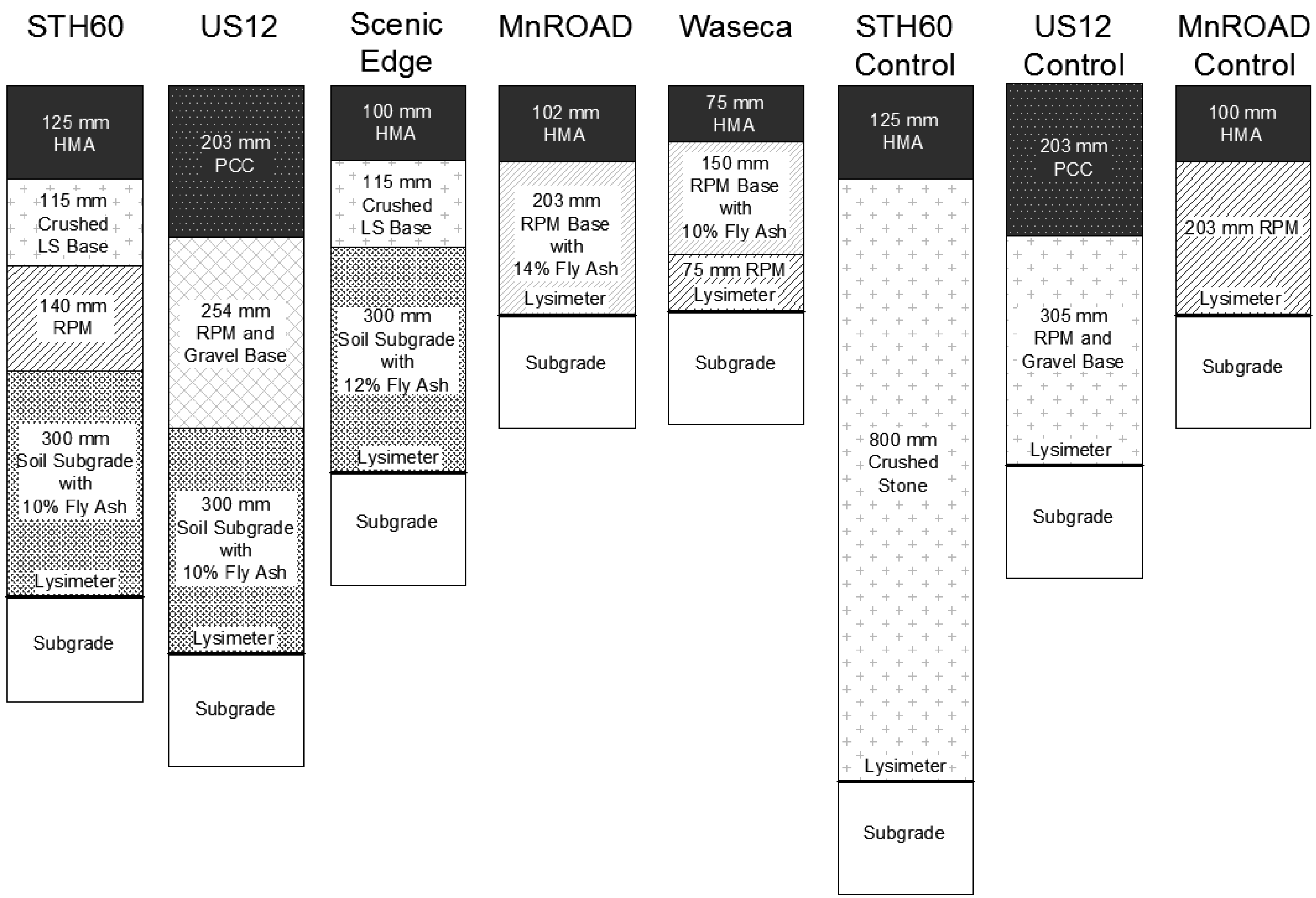


Figure 1-6
Construction profiles of stabilized fly ash roadways and control sites.

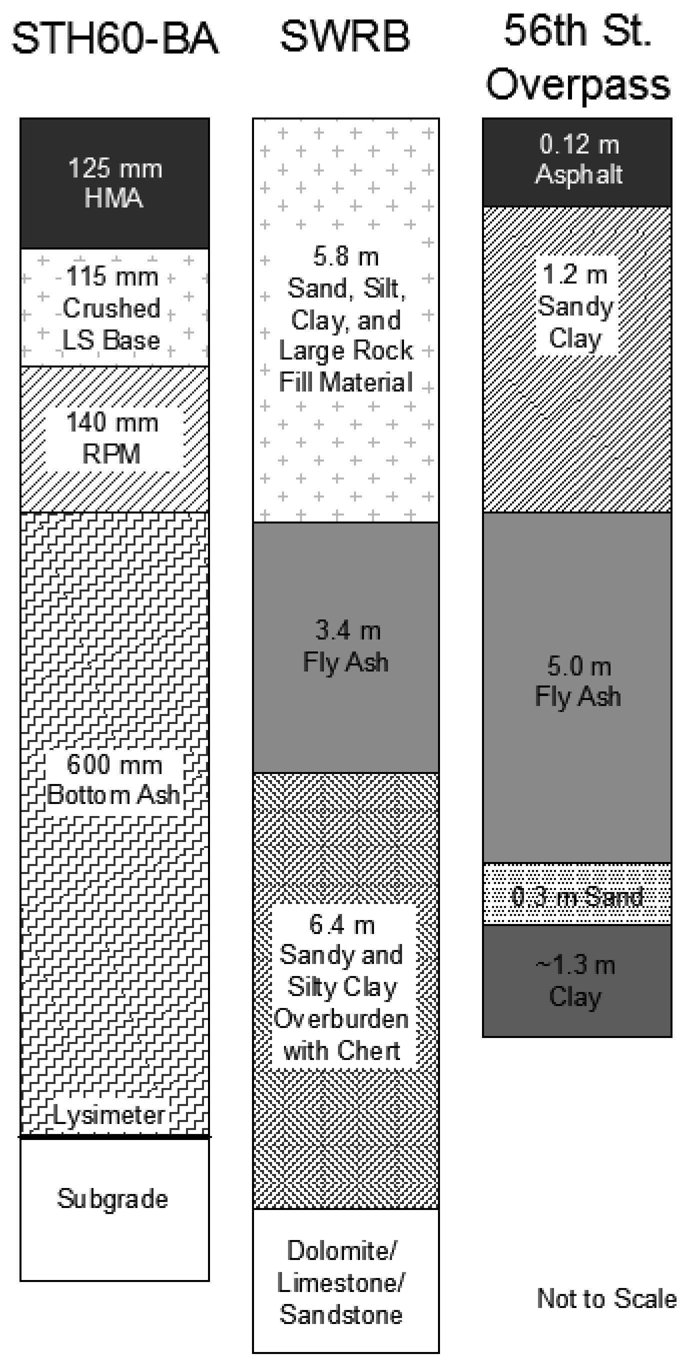


Figure 1-7
Construction profiles of fly ash and bottom ash fill roadways.

Methods

Data Evaluation

Data Quality and Availability Rating

Water quality data obtained from field sites was compiled into in a database and organized uniformly and consistently to ensure quality for analysis. The water quality data are organized by type of CCP used (e.g. fly ash, bottom ash) and application of the CCP (e.g., base fill, subgrade stabilization, etc.). Control data sets (i.e., from roadway sections constructed without CCPs) have also been included in the database and were subjected to the same quality assessment as the data from roadways with CCPs.

Each data set was thoroughly evaluated to ensure quality and reliability of the data. Data were rated for quality using criteria related to monitoring technique, sampling method, preservation, analysis, and data recording and evaluation (Table A-1). Scores were assigned based on the data quality criterion that was satisfied and the rankings of excellent, very good, good, and poor were assigned. Each field site received a quality rating of at least very good, except 56th Street overpass, which obtained a rating of good. 56th Street Overpass data was rated "good" due to lack of documentation of rate criteria.

Data availability was rated based on the frequency of sampling at a given site. Not all water quality data was collected directly after construction thus the maximum concentration may not have been realized in the datasets where this is the case. The data availability rating accounts for this by averaging the overall frequency of sampling and the frequency of sampling during the first year to create a composite data availability score that was then matched to a rating of excellent, good, or marginal. Most elements at each site obtianed a data availability rating of at least good. Data quality scores and ratings were included in the database to ensure the quality control and thus reliability of each data set is documented, and further information on the data evaluation is described in Appendix A.

Water Quality Limits

The apparent risk of trace element contamination imposed by using additive fly ash and bottom ash in roadway construction was evaluated through direct and indirect assessment according to the flow chart outlined in Figure 1-8.

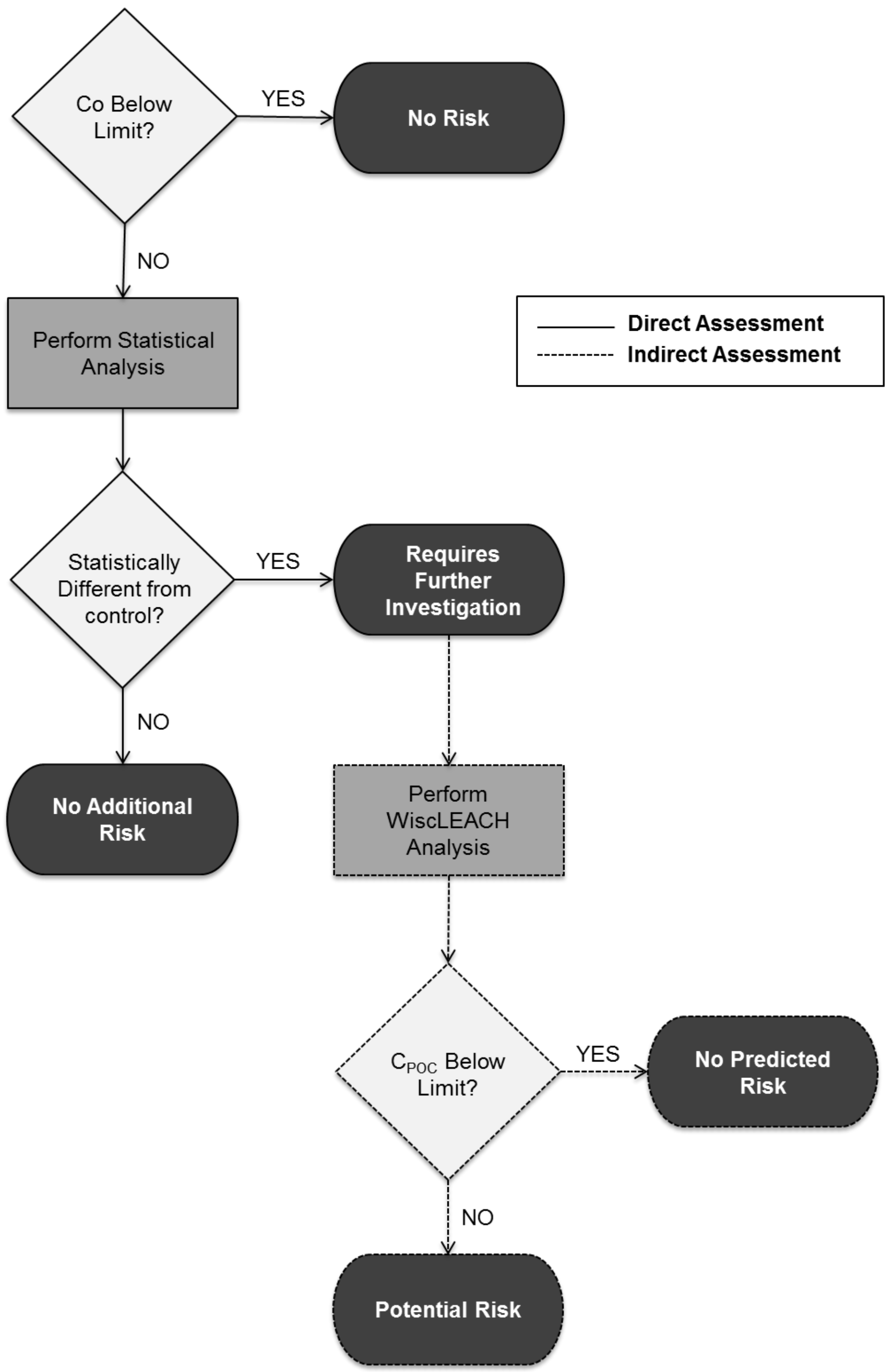


Figure 1-8
Flowchart depicting the process for categorizing the risk imposed by fly ash and bottom ash use in roadway construction based on the maximum trace element concentrations observed at roadway sites.

Water quality limits for trace elements were derived from drinking water limits and surface water limits. Federal drinking water quality limits as defined by the USEPA are referred to as maximum contaminant levels (MCLs) [38]. Most states also define MCLs that are the same as, or lower than, the federal MCLs. There are 13 trace elements that were assessed in this study that have MCLs (Table 1-3).

A summary of state and federal surface water standards is also shown in Table 1-3. Federally recommended water quality criteria for different surface water categories were established by the USEPA (United States Environmental Protection Agency) under Section 304(a)(1) of the Clean Water Act [40]. These non-enforceable criteria for freshwater aquatic life [38, 41] were used to assess the field data in the context of surface water quality from the perspective of federal criteria. State surface water criteria in Georgia, Minnesota, and Wisconsin were also considered (Table 1-3). Indiana does not have established water quality limits. Standards for freshwater acute aquatic life criteria were used for Georgia [42], Class 2a waters standards were used for Minnesota [43], and the acute toxicity criteria for cold waters were used for Wisconsin [44]. There are 13 elements that were assessed in this study that have surface water criteria.

Table 1-3
Federal and applicable state drinking water and surface water quality limits

Water Quality Limit	Drinking Water Limits (µg/L)					Surface Water Limits (µg/L)				
Authority	**Federal**	**IN**	**GA**	**MN**	**WI**	**Federal**	**IN**	**GA**	**MN**	**WI**
Ag	-	-	-	-	-	3.2	-	-	2	-
Al	-	-	-	-	-	-	-	-	748	-
As	10	10	10	10	10	340	-	340	360	340
Ba	2,000	2,000	2,000	2,000	2,000	-	-	-	-	-
Be	4	4	4	4	4	-	-	-	-	-
Cd	5	5	5	5	5	-	-	1	4.4	4.4
Co	-	-	-	-	-	-	-	-	-	-
Cr	100	100	100	100	100	570	-	336	1,803	1,803
Cu	1,300*	1,300*	1,300*	1,300*	1,300*	-	-	7	15	15
F	4,000	4,000	4,000	4,000	4,000	-	-	-	-	-
Hg	2	2	2	2	2	-	-	-	-	-
Ni	-	-	-	100	100	470	-	260	469	469
Pb	15*	15*	15*	15*	15*	65	-	30	107	107
Sb	6	6	6	6	6	-	-	-	-	-
Se	50	50	50	50	50	-	-	-	-	-
Tl	2	2	2	2	2	-	-	-	-	-
Zn	-	-	-	-	-	120	-	65	120	120

*Federal MCLs have not been set for copper (Cu) and lead (Pb), but concentrations of these elements are recommended not to exceed action levels (AL).
- Water quality limits do not exist for these elements.
Note: Indiana does not have surface water limits. For trace elements where the surface water criterion depends on hardness 100 mg/L $CaCO_3$ was assumed [43, 44, 45].

Direct Assessment

Direct assessments of water quality were made by evaluating whether observed trace element concentration (i.e. water quality data) exceeded state and federal surface and drinking water quality limits (Table 1-3). The direct assessment also evaluated if trace element concentrations were statistically different than the concentrations observed in the control lysimeters. Elements eluted from roadways utilizing fly or bottom ash were categorized as imposing “no risk” when the concentration profiles of each trace element were entirely below the water quality limit. Additionally, when elemental concentrations from a roadway constructed with fly ash were not statistically different from concentrations eluted from control sections, as determined by a paired-t test at the 5% significance level, the element was categorized as imposing “no additional risk” relative to that imposed by a roadway constructed using conventional materials. Elements falling into neither category required further investigation and were evaluated via indirect assessment at the point of compliance using WiscLEACH hydrologic transport modeling software.

The direct assessment provides a conservative assessment of risk for roadways utilizing lysimeters as the water sample collected directly beneath a roadway profile is not available for human consumption or for contact with biota in a surface water body. The direct assessment of trace element concentrations realized at the base of the roadway profile was especially conservative because dilution and attenuation will occur before any trace elements reach a point of compliance. Monitoring wells, on the other hand, provide trace element concentrations in the groundwater some distance away from the roadway layer.

Elements not falling into the “no risk” or “no additional risk” categories in the direct assessment required further evaluation and underwent an indirect assessment to take into consideration the dilution and attenuation via hydrologic transport modeling.

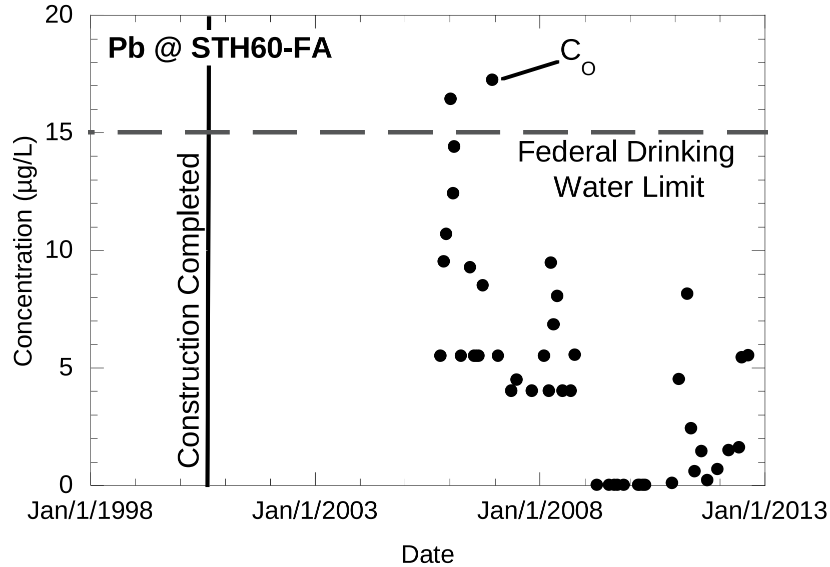
The water quality assessment did not take into account naturally occurring trace element concentrations. For instance, naturally occurring Arsenic is present at levels exceeding national drinking water quality limits in groundwater in the groundwater of some regions in Minnesota and Wisconsin [45]. The direct analysis of sites with lysimeters only compared leachate concentrations from the base of the roadway to water quality standards or to control lysimeter concentrations and thus ignored any risks imposed by existing trace element concentrations. The direct analyses of sites with monitoring wells, on the other hand, evaluated trace element concentrations in the groundwater and thus take into consideration background concentrations of trace elements. Any risk introduced from existing groundwater concentrations are eliminated by comparing monitoring well data to the control monitoring well or established background concentration (e.g. at the Southwest Rome Bypass site).

Indirect Assessment

Trace element concentrations that exceeded water quality limits or were elevated compared to the control were evaluated through an indirect assessment by modeling trace element concentrations at a point of compliance 20 m from the right-of-way of the roadways ($C_{POC@20}$) with WiscLEACH transport modeling software. The regulatory POC for water quality for many roadway applications is set 20 m from the roadway centerline to the edge of the right-of-way [40,

46. The resulting $C_{POC@20}$ was evaluated to ensure trace element concentration did not exceed state and federal surface and drinking water quality limits. Site specific conditions including the maximum observed trace element concentrations (C_O), roadway pavement and shoulder widths, layer thicknesses, depth to groundwater table, infiltration rate, hydraulic conductivities, porosities, and regional hydraulic gradient, which were used as inputs for WiscLEACH (Table 1-4).

Two representative trace element concentration profiles for lead (Pb) at STH60-FA and US12-W are shown in Figure 1-9. C_O is indicated in Figure 1-9 as the highest concentration observed in the profile. The federal drinking water limit and date in which the roadway construction was completed are also indicated in Figure 1-9 for reference. STH60-FA displays a decreasing, or first-flush, trend while US12-W does not appear to display any trend. In some cases such as that for STH60-FA illustrated in Figure 1-8, data was not collected directly after construction and the action maximum concentration may not have been realized. This uncertainty is accounted for in the data availability rating score assigned to each dataset.



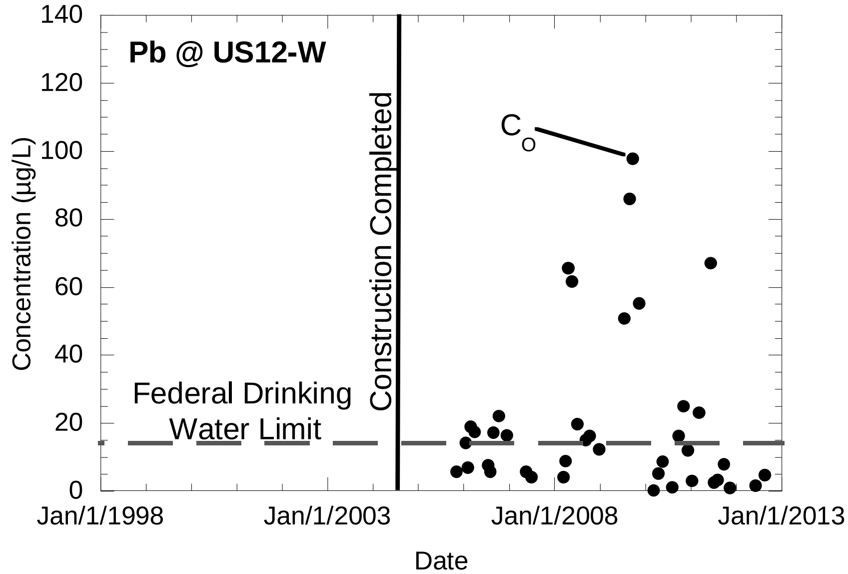


Figure 1-9
Field monitoring data examples to illustrate C_O selection.

WiscLEACH was developed specifically for evaluating the potential for impacts to ground water by industrial byproducts incorporated into a roadway [34, 46]. WiscLEACH follows the advective-dispersive-reaction-equation (ADRE) in one dimension through the vadose zone and in two dimensions through the saturated zone. The 2D column leach test simulation was used in WiscLEACH, which assumes steady 1D unit gradient flow in the vertical direction in the vadose zone (no horizontal mixing), steady 2D flow in the saturated zone (no cross-dispersion), and that each roadway layer is homogeneous and isotropic [19, 31, 47]. WiscLEACH also assumes instantaneous and reversible sorption, a linear isotherm, and that chemical and biological reactions are absent. These assumptions may not be entirely realistic, but are conservative as reactions that may consume or transform trace elements are likely to exist and mixing may occur horizontally in the vadose zone. Therefore in reality element concentrations would be lower than the concentrations calculated with WiscLEACH.

Infiltration was assumed to equal the average annual precipitation rate, which effectually ignores runoff. Scaling and retardation factors were conservatively assumed to be one, i.e., no sorption. Inorganic leaching is not typically dependent on retardation or partitioning, but varying the retardation factors from 1 to 4 to span the range of typical field conditions did not appreciably change $C_{POC@20}$ (difference in $C_{POC@20}$ was about one-tenth-µg/L) [48] .

Published molecular diffusion coefficients were input for each trace element or a low (conservative) molecular diffusion coefficient of 0.005 m^2/yr. was assumed for elements that had no published values (As, Sn, Ti, and V) [49]. Lower values of molecular diffusion are conservative because they initiate less trace element spreading within WiscLEACH and thus predict a higher $C_{POC@20}$. It is common to assume molecular diffusion coefficients of 1, which would predict $C_{POC@20}$ lower (less conservative) than the ranges actually used by approximately 1 µg/L.

Dispersivities were taken as one-tenth the domain and recommended grid parameters from Li et al. 2006 were used [46]. A summary of site-specific WiscLEACH model inputs is provided in Table 1-4. An additional discussion of input considerations is provided in Appendix A.

Input concentration, C_O, is applied evenly throughout the stabilized layer within the software at time zero, and was conservatively taken as the maximum concentration documented for each element at each field site. The maximum concentration observed used for C_O because adsorption control release prevails after time zero, which accounts for the first-flush release trend observed for many sites where the initial concentration decreases with time. Additional details for WiscLEACH can be found in Li et al. (2006) [46].

The assumptions built in and applied to WiscLEACH are conservative because they create a scenario that results in higher values of $C_{POC@20}$ than are likely to actually occur. A simulation with less-conservative assumptions (retardation factors of 4 and molecular diffusion coefficients of 1) resulted in a lower $C_{POC@20}$ than the conservative case by one order of magnitude, which is inappreciable on the scale of observed $C_{POC@20}$ (1 to 0.1 μg/L).

The initial injection modeled at the boundary beneath the stabilized layer simulated leachate and allowed the maximum predicted $C_{POC@20}$ to be obtained from the model. The breakthrough curve for a typical field site in Minnesota or Wisconsin was established to determine when the $C_{POC@20}$ was reached. Regardless of trace element modeled, the maximum $C_{POC@20}$ was reached within 5 years, which is within the lifetime of a road (typically 20 to 40 years) [2, 50]. The $C_{POC@20}$ for each element was evaluated as above or below the drinking water or surface water standard in a manner similar to the direct assessment.

Similar to the direct assessment, the indirect assessment of water quality data at the POC does not take into account naturally occurring trace element concentrations in the ground water or surface water. By not considering background concentrations any added trace elements due to the utilization of fly ash and bottom ash in the roadway structure can be assessed without interference. Site specific background concentrations can be added directly to the $C_{POC@20}$ to estimate the overall concentration of groundwater because superposition is allowed with the linear form of the ADRE used in WiscLEACH.

For instance, Arsenic is known to be naturally present in groundwater in Minnesota and Wisconsin and can be present in natural levels exceeding national drinking water quality limits [45]. The direct analysis only compares lysimeter leachate concentrations to water quality standards or control lysimeter concentrations and thus ignores any risks imposed by existing groundwater trace element concentrations. Monitoring well concentrations, on the other hand, are comprised of groundwater and thus take into consideration background concentrations. Any risk introduced from existing groundwater concentrations are eliminated by comparing monitoring well data to the control monitoring well or established background concentration.

Reduction factors (RF) were calculated by dividing C_O by $C_{POC@20}$ to present the amount of reduction that takes place and to facilitate the discussion and assessment of the impact on roadways. Reduction factors (RF) can allow for the quick estimation of $C_{POC@20}$ (concentration at the point of compliance) given leachate characteristic data (e.g. C_O) or the back-calculation of an allowable C_O given maximum allowable $C_{POC@20}$ (e.g. water quality limits). RFs are conservative because they are a product of the conservative assumptions discussed above

A parametric evaluation of the relationship between C_O and $C_{POC@20}$ indicated that a 10-fold decrease on C_O would result in a ten-fold decrease in $C_{POC@20}$ at a field site when all else remained constant. Based on typical RF observed at the roadways, the decrease between C_O and $C_{POC@20}$ were typically two orders of magnitude and produced $C_{POC@20}$ in a much smaller range than $C_{POC@20}$. For instance, values of C_O ranging from10 µg/L to1,000 µg/L for Cr at a typical fly ash stabilized field would result in values of C_{POC} ranging from 0.13 µg/L to 13 µg/L. This relationship indicates that the conservative assumption of taking the maximum observed field concentration as C_O has little effect on the predicted $C_{POC@20}$.

Table 1-4
Site-specific WiscLEACH model inputs for fly ash and bottom ash roadways.

Roadways	Point of Compliance (POC) (m)	Width of Pavement (m)	Width of Shoulder (m)	Distance to Groundwater Table (m)	Distance to Top of CCP Layer (m)
STH60-FA	20	10.4	1.5	>2.03	0.38
US12-W	20	10.4	1.5	1.52	0.457
US12-E	20	10.4	1.5	>2.03	0.457
Scenic Edge	20	10.4	1.5	>2.03	0.215
Waseca	20	10.4	1.5	1.09	0.075
MnROAD	20	10.4	1.5	1.09	0.102
STH60-BA	20	10.4	1.5	>2.03	0.38
Roadways	**Distance to Bottom of CCP Layer (m)**	**Infiltration Rate (m/yr.)**	**Hydraulic Conductivity of Aquifer (m/yr.)**	**Porosity of Aquifer**	**Regional Hydraulic Gradient**
STH60 Fly Ash	0.68	0.866	3156	0.3	0.001
US12-W	0.757	0.845	3156	0.3	0.001
US12-E	0.757	0.845	3156	0.3	0.001
Scenic Edge	0.515	0.839	3156	0.3	0.001
Waseca	0.225	0.871	3156	0.3	0.001
MnROAD	0.305	0.764	3156	0.3	0.001
STH60-BA	0.98	0.866	3156	0.3	0.001
Roadways	**Hydraulic Conductivity of Pavement (m/yr.)**	**Hydraulic Conductivity of Base (m/yr.)**	**Hydraulic Conductivity of CCP Layer (m/yr.)**	**Hydraulic Conductivity of Subgrade (m/yr.)**	**Porosity of Pavement**
STH60-FA	1.0	1.0	0.19	133.5	0.33
US12-W	1.0	1.0	0.19	126.9	0.33
US12-W	1.0	1.0	0.19	126.9	0.33
Scenic Edge	1.0	1.0	0.19	133.5	0.33
Waseca	1.0	1.0	757.4	126.9	0.33
MnROAD	1.0	1.0	757.4	133.5	0.33
STH60-BA	1.0	1.0	0.126	133.5	0.33
Roadways	**Porosity of Base**	**Porosity of CCP Layer**	**Porosity of Subgrade**	**Horizontal Dispersion**	**Vertical Dispersion**
STH60-FA	0.33	0.41	0.16	2.0	0.20
US12-W	0.33	0.27	0.10	2.0	0.15
US12-E	0.33	0.27	0.10	2.0	0.20
Scenic Edge	0.33	0.39	0.17	2.0	0.20
Waseca	0.33	0.39	0.19	2.0	0.11
MnROAD	0.33	0.25	0.10	2.0	0.11
STH60-BA	0.33	0.42	0.17	2.0	0.20

Note: Southwest Rome Bypass and 56th Street Overpass roadways did not require an indirect assessment thus data is not included here. R values for the subgrade layer were assumed to be 1, which implies that no element mass is partitioning. Realistically some degree of adsorption is taking place [17], but the assumption is conservative and model results at the receptor point being below water quality limits confirms that this assumption is reasonable. Scaling factors were not used because values were taken from the field, not column tests [20].

Results & Discussion

Direct Assessment

Table 1-5 and Table 1-6 display the results of the direct assessment for federal and state surface water limits and drinking water limits, respectively. Recall that only health-based standards were considered. Dark gray cells denote elements for which CCP use in roadway application imposed no risk; Light gray cells denote elements for which CCP use in roadway application imposed no additional risk as compared to traditional materials; Black cells denote elements that required further investigation; White cells denote elements that were not assessed (either no water quality limit or not analyzed). Gray (dark or light) cells imply that roadways employing fly or bottom ash were essentially no different for those elements, in terms of potential impact on the environment, than roadways constructed with conventional additive construction materials.

Elements and the risk associated with them as compared to conventional materials were independent of water quality limits because the paired-t test compared datasets to control datasets. Note that Scenic Edge & Waseca did not have a control and thus could not undergo this evaluation, but regardless did not require further investigation for more elements than other sites. Southwest Rome Bypass roadways were compared to SWRB-5 (determined to be the control well) or background concentrations. 56th St. Overpass-W was compared to background concentrations. Because background concentrations from monitoring wells were established prior to embankment construction, an unpaired-t test was used for the comparison.

Roadways where a lysimeter was the water monitoring device required further assessment for at least one element for both surface water and drinking water, while roadways that had monitoring wells did not require further investigation for any element. This can be attributed to the differences in water collection device employed and their location. The water collected in a lysimeter is obtained directly beneath the roadway profile and as such is a leachate with trace element concentrations the highest they will ever be. In contrast, water collected from monitoring wells was allowed to percolate from the base of a roadway and mix with pore water in the vadose and saturated zones and interact with mineral solids in the earthen materials beneath the roadway. These processes result in substantially lower concentrations due to the combined effects of dilution and adsorption, making lysimeter roadways appear to have elevated concentrations and thus impose more risk than monitoring well sites.

Roadways employing lysimeters are not necessarily imposing more risk than roadways employing monitoring wells and this underlines the importance of the indirect assessment for this study. The difference between water monitoring devices at roadways does not affect the risk analysis, however the difference can impart difficulties in comparing the behavior of different field types. For this reason, water monitoring device types and lateral offset distances are provided in the direct and indirect assessment result tables (Tables 1-5, 1-6, 1-7, and 1-8). The results on direct assessment of monitoring wells imply that roadways employing fly ash in roadway embankment fills were essentially no different for all elements monitored for, in terms of potential impact on the environment, than roadways constructed with conventional construction materials.

Generally, elements imposing no risk with respect to drinking water quality limits differed from elements imposing no risk with respect to surface water quality limits. This is due to the difference in water quality limits. The difference between roadways does not affect the risk analysis; however the difference can impart difficulties in comparing the behavior of different field types.

The four most common elements to impose no risk to drinking water were Cu, Cr, Be, and Ba. Concentrations of Cu were below drinking water quality limits at all roadways. Concentrations of Cr were below drinking water limits at all sites except the MnROAD lysimeter, where concentrations were not elevated with respect to the control at that site. Concentrations of Be and Ba were below drinking water standards at all sites but one (MnROAD and 56th Street Overpass, respectfully). The three most common elements imposing no risk to surface water were Cr, As, and Ni. Cr concentrations were below surface water quality criteria at all roadways. As and Ni concentrations were both below surface water standards at all sites but one (56th Street Overpass and STH60-FA, respectfully). These results suggest that overall Cu, Cr, Be, and Ba are not elements to be primarily concerned about for drinking water, and Cr, As, and Ni are not elements to be primarily concerned about for surface water.

Elements in the no risk or no additional risk category differed between US12-W and US12-E, with only 2 of 6 and 2 of 5 overlap, respectively. Between STH60, US12, and MnROAD, no element falls into this category for all three sites; even though fly ash was of common source between STH60, US23, and Scenic Edge. This implies that field conditions can vary between locations in close proximity to each other, and makes drawing conclusions based on locality difficult.

Elements eluted from roadway subbases stabilized with bottom ash (i.e. STH60-BA) categorized as imposing no risk were similar to elements falling into this category from STH60-FA, but were less similar between fly ash and bottom ash for the no additional risk category. The bottom ash site was found to have five more elements in that category. This suggests that overall STH60-BA is more similar to the control than is STH60-FA.

The detection limit (see Appendix A) of the analytical machine used to establish trace element concentration was larger than water quality values for some elements for some portions of monitoring periods at the RMRC roadways (Wisconsin and Minnesota roadways) for As, Sb, Se, and Tl. The high detection limits hinder the direct evaluation because a direct comparison of the analytical reading (which is actually the detection limit) is already higher than the water quality limit and so the cause of the water quality limit exceedances cannot be determined.

Of the elements with detection limits exceeding water quality limits, As and Se were the first and third most common elements that required further investigation and required an indirect assessment, and Sb and Tl were in a three-way tie for fourth most common element. Additionally, As, Sb, and Tl, stood out as three of the four most common elements classified as imposing no additional risk, which could be due to the paired-t analysis of concentrations all at the detection limit. Detection limits could thus be affecting the classification of elements. However, the detection limits did not hinder the overall risk assessment because As, Sb, Se, and Tl underwent the indirect assessment for roadways where further analysis was required. The uncertainty of field conditions highlights the need for detection limits to be smaller than trace element water quality limits in order to truly establish field conditions and understand leaching behavior.

Table 1-5
Direct Assessment Results for Federal and State Surface Water Limits.

Element			Ag		Al		As		Cd		Co		Cr		Cu		F		Hg		Ni		Pb		Sb		Se		Tl		Zn	
Water Quality Limit Authority			F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S
FA Stabilization	STH60-FA	Lysimeter; 0 m																														
	US12-W	Lysimeter; 0 m																														
	US12-E	Lysimeter; 0 m																														
	Scenic Edge	Lysimeter; 0 m																														
	MnROAD	Lysimeter; 0 m																														
	Waseca	Lysimeter; 0 m																														
FA Fill	SWRB-4	MW; 200 m																														
	SWRB-5	MW; 16.2 m																														
	SWRB-6	MW; 0 m																														
	SWRB-7	MW; 0 m																														
	SWRB-8	MW; 25.1 m																														
	SWRB-9	MW; 29.5 m																														
	SWRB-10	MW; 32.5 m																														
	SWRB-11	MW; 45.0 m																														
	SWRB-12	MW; 41.3 m																														
	56th St. Overpass-W	MW; 0 m																														
	56th St. Overpass-E	MW; 0 m																														
	56th St. overpass-L	Lysimeter; 0 m																														
BA Fill	STH60-BA	Lysimeter; 0 m																														

Key: Dark gray cells denote elements for which CCP use in roadway application imposed no risk; Light gray cells denote elements for which CCP use in roadway application imposed no additional risk as compared to traditional materials; Black cells denote elements that required further investigations; White cells denote elements not assessed (either no water quality limit or not analyzed).

Note: Scenic Edge, Waseca, and 56th St. Overpass-L did not have control lysimeters. Southwest Rome Bypass roadways were compared to SWRB-5 (determined to be the control well) or background concentrations. 56thSt. Overpass-W was compared to background concentrations. "F" denotes federal and "S" denotes state water quality limit authority. Water collection device and offset distance are also provided.

Table 1-6
Direct Assessment Results for Federal and State Drinking Water Limits.

Element			As		Ba		Be		Cd		Cr		Cu		F		Hg		Ni		Pb		Sb		Se		Tl	
Water Quality Limit Authority			F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S
FA Stabilization	STH60-FA	Lysimeter; 0 m																										
	US12-W	Lysimeter; 0 m																										
	US12-E	Lysimeter; 0 m																										
	Scenic Edge	Lysimeter; 0 m																										
	MnROAD	Lysimeter; 0 m																										
	Waseca	Lysimeter; 0 m																										
FA Fill	SWRB-4	MW; 200 m																										
	SWRB-5	MW; 16.2 m																										
	SWRB-6	MW; 0 m																										
	SWRB-7	MW; 0 m																										
	SWRB-8	MW; 25.1 m																										
	SWRB-9	MW; 29.5 m																										
	SWRB-10	MW; 32.5 m																										
	SWRB-11	MW; 45.0 m																										
	SWRB-12	MW; 41.3 m																										
	56th St. Overpass-W	MW; 0 m																										
	56th St. Overpass-E	MW; 0 m																										
	56th St. overpass-L	Lysimeter; 0 m																										
BA Fill	STH60-BA	Lysimeter; 0 m																										

Key: Dark gray cells denote elements for which CCP use in roadway application imposed no risk; Light gray cells denote elements for which CCP use in roadway application imposed no additional risk as compared to traditional materials; Black cells denote elements that required further investigations; White cells denote elements not assessed (either no water quality limit or not analyzed).
Note: Scenic Edge, Waseca, and 56th St. Overpass-L did not have control lysimeters. Southwest Rome Bypass roadways were compared to SWRB-5 (determined to be the control well) or background concentrations. 56thSt. Overpass-W was compared to background concentrations. "F" denotes federal and "S" denotes state water quality limit authority. Water collection device and offset distance are also provided.

Indirect Assessment

The direct assessment provides a conservative assessment of risk, as the water sample collected at a lysimeter directly beneath a roadway profile is not available for human consumption or for contact with biota in a surface water body. Dilution and attenuation between the monitoring point and a receptor will substantially reduce concentrations and risk imposed by using fly ash in roadway construction. Elements not falling into the “no risk” or “no additional risk” categories in the direct assessment required further evaluation and underwent an indirect assessment to take into consideration the dilution and attenuation via hydrologic flow modeling. WiscLEACH hydrologic modeling software had $C_{POC@20}$ below water quality limits, thus were categorized as imposing “no predicted risk.” Conservative assumptions were made when using WiscLEACH, as described in the methods section.

Table 1-7 and 1-8 display the results of the indirect assessment for federal and state surface water limits and drinking water limits, respectively. Dark gray cells denote elements for which CCP use in roadway application imposed no predicted risk; Black cells denote elements that were indeterminate; White cells denote elements not assessed (either no water quality limit or not analyzed). Water monitoring device types and lateral offset distances are also provided to help illustrate why roadways employing monitoring wells as the water monitoring device did not require further investigation while the roadways employing lysimeters did. Elements requiring further investigation varied per field site, but overall included Ag, Al, As, Be, Cd, Cu, Ni, Pb, Sb, Se, Tl, and Zn.

No elements were common between all 8 fly ash sites. At most, an element appears at five sites (occurred 4 times between all water quality limits) but more commonly an element appears for only two sites (occurred 8 times) or one site (occurred 7 times). No trend was found between sites.

A direct analysis to evaluate the elevated Cd, Pb and Zn concentration in the lysimeter was not possible because there was no control lysimeter, and an indirect assessment was not possible because lack of information would require so many assumptions to be made that confidence in the solution would be questionable. These elements were categorized as “indeterminate” but the overall risk of the roadway can be inferred from the monitoring wells at that site, i.e. that no risk or no additional risk is imposed by using the fly ash embankment as compared to background concentrations. A simulation in WiscLEACH using assumed parameters and C_O values from the lysimeter water quality data at 56th Street Overpass predicted a range of C_{POC} that fall within the range of values observed in the monitoring wells at 56th Street Overpass, confirming that no risk is imposed by the fly ash fill. However, a control lysimeter is recommended to always be installed at a field site location, and that field conditions be well documented so that an indirect assessment can be performed when required.

The indirect assessment showed that fly ash and bottom ash used in roadway fill or stabilization applications posed no predicted risk at the modeled receptor points and thus are suitable beneficial reuse applications with respect to water quality.

Table 1-7
Indirect Assessment Results for Federal and State Surface Water Limits.

Element			Ag		Al		As		Cd		Co		Cr		Cu		F		Hg		Ni		Pb		Sb		Se		Tl		Zn	
Water Quality Limit Authority			F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S
FA Stabilization	STH60-FA	Lysimeter; 0 m																														
FA Stabilization	US12-W	Lysimeter; 0 m																														
FA Stabilization	US12-E	Lysimeter; 0 m																														
FA Stabilization	Scenic Edge	Lysimeter; 0 m																														
FA Stabilization	MnROAD	Lysimeter; 0 m																														
FA Stabilization	Waseca	Lysimeter; 0 m																														
FA Fill	SWRB-4	MW; 200 m																														
FA Fill	SWRB-5	MW; 16.2 m																														
FA Fill	SWRB-6	MW; 0 m																														
FA Fill	SWRB-7	MW; 0 m																														
FA Fill	SWRB-8	MW; 25.1 m																														
FA Fill	SWRB-9	MW; 29.5 m																														
FA Fill	SWRB-10	MW; 32.5 m																														
FA Fill	SWRB-11	MW; 45.0 m																														
FA Fill	SWRB-12	MW; 41.3 m																														
FA Fill	56th St. Overpass-W	MW; 0 m																														
FA Fill	56th St. Overpass-E	MW; 0 m																														
FA Fill	56th St. overpass-L	Lysimeter; 0 m																														
BA Fill	STH60-BA	Lysimeter; 0 m																														

Key: Gray cells denote elements for which CCP use in roadway application imposed no predicted risk at POC; Black cells denote elements for which were indeterminate; White cells denote elements that were not assessed (either no water quality limit or not analyzed).
Note: 56th Street Overpass did not sufficient details supplied to perform an indirect assessment and thus are categorized as indeterminate. "F" denotes federal and "S" denotes state water quality limit authority. Water collection device and offset distance are also provided.

Table 1-8
Indirect Assessment Results for Federal and State Drinking Water Limits.

Element			As		Ba		Be		Cd		Cr		Cu		F		Hg		Ni		Pb		Sb		Se		Tl	
Water Quality Limit Authority			F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S
FA Stabilization	**STH60-FA**	Lysimeter; 0 m																										
	US12-W	Lysimeter; 0 m																										
	US12-E	Lysimeter; 0 m																										
	Scenic Edge	Lysimeter; 0 m																										
	MnROAD	Lysimeter; 0 m																										
	Waseca	Lysimeter; 0 m																										
FA Fill	**SWRB-4**	MW; 200 m																										
	SWRB-5	MW; 16.2 m																										
	SWRB-6	MW; 0 m																										
	SWRB-7	MW; 0 m																										
	SWRB-8	MW; 25.1 m																										
	SWRB-9	MW; 29.5 m																										
	SWRB-10	MW; 32.5 m																										
	SWRB-11	MW; 45.0 m																										
	SWRB-12	MW; 41.3 m																										
	56th St. Overpass-W	MW; 0 m																										
	56th St. Overpass-E	MW; 0 m																										
	56th St. overpass-L	Lysimeter; 0 m																										
BA Fill	**STH60-BA**	Lysimeter; 0 m																										

Key: Gray cells denote elements for which CCP use in roadway application imposed no predicted risk at POC; Black cells denote elements for which were indeterminate; White cells denote elements that were not assessed (either no water quality limit or not analyzed).
Note: 56th Street Overpass did not sufficient details supplied to perform an indirect assessment and thus are categorized as indeterminate. "F" denotes federal and "S" denotes state water quality limit authority. Water collection device and offset distance are also provided.

In order to determine if the $C_{POC@20}$ was sensitive to the distance to the POC, the concentration as a function of distance from the base of the fly ash layer was modeled in WiscLEACH and is shown in Figure 1-9. Concentration decreased by 6 times the C_O in the vadose zone as water flowed vertically underneath the centerline of the pavement section and decreased by 67 times the C_O just after the vadose-saturated zone boundary. The large decrease across the vadose-saturated zone boundary can be attributed to dilution, and the ten-fold decrease observed in the data falls within the range of dilutions expected for the Minnesota or Wisconsin roadways (5-fold to 14-fold decrease). A slight increase in concentration can be seen between a flow distance of 6.5 m and 11.5 m as a result of concentration build up as water moves horizontally from the centerline to the edge of the roadway. Concentration reduced to an ultimate 69 times from the vadose zone to the POC, demonstrating that most concentration reduction occurred at the vadose-saturated zone boundary underneath the pavement section. This implies that the distance to the POC from the pavement layer is not influential. However, as implied by Li et al.[34, 46] the distance to the groundwater table would impact the distance the element travels through the vadose zone, potentially affecting the magnitude of concentration reduction.

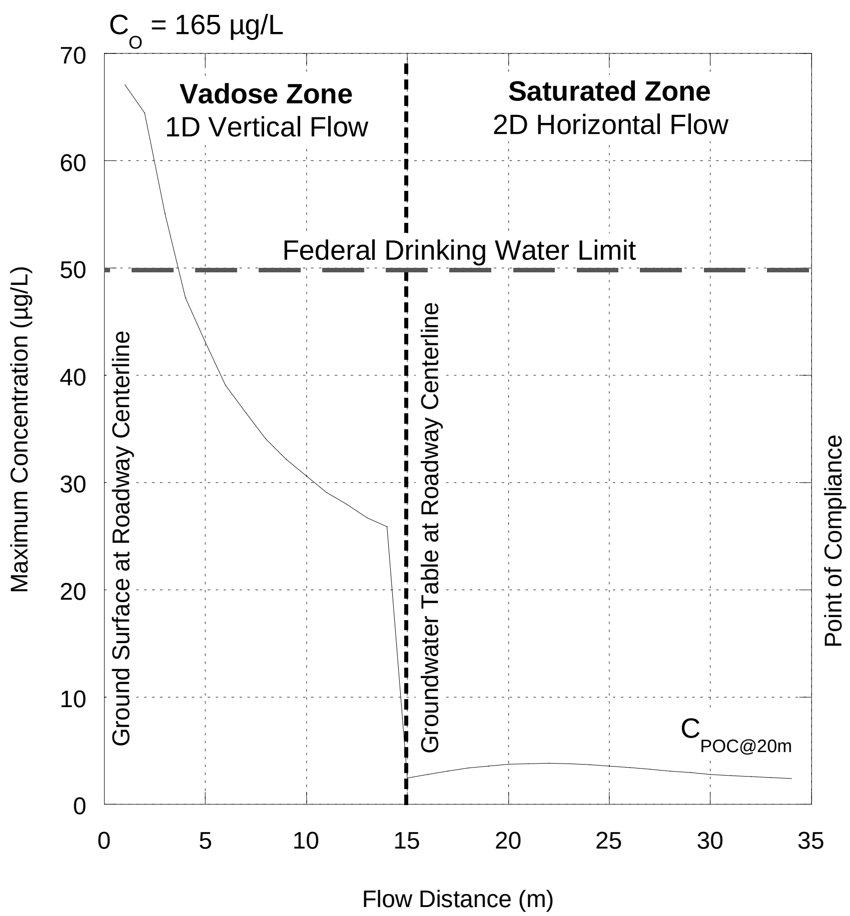


Figure 1-10
Concentration vs. flow distance for a typical field site in Minnesota and Wisconsin.

Maximum and minimum molecular diffusion coefficients were plotted. Concentration decreases in the vadose zone and drops dramatically after the groundwater table. This example is for selenium and the drinking water limit for selenium is marked.

Using the WiscLEACH model, reduction factors (RF) were calculated by dividing C_O by $C_{POC@20}$ to give a general sense of the amount of reduction that took place and to facilitate the discussion and ranking of roadways. RFs spanned 46-88, with increasing RF indicating that more reduction took place during water migration to POC.

RF represent the overall concentration reduction that occurred in field conditions and are a function of the input parameters that influence $C_{POC@20}$, of which were most influentially depth to groundwater table (Z_{GWT}), stabilized layer thickness, width of stabilized layer, hydraulic conductivity of the stabilized layer and aquifer, dispersivity, and C_O. Z_{GWT} was the most sensitive parameter because Z_{GWT} correlates to the length of the flow path and thus the amount of dispersion that took place [46]. Thickness of the stabilized layer was the second most sensitive parameter because stabilized layer thickness affects the total mass leached: higher concentrations occurred at the POC when more mass was leached from the fly ash stabilized layer [46]. Hydraulic conductivity of the stabilized layer typically controlled seepage velocity in the vadose zone, and hydraulic conductivity of the aquifer controlled seepage velocity in the saturated zone [34, 46]. Values of C_O and $C_{POC@20}$ varied greatly between elements and between roadways, but RF were constant for each trace element at a field site regardless of C_O input into WiscLEACH because all other factors remained constant and the ADRE used in WiscLEACH was linear.

The RF averaged for all elements field water quality data was collected for at fly ash stabilization roadways are shown in Figure 1-9. The depth to groundwater table and stabilized layer thickness are included for context in Figure 1-9. Because all other parameters were the same at a field site, the only influence on elemental RF per site was molecular diffusion, which differs between elements. Small standard deviations (2.5% to 7.5% of the mean) suggest that the average of the RF for all elements at a given field site can accurately represent all elements at that field site.

STH60-FA, US12-W, and US12-E sites are constructed very similarly; however RF for US12-W and US12-E are noticeably smaller. All three employ subgrade stabilized with fly ash (10% to 12% by weight) from the same source to a thickness of 0.3 m, are situated within similar geologic settings, and use almost identical input parameters in WiscLEACH. The main difference between sites is that the US12 field site's pavement is Portland cement, which was applied in a thicker layer than was hot-mix asphalt at STH60 and required a thicker base layer than did STH60. The difference in pavement and base layers resulted in the fly ash-stabilized subgrade layer at US12 to be situated deeper in the profile, which reduced the distance from the bottom of the stabilized layer to the groundwater table. A reduced distance from stabilized layer to groundwater table reduces the flow path water and thus the amount of dispersion that takes place, which accounts for the lower reduction factors at US12-W and US12-E. The reason the RF at US12-E is the lower of the two is that the depth to groundwater table at US12-E is 1.5 m rather than 2.0 m like at US12-W and STH60-FA.

Waseca is the only field site that did not demonstrate a downward trend in RF with decreasing depth to groundwater table (Figure 1-9). The other roadways appear to be controlled by depth to groundwater table. The average RF is higher at Waseca because the stabilized layer thickness was thinner (0.15 m) compared to the other roadways, which suggests Waseca was instead controlled by thickness of stabilized layer. Recall that a thinner stabilized layer results in a higher RF because stabilized layer thickness affects the total mass leached: higher concentrations occurred at the POC when more mass was leached from the fly ash stabilized layer [46].

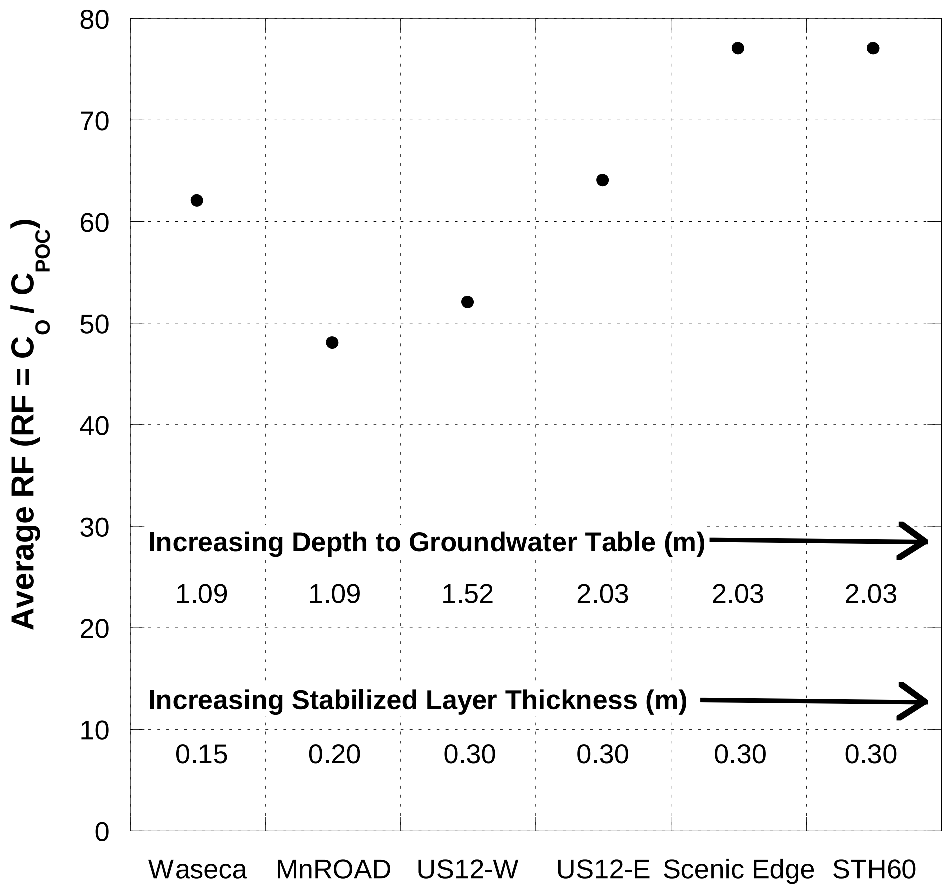


Figure 1-11
RF averaged over all elements at fly ash stabilization roadways plotted in order of increasing depth to groundwater table and stabilized layer thickness.

RF statistics are presented in Table 1-9. RF ranged between 46 (MnROAD) and 88 (STH60). Overall, STH60 had the highest RFs due primarily to a relatively thicker stabilized layer and deeper Z_{GWT} while MnROAD had the lowest reducing power due to a thinner stabilized layer and shallower Z_{GWT} [34, 46].

Using water quality limits as $C_{POC@20}$ instead of the predicted $C_{POC@20}$ to solve for RF effectually back-calculated the minimum required RF that a field site would need to obtain a $C_{POC@20}$ below water quality limits. For example, even though the maximum average RF (77) was obtained for STH60-FA, a RF as low as 38 would still reduce C_O to a $C_{POC@20}$ below the water quality limits.

Minimum required RF for fly ash fill roadways are provided in Table 1-9. The lowest RF calculated from $C_{POC@20}$ values (RF=46 at MnROAD) was larger than the smallest minimum required RF (RF=4 at US12-E), which confirms on a broader scale than individual indirect assessments that the required reduction will be obtained and $C_{POC@20}$ will be below water quality limits.

Table 1-9
Reduction factor (RF) statistics

Site	Minimum Value	Maximum Value	Average	Standard Deviation	Minimum Required RF
STH60-FA	67	88	77	5.1	38
US12-W	49	59	52	2.0	6
US12-E	60	70	64	1.9	4
Scenic Edge	72	86	77	2.7	31
Waseca	60	67	62	2.1	28
MnROAD	46	51	48	1.2	20

The overall minimum RF (46) was used to back-calculate a maximum allowable C_O given maximum allowable $C_{POC@20}$ set equal to water quality limits. Maximum allowable C_O are presented in Table 1-10. Additionally, RF from one of the roadways could be used to quickly estimate $C_{POC@20}$ given leachate characteristic data (C_O) of a similarly constructed and situated field site.

Table 1-10
Maximum allowable C_O back-calculated using lowest RF and water quality limits set equal to $C_{POC@20}$.

Water Quality Limit	Drinking Water Limits (µg/L)					Surface Water Limits (µg/L)				
Authority	**Federal**	**IN**	**GA**	**MN**	**WI**	**Federal**	**IN**	**GA**	**MN**	**WI**
Ag	-	-	-	-	-	147.2	-	-	92	-
Al	-	-	-	-	-	-	-	-	34,408	-
As	460	460	460	460	460	15,640	-	15,640	16,560	16,560
Ba	92,000	92,000	92,000	92,000	92,000	-	-	-	-	-
Be	184	184	184	184	184	-	-	-	-	-
Cd	230	230	230	230	230	-	-	46	202.4	202.4
Co	-	-	-	-	-	-	-	-	-	-
Cr	460	460	460	460	460	26,220	-	15,456	82,938	182,938
Cu	59,800	59,800	59,800	59,800	59,800	-	-	322	690	690
F	184,000	184,000	184,000	184,000	184,000	-	-	-	-	-
Hg	92	92	92	92	92	-	-	-	-	-
Ni	-	-	-	460	460	21,620	-	11,960	21,574	21,574
Pb	690	690	690	690	690	2,990	-	1,380	4,922	4,922
Sb	276	276	276	276	276	-	-	-	-	-
Se	2300	2300	2300	2300	2300	-	-	-	-	-
Tl	92	92	92	92	92	-	-	-	-	-
Zn	-	-	-	-	-	5,520	-	2,990	5,520	5,520

Note: Maximum allowable C_O for Cu and Pb for drinking water are based on action limits.
- Water quality limits do not exist for these elements.

Element concentrations measured in field lysimeters at levels equal to or below 46 times the water quality limit were imposed no additional risk in where the groundwater table was at least 1 m below ground surface. The utility of RF calculated in this study, however, is limited to the roadways of this study or other roadways that have very similar field conditions. Conducting additional model simulations is recommended to better determine a relationship between the most sensitive parameters in the WiscLEACH modeling software, namely depth to groundwater table and thickness of the CCP layer, to allow RF to be applied to as many other projects beyond the scope of this study as possible.

Data sources were found predominantly from Midwest states (MN, WI, IN) and were obtained through state DOT materials engineers. Conducting further searches is recommended to unearth additional roadways outside of the Midwest to add to the database. The DOT survey resulted in replies from 45 states, 17 of which wished to remain unnamed. Out of the 17 confidential states, 8 used CCPs in additive roadway applications. Out of the remaining 28 states, 8 also used CCPs in additive roadway applications, and three of those 8 reported that monitoring took place. Even though CCP use does not appear to correlate with region, the survey results indicate that overall

CCP use as additive in roadway applications is small, and monitoring of such projects is even smaller. This is not surprising considering the CCP statistics published by the ACAA (American Coal Ash Association). In 2012, 6.3% of all fly ash produced (or 14.1% of all fly ash reused) was reused in road base/subbase/subgrade or structural fill/embankments. The facts are that most of CCP reuse right now is for fly ash and FGD materials, and it is most commonly in bound applications, such as concrete or concrete products, or gypsum board. An explanation of why roadway applications do not exist frequently outside of the Midwest is likely that concern for contamination may be limiting CCP use in roadway projects.

Similarly, data sources were entirely using fly ash, with the exception of STH60-BA. Conducting further searches is recommended to unearth additional bottom ash use in roadways, or other CCP sites, to enhance the CCP diversity of the database. Even though a greater percentage of bottom ash is reused in road base/subbase/subgrade or structural fill/embankment applications (14.7% of bottom ash produced or 37.8% bottom ash reused) [8], the overall reuse rate of bottom ash is smaller than that of fly ash. Though the rate of bottom ash reuse is low and data is difficult to obtain, finding such data will be all the more important for the future of bottom ash reuse.

Summary & Conclusions

In this study, the potential risk of contaminating ground water and surface water by constituents leaching from coal ash used in roadways was evaluated using field water quality data collected from projects where coal ash (primarily fly ash) has been used in roadway bases and subgrades. Water quality data was obtained for seven roadways measured at various points in Minnesota, Wisconsin, Indiana, and Georgia. Data was obtained for MnROAD and Waseca roadways in Minnesota, which contained recycled pavement material (RPM) roadway base stabilized with fly ash. Data was obtained for STH60, US12, and Scenic Edge roadways in Wisconsin, which contained roadway subgrade stabilized with fly ash. STH60 additionally contained a roadway section employing bottom ash as subbase fill. Data was obtained for the 56th Street Overpass field site in Indiana. At this site, fly ash was used as embankment fill material for the reconstruction of a roadway overpass. Additionally, data was obtained for the Southwest Rome Bypass field site in Georgia, where fly ash was used as roadway embankment fill.

The assessment evaluated field water quality data collected from roadways where fly ash and bottom ash had been used in roadway substructures. Naturally occurring trace element concentrations in groundwater were eliminated from the study. Water quality data were compared directly to federal and state water quality standards to provide a conservative evaluation of the risk of contaminating surface water and ground water from base, subbase, and subgrade applications using fly ash. Elements were categorized as imposing “no risk” when the concentration profiles of each trace element were entirely below the water quality limit. Additionally, when elemental concentrations from a roadway constructed with coal ash were not statistically different from concentrations eluted from control sections without coal ash, as determined by a paired-t test at the 5% significance level, the element was categorized as imposing “no additional risk” relative to that imposed by a roadway constructed using conventional materials.

Indirect analyses were conducted to more realistically assess field conditions at a point of compliance (POC) using the maximum field trace element concentration data (C_O) as measured directly beneath the roadway as input to WiscLEACH hydrologic and transport modeling software. When the modeled concentrations at the POC ($C_{POC@20}$) were below water quality limits, the element was categorized as imposing "no predicted risk." Reduction factors (RF) were calculated by dividing the initial concentration by the predicted concentration at the point of compliance to give a general sense of the amount of reduction that took place and to facilitate the discussion and ranking of roadways. Additionally, RF could allow for the quick estimation of $C_{POC@20}$ given leachate characteristic data (e.g. C_O) or the back-calculation of an allowable C_O given maximum allowable $C_{POC@20}$ (e.g. water quality limits).

Findings include:

1. Roadways where a lysimeter was the water quality monitoring device required further assessment for at least one element for both surface water and drinking water, while roadways that had monitoring wells did not require further investigation for any element. This can be attributed to the differences in water collection device employed.

2. The direct assessment of fly ash stabilized roadway subgrades (STH60-FA, US12-W, US12-E, Scenic Edge, MnROAD, and Waseca) demonstrated that concentrations at the base of the fly ash stabilized layer of 11-13 of 17 trace elements were either below water quality limits or were not statistically different from control roadways and were consequently categorized as imposing "no risk" or "no additional risk."

3. Generally, elements imposing no risk with respect to drinking water quality limits differed from elements imposing no risk with respect to surface water quality limits.

4. Overall Cu, Cr, Be, and Ba are not elements to be primarily concerned about for drinking water, and Cr, As, and Ni are not elements to be primarily concerned about for surface water.

5. Field conditions can vary between locations in close proximity to each other, which makes drawing generalized conclusions based on local assessment difficult.

6. Bottom ash application (STH60-BA) is more similar to the control section without any coal ash than is fly ash application (STH60-FA).

7. The results on direct assessment of monitoring wells imply that roadways employing fly ash in embankment fills were essentially no different for all elements monitored for, in terms of potential impact on the environment, than roadways constructed with conventional additive construction materials.

8. A direct analysis to evaluate the elevated Cd, Pb and Zn concentration in the lysimeter at the 56th Street Overpass was not possible because there was no control lysimeter

9. The direct assessment of fly ash stabilized roadway subgrades (STH60-FA, US12-W, US12-E, Scenic Edge, MnROAD, and Waseca) demonstrated that 4-6 of 17 trace elements

exceeded water quality limits per field site at the base of the fly ash stabilized layer but subsequent indirect assessment via hydrologic transport modeling determined that $C_{POC@20}$ were predicted to be below water quality limits and were characterized as "no predicted risk". Elements indirectly assessed varied per field site and included Ag, Al, As, Be, Cd, Cu, Ni, Pb, Sb, Se, Tl, and Zn.

10. Indirect assessment was not required for any elements at the Southwest Rome Bypass field site.

11. An indirect assessment could not be conducted for elements elevated in the lysimeter (Cd, Pb, and Zn) at 56th Street Overpass field site because lack of information would require so many assumptions to be made that confidence in the solution would be questionable. These elements were categorized as "indeterminate" but the overall risk of the roadway can be inferred from monitoring wells at that site.

12. The indirect assessment was only required for one element (Se) for bottom ash fill application and showed that this use posed no predicted risk at the modeled receptor points. Thus, the bottom ash fill application studied is suitable for beneficial reuse applications with respect to water quality.

13. No trends were found for elements requiring further investigation between field sites.

14. Reduction factors (RF) for these sites ranged from 46-88 and the average of the trace elements modeled at a field site was found to represent that site. RFs were controlled primarily by depth to groundwater table and secondarily by thickness of stabilized layer. More reduction occurred in roadways with a relatively deeper Z_{GWT}, thinner stabilized layer,lower seepage velocity in the vadose zone, and higher seepage velocity in the saturated zone.

15. An extended analysis was performed on RF at fly ash stabilized subgrade roadways (STH60-FA, US12-W, US12-E, Scenic Edge, MnROAD, and Waseca). The RF actually required to decrease C_O to water quality levels at POC were well below the RF that roadways exhibited in this study. This implies that less reduction could have taken place at the roadways and still imposed "no predicted risk."

16. The lowest calculated RF was 46. Element concentrations measured in field lysimeters at levels equal to or below 46 times the water quality limit were imposed no additional risk in where the groundwater table was at least 1 m below ground surface.

17. Concentration decreased by 6 times the C_O in the vadose zone as water flowed vertically underneath the centerline of the pavement section and decreased by 67 times the C_O just after the vadose-saturated zone boundary. Concentration reduced to an ultimate 69 times the C_O from the vadose zone to the POC, demonstrating that most concentration reduction occurred at the vadose-saturated zone boundary underneath the pavement section. This implies that the distance to the POC from the pavement layer is not influential.

18. Based on the responses of state DOTs, CCP use does not appear to correlate with region, but overall CCP use in additive roadway applications is small and monitoring of such projects is even smaller.

Overall, the study of water quality data collected from a significant number of field lysimeters demonstrated that there is no risk, no additional risk, or no predicted risks imposed by using additive fly ash or bottom ash in stabilizing roadways than roadways constructed with conventional construction materials, in terms of potential trace element impact on the environment. The study of water quality data collected from monitoring wells demonstrated that there was no risk or no additional risk imposed by using fly ash in a limited number of roadway embankment fills considered in this study.

The additive fly ash and bottom ash applications described in this study have been concluded to be suitable beneficial reuse applications with respect to water quality based on obtained water quality data. Water quality data used spans seven locations in four states, three substructure applications (fly ash stabilization, fly ash fill, and bottom ash fill) and 19 monitoring points. This reasonably large database analysis implies that fly ash and bottom ash used in substructure roadway applications are largely low risk and should not be prohibited by future regulations regarding the beneficial reuse of CCPs. Conclusions and reduction factors can be applied to similar roadways, however roadways with different field conditions than evaluated in this study (especially those with a thicker stabilized layer or groundwater that is closer to the base of the pavement structure) should be evaluated using the analytical procedure provided herein to ensure eluted trace element concentrations meet the water quality standards at a point of compliance.

Additionally, the analysis of field data has identified gaps and weaknesses in the dataset and recommendations have been made.

Recommendations include:

1. That detection limits of the analytical machine used to determine trace element concentrations always be below the water quality limits of the elements in order to truly establish the concentrations of the field and thus risk of field conditions.

2. That a control lysimeter always be installed at a field site location, and that field conditions be well documented so that an indirect assessment can be performed when required. Control sites should be monitored simultaneously with coal ash field sites to enable a paired-t statistical analysis to be performed.

3. To conduct further searches to unearth additional roadways outside of the Midwest to add to the database.

4. To conduct further searches to unearth additional bottom ash roadways, or other CCP sites, to enhance the CCP diversity of the database.

5. To conduct additional model simulations to better determine a relationship between the most sensitive parameters in the WiscLEACH modeling software, namely depth to groundwater

table and thickness of the CCP layer, to allow RF to be applied to as many other projects beyond the scope of this study as possible.

2
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A RISK ANALYSIS APPENDIX

QA/QC

Quality control was practiced by documenting analytical information, rating the quality of the data, and rating the availability of the data that comprises the database.

Data Quality

The data for each field site were rated in terms of quality using criteria related to monitoring technique, sampling method, preservation, analysis, and data recording and evaluation (Table A-1). A score of zero was assigned for each data quality criterion that was satisfied. For criteria that were not satisfied, a score of one (less important) or two (more important) was assigned. The individual scores were summed for each element at a monitoring location to define a composite score, with the best possible score zero and the worst possible score 13. The data were then ranked based on composite scores as follows: excellent (0 – 1 point), very good (2 – 5 points), good (6 – 9 points), and poor (10 – 13 points). The data quality ranking is independent of element for a project site, and data quality scores and ratings were included in the database to ensure the quality control and thus reliability of each data set is documented.

Each field site received a quality rating of at least very good, except 56th Street overpass, which obtained a rating of good. Scenic Edge and STH 60 were rated as excellent (Table A-2). 56th Street Overpass project gained most of its points from criteria not being documented. Only two criteria were completely fulfilled: information on site construction and documenting standard analytical methods used.

Table A-1
Criteria Used for Data Quality Evaluation

Category	Question	Points assigned if Yes	Points assigned if No
Site Construction	Was information on site construction provided?	0	1
Sampling	Was a standard method used for sampling with any modifications documented?	0	2
Preservation	Were samples stored at 4°C prior to testing? *	0	1
	Were samples acidified/preserved?*	0	1
	Were samples filtered through at least a 0.45-um membrane filter?*	0	1
Analytical Analysis	Was a standardized analytical method used with any modifications documented?	0	2
Data Recording / Evaluation	Was QA/QC discussion provided?	0	2
	Was the MDL given?	0	2

*Criterion is included in most standard sampling methods (i.e. EPA Method 1669 for Sampling Ambient Water for Trace metals at EPA Water Quality Criteria Levels, 1996) and analysis methods (i.e. APHA, AWWA, WEF Standard Method 3010, 3020, 3030 for Sample Preparation) but is broken out to ensure the criterion's consideration.

Table A-2
Data Quality Scores and Ratings for Roadways

Site	Score	Rating
STH60-FA	0	Excellent
US12	1	Very Good
Scenic Edge	0	Excellent
MnROAD	1	Very Good
Waseca	1	Very Good
Southwest Rome Bypass	1	Very Good

56th Street Overpass	9	Good
STH60-BA	0	Excellent

Data Availability

An assessment of data availability was to quantify the sampling density of the database. A sampling rate was determined for each data set as the total number of sampling events divided by elapsed time between construction completion and last sampling date. Sampling density in the initial part of each data set was also evaluated as the sampling density during the first year, when changes in concentration often are greatest [17, 26, 27, 47]. The overall sampling density and the density during the first year were averaged to create a composite data availability score. Data sets with the longest histories were ranked highest for a given site, with overall sampling densities then differentiating sets collected over the same time period. A rubric was created to assign a data availability rating based on the composite score. A rating of “excellent” was assigned to elements with a composite score of at least 4, “marginal” was assigned to elements with less than 1, and “good” for a composite score larger than 1 and less than 4 (Table A-3). An “excellent” rating is taken to be four or more samples per year because the USEPA requires at maximum quarterly sampling for superfund sites [49, 50]. A “marginal” rating is taken to be less than one sample per year because one sample per year is the required sampling rate of city ground water wells [51, 52]. The number of elements for each rating at each site is summarized in Table A-4. Individual data availability scores for all elements at all roadways are included in Appendix B.

Table A-3
Data Availability Rubric

Rating	Score
Excellent	≥ 4.0
Good	1.0 – 3.9
Marginal	< 1.0

The lowest rating attained by an element at a field site was 0.93. The highest rating was 10.27. When the ratings for every element were averaged for each site (STH60-BA, STH60-FA, US12, Scenic Edge, MnROAD, Waseca, Southwest Rome Bypass, and 56th Street Overpass) values were, respectively, 3.27, 2.67, 2.69, 0.93, 3.82, 3.30, 3.82, and 10.27. The overall average for all sites was 2.81 samples per year. Comprehensive data availability ratings for all elements at all roadways are included in Appendix B.

Table A-4
Frequency of Data Availability Scores

Site	Monitoring Point	Marginal	Good	Excellent
STH60	Bottom Ash	4	22	4
	Fly Ash	4	22	4
	Control	4	22	4
UW12	West Fly Ash	4	26	0
	East Fly Ash	1	29	0
	Control	2	28	0
Scenic Edge	Scenic Edge	0	16	14
MnROAD	RPM & Fly Ash	2	2	27
	RPM Control	2	2	27
Waseca	Waseca	0	22	0
Southwest Rome Bypass	SWRB-4	0	0	16
	SWRB-5	0	16	0
	SWRB-6	0	16	0
	SWRB-7	0	16	0
	SWRB-8	0	16	0
	SWRB-9	0	16	0
	SWRB-10	0	16	0
	SWRB-11	0	16	0
	SWRB-12	0	16	0
Southwest 56^{th} Street Overpass	56^{th} St. Overpass-W	0	0	12
	56^{th} St. Overpass-E	0	0	12
	56^{th} St. Overpass-	0	0	12

Analytical Information

Table A-5
Analytical and Sampling Methods Used

Field Site			Analytical Methods	Sampling Methods
Fly Ash	Soil Subgrade Stabilization	STH60	- Atomic Absorption (AA) according to EPA Standard Methods 213.2, 218.2, 270.2, and 272.2 - Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) according to USEPA Method 200.8 - Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) according to USEPA Method 6010B - Cold Vapor Atomic Fluorescence Spectrometry according to USEPA Method 1631, 1669	- EPA Method 1669, with additional precautions taken (EPA Method 1669 Part 4.0)
		US12	- Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) according to USEPA Method 200.8 - Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) according to USEPA Method 6010B - Cold Vapor Atomic Fluorescence Spectrometry according to USEPA Method 1631, 1669	- EPA Method 1669, with additional precautions taken (EPA Method 1669 Part 4.0)
		Scenic Edge	- Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) according to USEPA Method 200.8 - Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) according to USEPA Method 6010B - Cold Vapor Atomic Fluorescence Spectrometry according to USEPA Method 1631, 1669	- EPA Method 1669, with additional precautions taken (EPA Method 1669 Part 4.0)
	RPM Stabilization	MnROAD	- Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) according to USEPA Method 200.8 - Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) according to USEPA Method 6010B - Cold Vapor Atomic Fluorescence Spectrometry according to USEPA Method 1631, 1669	- EPA Method 1669, with additional precautions taken (EPA Method 1669 Part 4.0)
		Waseca	- Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) according to USEPA Method 200.8	- EPA Method 1669, with additional precautions taken (EPA Method 1669 Part 4.0)
	Structural Fill	Southwest Rome Bypass	- Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) according to EPA 6020A - Inductively Coupled Plasma according to EPA SW-846 6010C (ICP) - Ion Chromatography (IC) according to EPA SQ-846 9056A	- USEPA Region 4's Environmental Investigations Standard Operating Procedures Quality Assurance Manual, 2001
		56^{th} Street Overpass	-Metal analysis using Inductively Coupled Plasma (ICP) spectrophotometric procedure	- No methods identified
Bottom Ash	Subbase Fill	STH60	- Atomic Absorption (AA) according to EPA Standard Methods 213.2, 218.2, 270.2, and 272.2 - Inductively Coupled Plasma - Mass Spectrometry (ICP-MS) according to USEPA Method 200.8 - Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) according to USEPA Method 6010B	- EPA Method 1669, with additional precautions taken (EPA Method 1669 Part 4.0)

Table A-6
Summary of Minimum Detection Limits of Analytical Mehtods used at Roadways

Field Site	STH60 & US12 & Scenic Edge & MnROAD					Waseca	Southwest Rome Bypass	
Year	**2000-05**	**2005-07**	**2007-09**	**2009-10**	**2011-12**	**2004-08**	**2009-10**	**2010 -11**
Element	**AA**	**ICP MS**	**ICP–OES***	**ICP / MS**	**ICP -OES**	**ICP -MS**	**ICP-MS**	**ICP-MS**
Ag	0.2	1.9	1.9	2.0	0.9	0.02	2.0	2.0
Al	-	3.0	2.5	-	2.1	-	-	-
As	-	2.6	2	4.0	28.6	30	4.0	4.0
B	-	-	4	-	2.2	3	-	-
Ba	-	1.2	0.04	-	0.08	0.08	-	-
Be	-	0.5	1	1.0	0.11	0.1	1.0	1.0
Cd	0.1	1.0	0.2	1.0	0.53	3.0	1.0	1.0
Co	-	1.0	0.6	-	0.8	4.0	-	-
Cr	2.0	1.1	0.5	2.0	0.3	1.0	2.0	2.0
Cu	-	2	0.7	2.0	2.7	1.0	2.0	2.0
Hg	-	-	0.001*	0.07	-	0.02	0.07	0.07
F	-	-	10.0*	200	-	-	200	18.0
Fe	-	1.5	3.2	-	2.6	-	-	-
Mn	-	0.8	0.05	-	0.13	0.5	-	-
Mo	-	-	0.5	-	2.1	4.0	-	-
Ni	-	1.5	0.7	-	1.8	3.0	3.0	3.0
Pb	-	5.5	4	-	3.8	20	2.0	2.0
Sb	-	4	3	-	6.1	1.0	2.0	2.0
Se	2.0	3.7	17	-	44.2	30	4.0	4.0
Sn	-	-	5	-	8.0	1.0	-	-
Sr	-	-	0.3	-	0.13	1.0	-	-
Ti	-	-	0.4	-	0.3	?	-	-
Tl	-	2.7	4.7	-	14.2	1.0	0.25	0.25
V	-	-	0.1	-	1.0	3.0	2.0	2.0
Zn	-	0.8	0.1	-	0.5	1.0	8.0	8.0

*OPT-CVAFS 2008-2009
- Denotes elements that were not sampled
Note: No detection limits were available for the 56th Street overpass field site in Indiana

Paired-T Analysis

Table A-7
Summary of Paired-T statistics for elements imposing no additional risk

Field Site	Element	As	Ag	Cd	Cr	Cu	F	Ni	Pb	Sb	Tl	Zn
STH60-FA	# Samples	9	-	-	-	27	-	11	3	5	-	40
	P-value	0.831	-	-	-	0.907	-	0.257	0.477	0.738	-	0.558
US12-W	# Samples	-	10	-	-	-	-	-	14	15	3	-
	P-value	-	0.327	-	-	-	-	-	0.145	0.286	0.263	-
US12-E	# Samples	-	11	-	-	23	-	-	-	-	5	-
	P-value	-	0.511	-	-	0.936	-	-	-	-	0.479	-
MnROAD	# Samples	5	-	2	4	-	5	-	-	6	5	9
	P-value	0.212	-	0.500	0.207	-	0.190	-	-	0.344	0.966	0.197
SWRB-4	# Samples	8	-	8	-	8	-	-	8	-	-	8
	P-value	0.190	-	0.351	-	0.171	-	-	0.116	-	-	0.003
SWRB-6	# Samples	12	-	12	-	12	-	-	12	-	-	12
	P-value	0.3388	-	0.339	-	0.312	-	-	0.307	-	-	0.240
SWRB-7	# Samples	-	-	-	-	-	-	-	-	-	-	12
	P-value	-	-	-	-	-	-	-	-	-	-	0.249
SWRB-10	# Samples	-	-	-	-	-	-	-	12	-	-	-
	P-value	-	-	-	-	-	-	-	0.339	-	-	-
SWRB-11	# Samples	11	-	-	-	11	-	-	-	-	-	11
	P-value	0.341	-	-	-	0.341	-	-	-	-	-	0.261
56th St. Overpass-W	# Samples	-	-	2	-	-	-	-	-	-	-	2
	P-value	-	-	0.347	-	-	-	-	-	-	-	0.734
56th St. Overpass-E	# Samples	-	-	-	-	-	-	-	-	-	-	2
	P-value	-	-	-	-	-	-	-	-	-	-	0.248
STH60-BA	# Samples	17	16	19	-	-	-	-	9	13	2	47
	P-value	0.0526	0.299	0.724	-	-	-	-	0.858	0.318	0.560	0.548

No Risk after First Flush

Non-CCP conditions constitute an assumed risk level society is willing to accept. Elements at a site were identified if they had time varying concentrations that were initially above water quality standards and fell below standards within the first flush period. A first flush period is defined for this study as 2 pore volumes of flow (PVF), which is an alternative measure to time that instead measures how many times the pore volume of a soil/material is replaced by a liquid. Two PVF can correspond to anywhere from about 3.5 years to greater than 9 years depending on material, according to RMRC data. Time varying elements that were initially above limits but that fell below by 2 PVF would impose no risk after first flush, but would still require additional analysis via the indirect assessment.

Two elements, Cd and Pb, posed no risk after the first flush (and were not already categorized as no risk) in the cases summarized in Table C-2. Note that eight of the 13 instances could be categorized as imposing no additional risk relative to controls, and the remaining four were categorized as imposing no predicted risk. Because all elements initially categorized as imposing no risk after first flush were given a second categorization, the no risk after first flush nomenclature was abandoned.

No elements were identified as imposing no risk after first flush (and were not already categorized as no risk) for roadways where monitoring wells were the monitoring method. This could be due to the detection limits of the analytical machines used to determine trace element concentrations or due to the dilution and attenuation that takes place in water as water flows through the vadose and saturated zones.

Table A-8
No Risk After First Flush

Category		No Risk After First Flush			
Water Quality Limit		Drinking Water		Surface Water	
		Federal	State	Federal	State
FA	STH60	Cd, Pb*	Cd	-	Cd
	US12-W	Pb*	-	Pb*	-
	US12-E	Pb*	-	-	-
	Scenic Edge	-	-	-	-
	MnROAD	Cr	-	-	-
	Waseca	-	-	-	-
BA	STH60	Cd*, Pb*	Cd*, Pb*	-	Cd

- Denotes water quality limits for which no element fell in to the no risk after first flush category.
* Denotes elements that were also found to impose no additional risk. All elements NOT denoted by * were found to also impose no predicted risk.

Direct Analysis Results

Table A-9
Direct Analysis Results [26].

Field Site	Element	Ag	Al	As	Be	Cd	Cu	Ni	Pb	Sb	Se	Tl	Zn
STH60-FA	C_O	11.3	-	-	-	32.1	-	-	-	-	164.5	75.1	-
	$C_{POC@20}$	0.14	-	-	-	0.42	-	-	-	-	2.02	0.87	-
	RF	80.7	-	-	-	76.3	-	-	-	-	81.4	86.3	-
US12-W	C_O	4.0	10744	-	-	-	421.4	229.0	-	-	147.6	-	2204
	$C_{POC@20}$	0.07	210.7	-	-	-	8.09	4.43	-	-	2.65	-	42.5
	RF	57.1	51.0	-	-	-	52.1	51.7	-	-	55.6	-	51.9
US12-E	C_O	-	-	108.8	-	-	-	350.8	23.4	20.9	148.5	-	427.2
	$C_{POC@20}$	-	-	1.72	-	-	-	5.57	0.36	0.33	2.24	-	6.77
	RF	-	-	63.1	-	-	-	63.0	64.4	64.1	66.3	-	63.1
Scenic Edge	C_O	-	-	311.8	-	-	52.7	-	-	8.3	-	-	274.0
	$C_{POC@20}$	-	-	4.35	-	-	0.69	-	-	0.11	-	-	3.59
	RF	-	-	71.7	-	-	76.5	-	-	77.2	-	-	76.2
MnROAD	C_O	8.9	-	-	5.8	-	-	-	-	-	392.8	-	-
	$C_{POC@20}$	0.18	-	-	0.12	-	-	-	-	-	7.93	-	-
	RF	50.3	-	-	47.2	-	-	-	-	-	49.5	-	-
Waseca	C_O	-	-	42.8	-	-	-	-	125.0	21.8	-	55.9	-
	$C_{POC@20}$	-	-	0.72	-	-	-	-	1.99	0.35	-	0.83	-
	RF	-	-	59.6	-	-	-	-	62.5	62.5	-	67.0	-
STH60-BA	C_O	-	-	-	-	-	-	-	-	-	208.3	-	-
	$C_{POC@20}$	-	-	-	-	-	-	-	-	-	3.79	-	-
	RF	-	-	-	-	-	-	-	-	-	55.0	-	-

Table A-10
Elements for which CCP use in roadway applications posed no risk.

Category		No Risk			
Water Quality Limit		Drinking Water		Surface Water	
		Federal	State	Federal	State
FA Stabilization	STH60-FA	Ba, Be, Cr, Cu	Ba, Be, Cr, Cu	Al, As, Cr, Pb	As, Cr, Pb
	US12-W	Ba, Be, Cd, Cr, Cu	Ba, Be, Cd, Cr, Cu	As, Cr, Ni	As, Cd, Cr, Ni, Pb
	US12-E	Ba, Be, Cd, Cr, Cu	Ba, Be, Cd, Cr, Cu	Al, As, Cr, Ni, Pb	As, Cd, Cr, Ni, Pb
	Scenic Edge	Ba, Be, Cd, Cr, Cu, Pb, Se, Tl	Ba, Be, Cd, Cr, Cu, Pb, Ni, Se, Tl	Ag, Al, As, Cr, Ni, Pb	As, Cd, Cr, Ni, Pb
	MnROAD	Ba, Cd, Cu, Pb	Ba, Cd, Cu, Ni, Pb	Al, Cr, Ni, Pb	Al, Co, Cr, Cu, Ni, Pb
	Waseca	Ba, Be, Cd, Cr, Cu, Hg, Se	Ba, Be, Cd, Cr, Cu, Hg, Ni, Se	Ag, As, Cr, Hg, Ni, Zn	Ag, As, Cd, Co, Cr, Cu, Ni, Sb, Se, Tl, Zn
FA Fill	SWRB-4	Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb	As, Cr, F, Ni
	SWRB-5	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb, Zn	As, Cd, Cr, Cu, Ni, Pb, Zn
	SWRB-6	Ba, Be, Cd, Cr, Cu, F, Hg, Sb, Se, Tl	Ba, Be, Cd, Cr, Cu, F, Hg, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb	As, Cr, Ni
	SWRB-7	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb, Zn	As, Cd, Cr, Cu, Ni, Pb
	SWRB-8	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb, Zn	As, Cd, Cr, Cu, Ni, Pb, Zn
	SWRB-9	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb, Zn	As, Cd, Cr, Cu, Ni, Pb, Zn
	SWRB-10	As, Ba, Be, Cd, Cr, Cu, F, Hg, Sb, Se, Tl	As, Ba, Be, Cd, Cr, Cu, F, Hg, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb, Zn	As, Cd, Cr, Cu, Ni, Pb, Zn
	SWRB-11	Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb, Zn	As, Cd, Cr, Ni, Pb
	SWRB-12	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	As, Ba, Be, Cd, Cr, Cu, F, Hg, Pb, Sb, Se, Tl	Ag, As, Cr, Hg, Ni, Pb, Zn	As, Cd, Cr, Cu, Ni, Pb, Zn
	56th St. Overpass-W	Cr, Cu, Pb,	Cr, Cu, Pb	Al, Cr, Ni, Pb	-
	56th St. Overpass-E	Cd, Cr, Cu, Pb	Cd, Cr, Cu, Pb	Al, Cr, Ni, Pb	-
	56th St. overpass-L	Cr, Cu	Cr, Cu	Al, Cr, Ni	-
BA	STH60-BA	Ba, Be, Cr, Cu	Ba, Be, Cr, Cu, Ni	Al, As, Cr, Ni, Pb	As, Cr, Ni, Pb

- Denotes roadways for which no water quality limit existed.

Table A-11
Elements for which CCP use in roadway applications posed no additional risk relative to controls.

Category		No Additional Risk			
Water Quality Limit		Drinking Water		Surface Water	
		Federal	State	Federal	State
FA Stabilization	STH60-FA	As, Pb, Sb	As, Ni, Pb, Sb	Ni, Zn	Cu, Ni, Zn
	US12-W	As, Pb, Sb, Tl	As, Pb, Sb, Tl	Pb	-
	US12-E	Tl	Tl	Ag	Cu
	Scenic Edge	-	-	-	-
	MnROAD	As, Cr, F, Sb, Tl	As, Cr, F, Sb, Tl	As, Zn	As, Cd, Sb, Tl, Zn
	Waseca	-	-	-	-
FA Fill	SWRB-4	As	As	Zn*	Cd, Cu, Pb, Zn*
	SWRB-5	-	-	-	-
	SWRB-6	As, Pb	As, Pb	Zn	Cd, Cu, Pb, Zn
	SWRB-7	-	-	-	Zn
	SWRB-8	-	-	-	-
	SWRB-9	-	-	-	-
	SWRB-10	Pb	Pb	-	-
	SWRB-11	As	As	-	Cu, Zn
	SWRB-12	-	-	-	-
	56th St. Overpass-W	Cd*	Cd*	Zn*	-
	56th St. Overpass-E	-	-	Zn*	-
	56th St. overpass-L	-	-	-	-
BA	STH60-BA	As, Cd, Pb, Sb, Tl	As, Cd, Pb, Sb, Tl	Ag, Zn	Cd, Cu, Zn

- Denotes roadways where paired-t test was not performed (no control lysimeter or not required).
* Denotes elements compared to background concentrations via unpaired-t test to be classified as no additional risk.
Note: Scenic Edge, Waseca, and 56th St. Overpass-L did not have control lysimeters. Southwest Rome Bypass roadways were compared to SWRB-5 (determined to be the control well).

Indirect Assessment Results

Table A-12
Number of sites for which an element requires further evaluation.

Element	Total	No. of Sites Requiring Further Evaluation for Drinking Water Standards		No. of Sites Requiring Further Evaluation for Surface Water Standards	
		Federal	State	Federal	State
Ag	4	0	0	3	1
Al	1	0	0	1	0
As	6	3	3	0	0
Be	2	1	1	0	0
Cd	3	1	1	0	1
Cu	2	0	0	0	2
Ni	2	0	2	0	0
Pb	7	2	2	2	1
Sb	4	2	2	0	0
Se	11	5	5	0	1
Tl	4	2	2	0	0
Zn	6	0	0	3	3

Note: Indirect assessment could not be performed on 56th St. Overpass-L field site.

Table A-13
Elements for which fly ash use in roadway applications posed no predicted risk at POC.

Category		No Predicted Risk at Point of Compliance (POC)			
Water Quality Limit		Drinking Water		Surface Water	
		Federal	State	Federal	State
FA	STH60-FA	Cd, Se, Tl	Cd, Se, Tl	Ag	Cd
FA	US12-W	Se	Ni, Se	Ag, Al, Zn	Cu, Zn
FA	US12-E	As, Pb, Sb, Se	As, Ni, Pb, Sb, Se	Zn	Zn
FA	Scenic Edge	As, Sb	As, Sb	Zn	Cu, Zn
FA	MnROAD	Be, Se	Be, Se	Ag	Ag, Se
FA	Waseca	As, Pb, Sb, Tl	As, Pb, Sb, Tl	Pb	Pb
FA Fill	SWRB-4	-	-	-	-
FA Fill	SWRB-5	-	-	-	-
FA Fill	SWRB-6	-	-	-	-
FA Fill	SWRB-7	-	-	-	-
FA Fill	SWRB-8	-	-	-	-
FA Fill	SWRB-9	-	-	-	-
FA Fill	SWRB-10	-	-	-	-
FA Fill	SWRB-11	-	-	-	-
FA Fill	SWRB-12	-	-	-	-
FA Fill	56th St. Overpass-W	-	-	-	-
FA Fill	56th St. Overpass-E	-	-	-	-
BA	56th St. overpass-L	Se	Se	-	-

Note: Southwest Rome Bypass and 56th Street Overpass roadways did not require an indirect assessment
- Denotes roadways where indirect assessment was not performed (not required or not possible).

Additional WiscLEACH Modeling Information

The hydrologic modeling that comprised the indirect assessment was conducted using WiscLEACH software, which was developed specifically for evaluating the potential for impacts to ground water by industrial byproducts incorporated into a roadway [34, 46]. WiscLEACH follows the advective-dispersive-reaction-equation (ADRE) in one dimension through the vadose zone and in two dimensions through the saturated zone. The 2D column leach test simulation for adsorption controlled release was used in WiscLEACH [19, 31, 47]. Input concentration, C_O, is applied evenly throughout the stabilized layer within the software, and was conservatively taken as the maximum concentration documented for each element at each field site.

Maximum concentration at POC, or $C_{POC@20}$, was output. The continuous injection type-2 boundary modeled at the boundary beneath the stabilized layer implies that a sustained mass was leached, which is a conservative assumption that allowed the maximum $C_{POC@20}$ to be obtained from the model. The breakthrough curve for a typical field site in Minnesota or Wisconsin was established to determine when the $C_{POC@20}$ was reached. Regardless of trace element modeled, $C_{POC@20}$ was reached by 5 years, which is within the lifetime of a road (typically 20 to 40 years) [2, 53]. Values of $C_{POC@20}$ for each element were evaluated as above or below the drinking water or surface water standard in a manner similar to the direct assessment.

The POC was taken as the right-of-way of the roadways (20 m), which is the regulatory POC for water quality for many roadway applications [46], defined from the center-line of the road to the edge of the right-of-way. Scaling and retardation factors were conservatively assumed to be one, i.e., no retardation. Published molecular diffusion coefficients were input for each trace element or a low (conservative) molecular diffusion coefficient of 0.005 m^2/yr. was assumed for elements that had no published values (As, Sn, Ti, and V) [54]. Dispersivities were taken as one-tenth the domain and recommended grid parameters from Li et al. 2006 were used [46]. A summary of site-specific WiscLEACH model inputs is provided in Table 1-4.

Hydraulic conductivities of pavement and base layers were taken to be 1 since these layers do not limit infiltration. Since WiscLEACH assumed steady 1D unit gradient flow the software applies an average seepage velocity above the groundwater table, taken as the smallest combination of hydraulic conductivity divided by porosity, or infiltration rate divided by porosity [34]. For fly ash-stabilized subgrade sites (i.e. STH60, US12, and Scenic Edge), hydraulic conductivity of the subgrade is limiting. For fly ash-stabilized RPM sites (i.e. Waseca and MnROAD), infiltration is limiting. Hydraulic conductivity of the subbase constructed of bottom ash at SHT60-BA was varied using typical values for lean silt or lean clays [55]. The upper range of hydraulic conductivities was chosen (0.126 m/yr.) because higher values predict larger $C_{POC@20}$ and are thus more conservative. Porosity of the CCP layer was calculated as 0.42 based off given parameters. Site specific field parameters can be found in Table 1-4.

The hydraulic conductivity of the stabilized layer was assumed to be the same for US12 and Scenic Edge as was reported for STH60 (i.e. 0.19m/yr.) because all three roadways were constructed almost identically [34, 46]. The percent fly ash composition is similar for these sites (10% or 12%), fly ash is from the same plant source, and the fly ash-stabilized layers were constructed to the same thicknesses and to similar densities [20, 31].

The hydraulic conductivity of fly ash-stabilized RPM was assumed to be 757.4 m/year, which is from the bottom range of values published by Trzebiatowski et al. 2005 [56] for RPM as base course aggregate in pavement construction. The values do not take into account fine content or self-cementing properties of fly ash, but the values fall within the typical hydraulic conductivity ranges of sand (course, medium, and fine) and silt/loess [55]. The values are 3 to 4 orders of magnitude larger than the hydraulic conductivity values used for the fly ash-stabilized layers. Larger hydraulic conductivities in the limiting layer results in a more conservative $C_{POC@20}$, but this is irrelevant at RPM roadways because hydraulic conductivity of the fly ash-stabilized RPM layer is not affecting the limiting seepage velocity.

Subgrade types were established from soil survey maps and the accompanying hydraulic conductivity values were used. Subgrade soil types were taken to be Plano Silt Loam (PnB) at STH60, Fox silt loam (FsB) at US12 West, Fox silt loam (FsA) at US12 East, Plano silt loam

(PoA) at Scenic Edge, Reedslake loam (L113B) at Waseca, and Angus-Cordova complex (1094B) at MnROAD [57]. The smallest published values were used for hydraulic conductivity because the subgrade was compacted, and not in-situ conditions. This is most likely an over-estimation of what the k values should be in-situ, but the parameter was not found to be sensitive in the sensitivity analysis [34, 46].

Infiltration rates were taken as the average annual precipitation from the nearest NOAA weather station [58, 61]. Weather stations were matched to those used in literature where applicable [36]. Average annual precipitation was calculated from years of complete historical precipitation data. O'Donnell et al. 2010 showed that long-term leachate flux measured in the field from fly ash-stabilized layers was discharged at rates significantly less than the precipitation rate. This is supported during modeling by the hydraulic conductivity of the fly ash-stabilized subgrade layer being the limiting hydraulic conductivity and controlling seepage velocity. O'Donnell's study also showed that infiltration rates were slightly higher for fly ash-stabilize base course layers than fly ash-stabilized subgrade, which is supported during modeling by the infiltration rate, or precipitation rate, being the limiting hydraulic conductivity and controlling seepage.

Porosity for stabilized layer was given by the literature [17, 20]. Porosity was determined for subgrade soils from optimum water content and dry unit weight given by the literature. The water content in situ was assumed to be equivalent to the optimum water content, wet unit weight was 9.807 kN/m3 (standard value), and specific gravity was 2.65 for silt and 2.7 for clay. The subgrade values calculated were lower than the in-situ ranges published in Schwartz and Zhang, 2003 [55], which is to be expected because the subgrade was compacted to a specified field density at the optimum water content. Additionally, the porosity of the subgrade did not affect the $C_{POC@20}$ in the sensitivity analysis performed, which is supported by the literature [34, 46]. Larger porosity for the subgrade is more conservative, so for the stabilized layer values, the larger values published were used (in the literature).

Depths to GWT (Z_{GWT}) were taken from the NRCS's Soil Survey because they were shallower (more conservative) than depths observed by USGS monitoring wells (see Table A-14) [57]. Choosing the more conservative Z_{GWT} was imperative because parametric studies and the literature showed that depth to ground water was the most sensitive WiscLEACH parameter [34, 46]. Depths to ground water table (Z_{GWT}) were evaluated from wells located in the county of roadways monitored by the USGS [59]. Average values were compared to the depths reported by the Soil Survey (NRCS Web Soil Survey). Additionally, GWM wells at STH60 were dry at 2.74, 2.44, and 2.44 m, which corroborate soil survey depths [27].

Table A-14
Depths to Groundwater from USGS [59] and Soil Survey [57].

Roadways	Z_{GWT} (m) USGS	Z_{GWT} (m) Soil Survey
STH60-FA	3.24	>2.032
US12-W	3.24	1.524-2.032
US12-E	3.24	>2.032
Scenic Edge	3.24	>2.032
Waseca	NA	1.092 - 2.032
MnROAD	3.694-3.917	1.092
STH60-BA	3.24	>2.032

*Given in literature.
Note: Smaller values were chosen for WiscLEACH modeling, which in all cases was Soil Survey.

Horizontal and vertical dispersivities were assumed to be one tenth the horizontal and vertical domain [34, 61]. This assumption is consistent with dispersivities used in Bin-Shafique et al. 2002 [20]. Additionally, dispersivities were not determined to be a sensitive parameter [40].

Typical values of saturated hydraulic conductivity, porosity, and regional hydraulic gradient for sand and gravel [34, 60, 61] were used for all roadways because they are all within the Cambrian-Ordivician Sandstone aquifer system [62]. Saturated hydraulic conductivity was 3156 m/yr.; porosity was 0.3; and the regional hydraulic gradient was 0.001.

Maximum temporal and spatial discretizations were used based off the maximum values that would obtain accurate solutions [34], i.e. a grid x of 1.0 m, a grid z of 0.1 m, and a time step of 0.4 yr. A maximum simulation time of 200 years was used [34].

To evaluate the bottom ash field site at STH60, hydraulic conductivity of the stabilized layer was varied using typical values for silty-clay [55], which is what the bottom ash at STH60 was categorized as. The upper range of hydraulic conductivities was chosen (0.126 m/yr.) because higher values predict larger $C_{POC@20}$ and are thus more conservative.

Tabulated values of molecular diffusion were used for each element [54] are presented in Table A-15. Conservative assumptions of 0.005 m^2/yr. were made if there was no published value.

Table A-15
Tabulated values of molecular diffusion for elements.

Element	Diffusion Coefficient (m^2/yr.)	Element	Diffusion Coefficient (m^2/yr.)
Ag	0.052	Mn	0.022
Al	0.017	Mo	0.063
As	0.005*	Ni	0.021
B	0.018	Pb	0.030
Ba	0.027	Sb	0.027
Be	0.019	Se	0.043
Br	0.066	Sn	0.005*
Cd	0.023	Sr	0.025
Co	0.023	Ti	0.005*
Cr	0.019	Tl	0.063
Cu	0.023	V	0.005*
F	0.0046	Zn	0.022
Fe	0.019	-	-

*Denotes conservative assessment. Values from [53].

B CCP USE APPENDIX

CCP Use

State Departments of Transportations were contacted to obtain information on states' use of CCPs in roadway applications, of which 45 provided responses (Table B-1). Illinois, Kansas, Maryland, New Hampshire, and Wyoming (5states) did not. The information collected in this survey is valuable becuase indiciduatl power plants are not allowed to divulge their use or selling of CCPs in otder to comply with antitrust laws. All power company data, however, can be reported to a source aggregator, such as the American Coal Ash Association (ACAA). Of the responding states, 17 states wished to remain confidential. CCPs reportedly utilized on an annual basis include fly ash (43 states), bottom ash (4 states), and CCP boiler slag (2 states). No states reported using FGD material in roadway construction. Most of these were a single CCP used per state, with only 6 states using two CCP types. Hawaii and Maine were the only states to report no use of CCPs.

Reported matrix applications include concrete additive (38 states), hot mix asphalt additive (7 states), flowable fill (3 states), and foamed asphalt for full-depth reclamation material (1 state). Additive applications include subgrade stabilization (11 states), base stiffener (5 states), fill (3 states), subbase stiffener (2 states), and anti-skid (1 state). The trend of fly ash being used more tha bottom, which is used more boiler slag, is consistent with the ACAA 2012 report of use [8]. FGD material was repotedly not used in anys tate, eventhough its national reuse rate is second only to fly ash [8]. This is because FGD materials is primarily used in gypsum panel products, such as wallboard [8].

Table B-1
CCP Uses in the United States

State	Approximate CCPs Utilized Per Year	Matrix Applications Utilized	Additive Applications Utilized	Percent of CCPs used in Additive Applications
Alaska	Fly ash - unknown qty.	Foamed asphalt for FDR material	-	0%
Colorado	Fly ash - unknown qty.	Concrete additive	-	0%
Connecticut	Fly ash - unknown qty. Boiler slag - unknown qty.	Concrete additive	-	0%
Florida	Fly ash - unknown qty.	Concrete additive	-	0%
Georgia	Fly ash - unknown qty.	Concrete additive HMA additive	Base stiffener Fill	0.01%
Hawaii	None	-	-	0%
Idaho	Fly ash - unknown qty.	-	Subgrade stabilizer	Unknown
Indiana	Fly ash - unknown qty. Bottom ash - unknown qty.	Flowable fill	Fill (BA) Subgrade stabilizer	10% and 100% respectively
Kentucky	Fly ash - unknown qty.	Concrete additive	-	0%
Maine	None	-	-	0%
Massachusetts	Fly ash - unknown qty.	Concrete additive Flowable fill	-	0%
Michigan	Fly ash – unknown qty.	Concrete additive	-	0%
Minnesota	Fly ash - unknown qty.	Concrete additive	Subgrade stabilizer	>5%
Mississippi	Fly ash - low/zero quantities	-	Base stiffener	100%
Missouri	Fly ash - 40,400 tons Boiler slag - unknown qty.	Concrete additive Asphalt additive	Base stiffener	Unknown and 0% respectively
Montana	Fly ash - 189,000 tons	Concrete additive	Base stiffener	Very little
Nevada	Fly ash - 4,000 tons	Concrete additive	-	0%
New Jersey	Fly ash - 1,000 tons	Concrete additive	-	0%
New Mexico	Fly ash - unknown qty.	Concrete additive	-	0%
New York	Fly ash - unknown qty.	Concrete additive	-	0%
Ohio	Fly ash - unknown qty.	Concrete additive	-	0%
Rhode Island	Fly ash - 31 tons	Concrete additive	-	0%
Confidential	Fly ash - unknown qty.	Concrete additive	-	0%
South Dakota	Fly ash - unknown qty.	Concrete additive HMA additive	Subgrade stabilizer	Unknown
Tennessee	Fly ash - unknown qty.	Concrete additive	-	0%
Utah	Fly ash - unknown qty.	Concrete additive	-	0%
Vermont	Fly ash - 3,250 tons	Concrete additive	-	0%

Washington	Fly ash - unknown qty.	Concrete additive HMA additive	-	0%
Wisconsin	Fly ash - 50,000 tons	Concrete additive	-	0%
Confidential	Fly ash - unknown qty.	Concrete additive HMA additive	-	0%
Confidential	Fly ash - 35,000 tons	Concrete additive	-	0%
Confidential	Fly ash - unknown qty.	Concrete additive	Subgrade stabilizer	Very little
Confidential	Fly ash - unknown qty.	Concrete additive	-	0%
Confidential	Fly ash - 1,300 tons	Concrete additive	Fill	Very little
Confidential	Fly ash - unknown qty.	Concrete additive	Subbase stiffener	<5%
Confidential	Fly ash - 30,000 tons Bottom ash - unknown qty.	Concrete additive HMA additive	Base stiffener Subbase stiffener Subgrade stabilizer	Unknown
Confidential	Fly ash - 58,000 tons	Concrete additive	Subgrade stabilizer	50%
Confidential	Fly ash - 20,000 tons	Concrete additive	-	0%
Confidential	Fly ash - unknown qty.	Concrete additive	-	0%
Confidential	Fly ash - unknown qty.	-	Subgrade stabilizer	100%
Confidential	Fly ash - unknown qty.	Concrete additive	-	0%
Confidential	Fly ash – 378,000 tons Bottom ash - unknown qty.	Concrete additive HMA additive Flowable fill (fa)	Subgrade stabilizer (fa) Anti-skid (ba)	5% & 50% respectively
Confidential	Fly ash - 150,000 tons	Concrete additive	Subgrade stabilizer	>5%
Confidential	Fly ash - unknown qty.	Concrete additive	-	>5%
Confidential	Fly ash - unknown qty. Bottom ash – unknown qty.	Concrete additive	Subgrade stabilizer	Unknown & 100% (respectively)

FDR = full-depth reclamation
HMA = hot mix asphalt

Fly Ash

Fly ash was the most commonly reported CCP used both in matrix applications (40 out of 45 states) and additive applications (18 out of 45 states). Matrix applications used include concrete, hot mix asphalt, and/or flowable fill. Additive applications used include subgrade stabilizer, base stiffener, fill, subbase stabilizer, and anti-skid, with the number of states using them descending in that order. The use of fly ash by DOTs was difficult to compare to CCP-use summaries from ACAA since the latter includes many construction applications besides roadway applications. Out of the 45 states that utilize fly ash, 62% (28 states) did not or could not report a quantity of weight or volume used.

Most states using fly ash in additive applications were also using fly ash in matrix applications (15 of 18 states, or 83%), but less than half of states using fly ash in matrix applications also used fly ash in additive applications (15 of 40 states, or 38%).

State DOTs were queried regarding the relative proportion of fly ash used in additive versus matrix applications. Two out of 46 states using fly ash in additive applications use >90% of fly ash in additive conditions, 1 state uses 50% of fly ash in additive conditions, 28 states use <10% of fly ash in additive conditions, and 5 states use an unknown percent of fly ash in additive conditions (Figure B-1). That amounts to 61% of states using a low percentage of fly ash in additive conditions, with an additional 11% of states reporting an unknown percentage of fly ash.

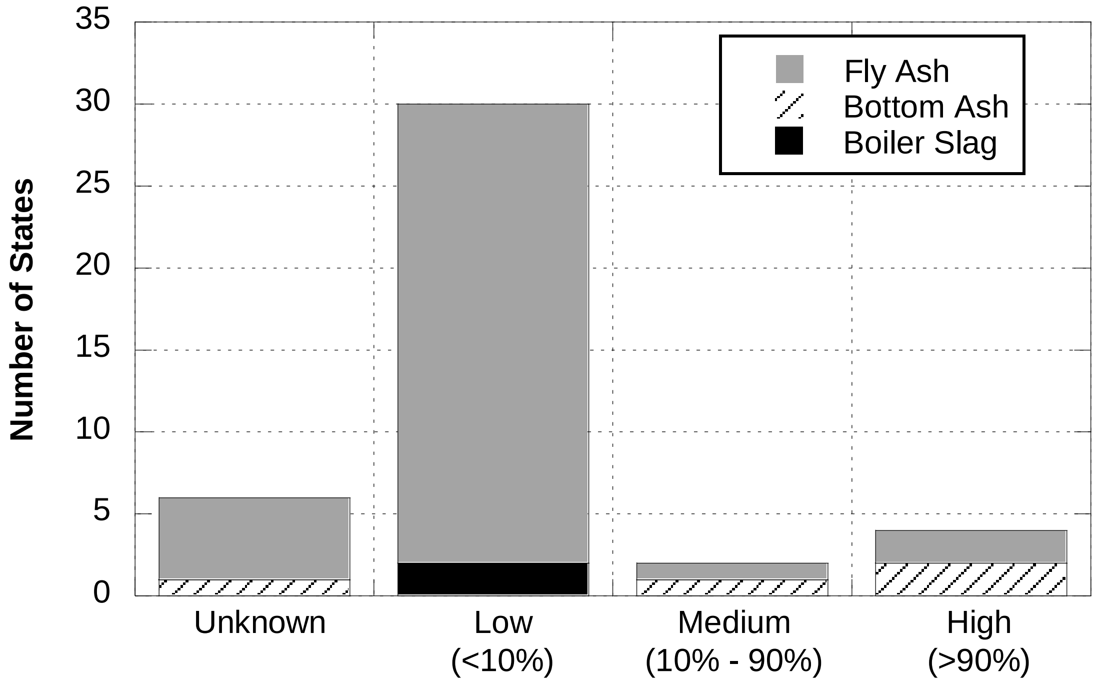

Figure B-1
Proportions of CCP used be DOTs in additive roadway applications.

Bottom Ash

Bottom ash was used in additive applications in 4 out of 4 states that utilized bottom ash (Indiana and 3 confidential states). Two of these sites used fly ash in matrix applications as well. The percent of bottom ash used in additive applications (out of all bottom ash used in both additive and matrix roadway applications) were 100%, 100%, 50%, and unknown. Additive bottom ash applications included subgrade stabilization, fill, and anti-skid. Out of the 4 states that utilize fly ash, 75% (3 states) did not or could not report a quantity of weight or volume used. All four states utilizing bottom ash also used fly ash (in additive applications).

Bottom ash was used in additive applications in all four states that use bottom ash in roadway applications. Additive applications of bottom ash included subgrade stabilization, structural and embankment fill, and anti-skid material. All of the states that use bottom ash did not or could not report a quantity used and all four states using bottom ash also used fly ash in additive applications. This is consistent with ACAA use reports. Blended cement and structural fill/embankments are the two leading uses, and they are tied in magnitude.

Boiler Slag

Boiler slag is solid material that forms during cooling of molten slag in the boiler. Boiler slag generally consists of black or grey particles that are relatively uniform in size, angular, hard, and resistant to surface wear. Boiler slag is used as a blasting grit, roofing granules, mineral filler in hot mix asphalt, structural and embankment fill, as aggregate in in concrete, and for traction control in regions with snow and ice. The durability and color of boiler slag make it particularly desirable for use in hot mix asphalt.

Boiler slag was only reportedly used in matrix applications (Connecticut and Missouri) as concrete or HMA additive. Fly ash was also used in these states. This is surprising as ACAA reports no use of boiler slag in concrete or cement, and instead cites the largest roadway uses to be fill or road base/subbase. The amount of boiler slag being used was not reported by any of the states.

Evaluation against Regulatory Statuses

In the US, 18 states have fly ash use in additive roadway applications specifically authorized in state law or regulations, and 11 states have fly ash use in additive roadway applications authorized with permission. This amounts to only 58% of the US possessing legislature in favor of fly ash use. The remaining states' laws and regulations do not contain any specification to fly ash use in additive applications [67].

The DOT survey found that the chance of CCPs being used in additive applications increased in states where fly ash authorization is explicitly included in legislation or regulation: 50% of states reporting additive fly ash use had legislation authorizing fly ash use, 39% had legislation authorizing fly ash with some sort of permission, and 75% of states reporting additive bottom ash use had no mention in legislation [67]. The likelihood of bottom ash being used also goes up when fly ash is authorized in legislation (3 authorized, 1 authorized with permission, 0 not specified).

Wisconsin DOT (WisDOT) is an excellent example. As part of a beneficial use of industrial byproducts initiative, Wisconsin has adopted fly ash-stabilization of soft subgrades as a preferred technology through NR 538 of the WI Administrative Code because of substantial reductions in construction time, which is important in regions that have a short construction season. Fly ash use is allowed in different soil and pavement applications based on ASTM C618 criteria for coal fly ash (NR 538). This legislation allows for the streamlined approval of fly ash. As a result, WisDOT has been able to take advantage of the material property enhancements and economic benefits of using fly ash, so much so that all fly ash meeting the ASTM criteria is used in Wisconsin [63]. The demand for fly ash is so high that WisDOT is actively seeking out-of-state sources within an economical shipping radius [63]. This demand was created by having legislation that facilitated safe reuse of CCPs.

Summary

A survey of state DOTs (45 states responding) indicated that matrix applications of CCPs include concrete (38 states), hot mix asphalt (7 states), flowable fill (3 states), and full-depth reclamation material (1 state). Additive applications of CCPs included subgrade stabilization (11 states), base stiffener (5 states), structural or embankment fill (3 states), subbase stiffener (2 states), and anti-skid applications (1 state), with the number of states using them descending in that order. Additive applications of fly ash generally comprised less than 10% of the total fly ash used in roadway construction. Thus, a large opportunity exists to increase the amount of fly ash used in roadway construction by expanding use in additive applications. For bottom ash, uses in additive and matrix applications were comparable. Boiler slag was used solely in matrix applications.

C EXTENDED BACKGROUND APPENDIX

CCP Support and Regulation

State environmental agencies are primarily responsible for regulating the beneficial reuse of CCPs. Eighteen states specifically authorize the use of fly ash in additive applications via state statute or by regulation (Table C-1). Eleven states authorize beneficial reuse of CCPs on a case-by-case basis. USEPA does not currently regulate beneficial reuse of CCPs.

The status of fly ash regulations in the US is summarized in Table C-1. States typically have defined CCPs as hazardous or non-hazardous waste. CCPs that are defined as exempt from hazardous waste status are assigned a secondary status, such as special waste, industrial solid waste, or recovered material, allowing the CCP to used beneficially. In states where CCPs are not specifically exempted, beneficial use can be approved provided that results of a toxicity characteristic leaching procedure (TCLP) test, demonstrate that the CCP is not a hazardous waste.

USEPA has concluded that environmental releases of constituents of potential concern from concrete containing fly ash are at or below regulatory and health-based criteria for human and ecological receptors, or are comparable to, or lower than, those from concrete not containing CCPs [18]. Similarly, USEPA indicates that constituents of potential concern in FGD gypsum wallboard are released below relevant regulatory and health-based criteria for human and ecological receptors [18]. Thus, neither application requires unique regulation.

Fly Ash

Ash was used in the construction of the great pyramids of Egypt, and Engineering News Record reports fly ash was used as early as 1914 [20, 21]. At the national level, the EPA does not regulate but supports the use of fly ash in highway applications, which is a categorized as beneficial highway applications [64, 65]. The Federal Highway Administration encouraged its use the partial substitution of fly ash for cement in concrete pavement wherever possible in the 1974 Notice N 5080.4, and the EPA encouraged its use by publishing federal comprehensive procurement guidelines for cement and concrete in 1983 [65]. Additionally, a 2014 EPA report concluded that environmental releases of constituents of potential concern from CCP fly ash concrete were at or below relevant regulatory and health-based benchmarks for human and ecological receptors when used by the consumer, or are comparable to or lower than those from analogous non-CCP products [64, 65].

Environmental agencies at the state level are primarily responsible for regulating fly ash use, through assigning or not assigning fly ash status and/or hazardous waste status. A hazardous waste status of exempt allows fly ash to be assigned a secondary status (such as special waste, industrial solid waste, or recovered materials) that allows the fly ash to be used in applications. Not exempt status can usually be overcome with TCLP proof, which may allow its use. Fly ash regulatory statuses were compiled for the United States (Table C-1) [67]. As a part of a beneficial use of industrial byproducts initiative, Wisconsin has adopted fly ash stabilization of soft subgrades as a preferred technology through NR 538 of the WI Administrative Code because of substantial reductions in construction time, which is important in regions that have a short construction season.

Table C-1
Fly Ash Regulatory Statuses in the United States. Based on Wen et al. 2011 [33]; O'Donnell 2009 [27], source from US DOE - NETL, 2014 [67].

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 Waste or Inert Waste	No	No	Yes, with TCLP and metals
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	Solid Waste	No	No	No
Connecticut	Exempt	Special or Regulated Waste	No	No	Yes
Delaware	Exempt	Nonhaz. Indust. Waste with TCLP	No	No	Yes
Florida	Exempt	Solid Waste or Indust. Byproduct	Yes	No	No
Georgia	Exempt	Indust. Solid Waste	No	No	No
Hawaii	Exempt	None	No	No	Yes, with TCLP and metals
Idaho	Exempt	Indust. Solid Waste	No	No	No
Illinois	Exempt	CCW or CCB	Yes	Yes	-

Indiana	Exempt	None	Yes	Yes	-
Iowa	Exempt	None	Yes	Yes	-
Kansas	Exempt	Indust. Solid Waste	No	No	No
Kentucky	Exempt	Special Waste	Yes	Yes	-
Louisiana	Exempt	Indust. Solid Waste	No	No	Yes
Maine	Exempt	Special Waste	Yes	No	No
Maryland	Exempt	Pozzolan	No	No	No
Massachusetts	Exempt	Solid waste unless beneficial reuse	Yes	Yes	-
Michigan	Exempt	Low Hazard Indust. Waste	Yes	Yes	-
Minnesota	Exempt	None	No	No	Yes
Mississippi	Exempt	Indust. Solid Waste	No	No	Yes
Missouri	Exempt	None	Yes	Yes	-
Montana	Exempt	Indust. Solid Waste	Yes	No	Yes
Nebraska	Exempt	Special Waste	Yes	Yes	-
Nevada	Exempt	Industrial Waste	No	No	No
New Hampshire	Exempt	Waste derived product	Yes	Yes	-
New Jersey	Exempt	Solid Waste unless beneficial reuse	Yes	Yes	-
New Mexico	Exempt	Indust. Solid Waste	No	No	No
New York	Exempt	None	Yes	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	-
Rhode Island	NOT Exempt	Haz. Waste unless proven	No	No	No

		not by TCLP			
South Carolina	Exempt	Indust. Solid Waste	No	No	Yes
South Dakota	Exempt	Solid Waste	No	No	Yes
Tennessee	NOT Exempt	Haz. Waste unless proven not by TCLP	Yes	No	No
Texas	Exempt	Indust. Solid Waste	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. Product	Yes	Yes	-
Wyoming	Exempt	Indust. Solid Waste	No	No	No

Bottom Ash

At the national level, the EPA supports the use of coal ash in highway applications, which is a categorized as beneficial highway applications. The EPA's proposed rule of 2010 to regulate CCPs under the Resource Conservation and Recovery Act (RCRA) will not affect the current status of coal combustion products that are beneficially used [64] . The U.S. Department of Transportation Federal Highway Administration policy outlines the importance of re-using materials previously used in constructing our Nation's highway system, and calls upon us, and the State transportation departments, to explicitly consider recycling as early as possible in the development of every project. The NRC strongly encourages the secondary use of CCRs that pose minimal risk to human health and the environment [64].

FGD Material

Environmental releases of constituents of potential concern from FGD gypsum wallboard were reported in a 2014 EPA report to be at or below relevant regulatory and health-based benchmarks for human and ecological receptors when used by the consumer. Based on the analysis set forth in this document, the evaluation concludes that environmental releases of constituents of potential concern (COPCs) from CCR fly ash concrete and FGD gypsum wallboard during use by the consumer are comparable to or lower than those from analogous non-CCR products, or are at or below relevant regulatory and health-based benchmarks for human and ecological receptors [62].

Previous Research

STH60 Fly Ash, WI

Data from this study have been reported by Bin-Shafique [9] and Sauer et al. [36, 37]. They indicate that the concentration of Cd was slightly higher in the control section than in the section with fly ash, whereas concentrations of Cr, Se, and Ag for the control section were lower than those for the fly ash section. Sauer et al. [36] indicate that leachate collected in the lysimeter had Cd, Se, and Ag concentrations that initially exceeded Wisconsin ground water quality standards, but that dilution and attenuation between the bottom of the pavement profile and the ground water table reduced concentrations below Wisconsin ground water quality standards.

Li et al. [46] compared predictions from the flow and transport code WiscLEACH to the field data from STH60 and found reasonable agreement between the model predictions and field data when the retardation factor was identified appropriately. Li et al also concluded that maximum ground water concentrations were likely to occur near the ground water table and near the centerline of the pavement structure.

US12, WI

O'Donnell et al. [27] report that concentrations of most elements diminished over time at this site, and that concentrations at the base of the pavement profile fell below federal drinking water standards within 2 to 4 pore volumes of flow (PVF). Concentrations of four elements (B, Mo, Cr, and Cd) were elevated in leachate from the fly-ash-stabilized sections relative to the control section. Of these elements, both B and Mo persistently exceeded the MCL. In contrast, concentrations of Cd and Cr only exceeded MCLs in the first few samples collected (PVF < 0.25), and then remained well below the MCL in all subsequent samples.

Scenic Edge, WI

Bin-Shafique et al. [9] and O'Donnell et al. [27] report on leachate concentrations at the STH 60 and Scenic Edge sites. Concentrations of all elements measured at Scenic Edge, except for Ag, were slightly higher in concentration than for the STH 60 leachate. Concentrations decreased over time at both sites, and typically fell below federal drinking water limits within 2 to 4 PVF.

MnROAD, MN

O'Donnell et al. [27] and Wen et al. [32, 33] reported on all of the fly ash sites in this study, focusing on leachate evaluation. Concentrations diminished over time and fell below federal drinking water limits within 2 – 4 PVF for many elements. Concentrations of four elements from fly-ash-stabilized materials were reported as elevated relative to the control sections at all sites (As, B, Mo, Cr, and Cd) and also exceeded MCLs. Of these elements, both B and Mo had exceeded the MCL for many PVF. In contrast, concentrations of Cd and Cr only exceeded MCLs in the first samples collected (PVF < 0.25), and then remained well below the MCL in all subsequent samples.

Waseca, MN

O'Donnell et al. [27] reported on all of the fly ash sites in this study, focusing on leachate evaluation. Concentrations diminished over time and fell below federal drinking water limits within 2 – 4 PVF for many elements. Concentrations of four elements from fly-ash-stabilized materials were reported as elevated relative to the control sections at all sites (As, B, Mo, Cr, and Cd) and also exceeded MCLs. Li et al. [34] indicate that the concentrations of all trace elements were below federal drinking water limits.

Southwest Rome Bypass, GA

Earth Science and Environmental Engineering, & Southern Company Generation (2012) concluded that fly ash is an acceptable substitute for fill applications (i.e. road base) based on the geotechnical investigation conducted to date, with no discernable difference noted between fly ash and normal fill sections. Arsenic and lead levels were found to exceed drinking water quality limits in background wells monitored prior to site construction. Groundwater wells surrounding and within the test section did not exhibit exceedances of Georgia drinking water quality criteria that could not be explained by background concentrations in the area, and were rare and isolated events that did not represent trends.

56th Street Overpass, IN

Alleman et al. 1996 studied INDOT 56th Street embankment, evaluating the mechanical properties and field site leachate behavior. He concluded that the ash-filled embankment did not have any detrimental impact on the adjacent wells. This conclusion was reached after comparing trace element concentrations to Indiana's Type III restricted waste citing criteria. The only metal tested which provided distinct evidence to show an impact on the adjacent well waters was Boron, which was not evaluated in this study because there is no water quality limit established for Boron. Additionally, although not above standard concentration levels, Nickel was also concluded to be present in higher concentrations in the leachate from lysimeter tank than the samples from either well.

STH60 Bottom Ash, WI

Sauer et al. [36] gave a 5 year report on the leachate at STH60, stating that lysimeter leachate commonly had Cd, Se, and Ag concentrations exceeding WI groundwater quality standards, but that applying dilution factors to account for the reduction in concentration expected between the bottom of the pavement structure and the groundwater table would not result in exceedances at the water table.

Additional Information

Material Properties

Table C-2
Fly Ashe Compositions [26].

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 sieves (%)	12.4	15.5	<34	34 Max	34 Max
Classification	C	Off-Spec.	C		

Table C-3
Total Elemental Analysis of Riverside 8, Columbia, and Yates Fly Ashes [26, 35].

Element	Riverside 8 Ash		Columbia Ash		Yates Ash
	(mg/kg)	% of Total Mass	(mg/kg)	% of Total Mass	(mg/kg)
Ag	0.40	0.000040	0.50	0.000050	<1.2
Al	66000	6.600000	75000	7.500000	Not Tested
As	24	0.002400	28	0.002800	130
B	780	0.078000	610	0.061000	Not Tested
Ba	2600	0.260000	3600	0.360000	523
Be	5.3	0.000530	2.6	0.000260	4.6
Ca	120000	12.000000	240000	24.000000	Not Tested
Cd	5.4	0.000540	1.5	0.000150	<0.77
Co	28	0.002800	5.6	0.000560	17
Cr	71	0.007100	60	0.006000	35
Cu	230	0.023000	180	0.018000	Not Tested
Fe	36000	3.600000	20000	2.000000	Not Tested
Hg	0.80	0.000080	Not Tested	-	0.275
K	2600	0.260000	3000	0.300000	Not Tested
Mg	29000	2.900000	25000	2.500000	Not Tested
Mn	120	0.012000	180	0.018000	Not Tested
Mo	140	0.014000	7.2	0.000720	Not Tested
Na	15000	1.500000	8700	0.870000	Not Tested
Ni	620	0.062000	45	0.004500	38
P	4800	0.480000	3400	0.340000	Not Tested
Pb	63	0.006300	28	0.002800	28
S	1.1	0.000110	ND	-	Not Tested
Sb	3.3	0.000330	7.7	0.000770	<7.5
Se	16	0.001600	9.4	0.000940	<13
Sn	1400	0.140000	200	0.020000	Not Tested
Sr	ND		1600	0.160000	Not Tested
Ti	130	0.013000	94	0.009400	Not Tested
Tl	ND	-	8.4	0.000840	<10
V	66000	6.600000	75000	7.500000	108
Zn	3.3	0.000330	7.7	0.000770	91

Note: Values follow "<" indicate detection limits.

Table C-4
Concentration from WLTs of bottom ash used at STH60 [28].

Material	WLT pH and Concentration (μg/L)						
	Cd	**Cr**	**Se**	**Ag**	**Fe**	**Pb**	**pH**
Bottom Ash	<0.2	1.1	32.5	<2.5	-	-	10.3

Field Site Sources

Table C-5
Field Site Sources per CCP Type and Application

CCP	Application	Field Site	Sources
Fly Ash	Soil Subgrade Stabilization	STH60	Edil *et al.* 2002 Bin Shafique *et al.* 2002, 2004, 2006 Sauer et al. 2005, 2010 Li et al. 2006, 2009 Carpenter et al. 2007 O'Donnell et al. 2010 Edil et al (Transp. Research Record)
		US12	Li *et al.* 2009 O'Donnell et al. 2010
		Scenic Edge	Bin Shafique *et al.* (2002, 2004, 2006 Li et al. 2009 O'Donnell et al. 2010
	RPM Stabilization	MnROAD	O'Donnell et al. 2011 Wen et al. 2011
		Waseca	Li et al. 2007 O'Donnell et al. 2010
	Structural Fill	Southwest Rome Bypass	Earth Science & Environmental Engineering, Southern Power Co. 2010 Southern Power Co. 2012
		56th Street Overpass	Alleman et al. 1996
Bottom Ash	Soil Subgrade Stabilization	STH60	Sauer et al. 2005, 2010