

Leaching from Roadways Stabilized with Fly Ash: Data Assessment and Synthesis

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INTRODUCTION

Approximately 37% of the electrical power used in the United States is generated by coal-fired power plants¹. 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). The 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 benefit^{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% as reported by the Department of Energy (Fig. 1)⁷. Considering ACAA extrapolations that adjust for missing data increases the reuse rate to 43%². There is yet a great opportunity for increased beneficial reuse. Increasing the rate of fly ash reuse will enhance sustainability while reducing disposal costs. Most fly ash is used as a partial replacement for Portland cement in concrete, and most concrete applications today include fly ash in the mixture⁸. Roadway applications such as stabilization of subgrade and base course are less common uses for fly ash, and

present an opportunity for increasing reuse of CCPs. 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 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}. In many roadway cases, construction costs are lower and construction is more expedient when CCPs are employed¹⁶. However, the perceived risk of trace element leaching often prevents fly ash from being employed in unbound applications (e.g., bases and subgrades).

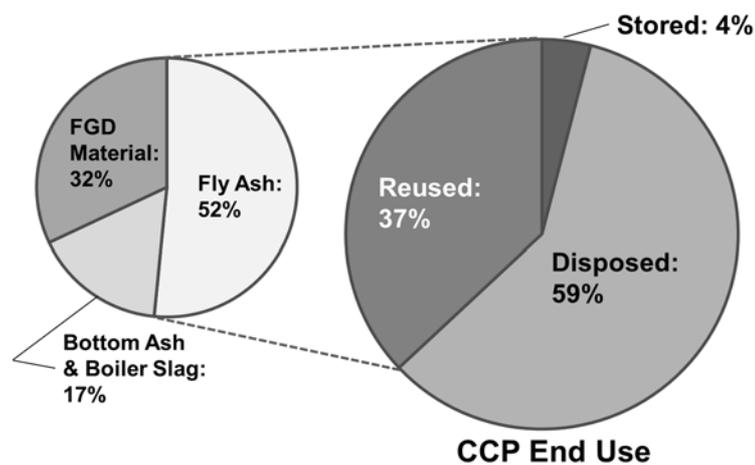


Figure 1. Uses of CCPs as identified by EIA⁷.

In this study, the potential risk of contaminating ground water and surface water by constituents leaching from fly ash used in roadways is being evaluated using field water quality data collected from projects where fly ash has been used in roadway bases and subgrades. Water quality data from the leachate of these projects 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 and subgrade applications using fly ash. More realistic analyses were also conducted by predicting contaminant concentrations at points of compliance (POC) using the field data as input to groundwater modeling software.

BACKGROUND

Fly ash is a powdery material removed from the flue gas from a coal-fired electric generating plant that is comprised of silt-size spherical particles composed primarily of silica and having the consistency of talcum powder¹⁸. Fly ash particles also contain trace elements (e.g., heavy metals) that the coal contained prior to combustion¹⁹. The perceived risk is that trace elements will leach from fly ash when used in construction applications exposed to precipitation or other sources of water.

Fly ash is a pozzolan that becomes cementitious when combined with water and an activator (lime, Portland cement, or kiln dust)^{18, 20, 21}. Some fly ashes are self-cementing when hydrated. Fly ash is used as feed stock in production of Portland cement, cementitious material in concrete in lieu of (or in addition to) Portland cement, mineral filler in hot-mix asphalt, structural and embankment fill, stabilizer or solidifying agent for soft materials, cementing and flow agent in flowable fill, and stabilizer for roadway bases, sub-bases, and subgrades¹⁸.

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 from 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 standards⁵. Class C fly ashes often are self-cementing. Class F fly ashes generally are not self-cementing. There are also fly ashes not conforming to these specifications that are self-cementing²⁵.

MONITORING DATA

Lysimeter leachate water quality monitoring data from six field sites utilizing fly ash stabilized subgrade or base layers in Minnesota and Wisconsin were obtained from the RMRC for this study. Fig. 2 shows the location of the field sites, which included STH60, US12-E, US12-W, Scenic Edge, Waseca, and MnROAD. Construction details for the field sites are provided in Fig. 3. Field site characteristics are detailed in Table 1.



Figure 2. Locations of field sites where field data were available for use in this study, which included STH60, US12-E, US12-W, Scenic Edge, Waseca, and MnRoad^{26, 27, 28}.

Soft soil subgrade was stabilized at the Wisconsin field sites with 10% to 12% fly ash by weight to a depth of 300 mm. Fly ash was obtained from Columbia power plant from Alliant Energy's Columbia Power Station in Portage, WI. The STH60 field site is located along a 0.1-km stretch of State Trunk Highway 60 (STH60) near Lodi, WI. The site contained several test sections employing industrial byproducts in lieu of earthen construction materials. The section of interest employed subgrade stabilized in place with fly ash^{17, 20}. The US12 site is located along a 0.6-km section of US Highway 12 (US12) near Cambridge, Wisconsin. 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, 29}. 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, 29, 30}.

Recycled pavement material was stabilized at the Minnesota field sites with 10% to 14% fly ash by weight to a depth of 150 mm and 203 mm. Fly ash was obtained from Excel Energy's Riverside Power Plant. The MnROAD field site is located along a low-volume loop at the Minnesota Department of Transportation (MnDOT) highway testing laboratory located adjacent to Interstate 94 between Albertville and Monticello, Minnesota^{28, 31, 32}. The Waseca field site is located at the intersection at 7th Street and 7th Avenue in Waseca, Minnesota^{33, 27, 28}. At both of these sites the RPM was reclaimed on site and blended with fly ash using a road reclaimer.

Table 1. Characteristics of field sites.

| Application | Field Site | Stabilized Layer Thickness | Fly Ash Percentage and Source | Control | CCP Properties | Construction End | Sampling Period |
|-----------------------------|-------------|----------------------------|-------------------------------|------------------------------|--|------------------|----------------------|
| Soil Subgrade Stabilization | STH60 | 300 mm | 12% Columbia Plant | Dolostone Subbase | Class C in ASTM C 618 and AASHTO M 295 | August 2000 | 9/14/00 to 8/20/12 |
| | US12 | 300 mm | 12% Columbia Plant | Un-Stabilized Subgrade Soils | Class C in ASTM C 618 and AASHTO M 295 | October 2004 | 11/10/05 to 8/20/12 |
| | Scenic Edge | 300 mm | 10% Columbia Plant | None | Class C in ASTM C 618 and AASHTO M 295 | October 2000 | 02/27/06 to 03/12/10 |
| RPM Stabilization | MnROAD | 203 mm | 14% Riverside 8 Plant | RPM Base | Off-specification ash (>5% carbon content) | August 2007 | 09/11/07 to 06/30/12 |
| | Waseca | 150 mm | 10% Riverside 7 Plant | None | Class C in ASTM C 618 and AASHTO M 295 | August 2004 | 07/07/05 to 06/20/08 |

A control lysimeter was also installed at some field sites where conventional construction methods and materials were employed (i.e., no fly ash). STH60 field site contained a control section composed of an 840-mm-thick layer of crushed dolostone subbase on top of the subgrade to ensure adequate support for the pavement (Fig. 3). A control lysimeter was also installed beneath the centerline of the road near the west end, where unstabilized subgrade was used in lieu of subgrade stabilized with fly ash. The MnROAD field site contained two control lysimeters: one control lysimeter was installed beneath an identical roadway profile except the RPM base course was not stabilized with fly ash and the other was installed beneath a similar profile where Class 5 crushed stone was used as base course but was not considered for this study. Construction details for the control field sites are provided in Fig. 3.

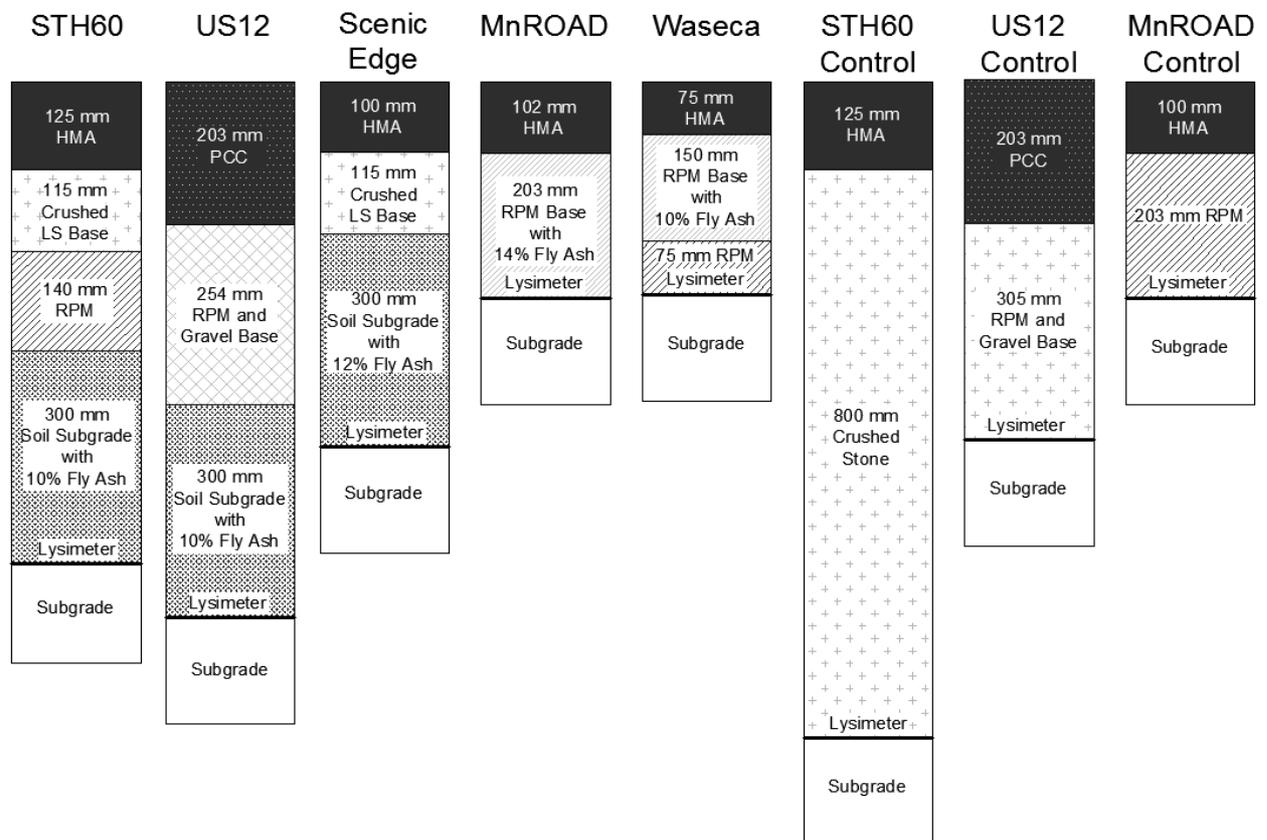


Figure 3. Schematics of roadway profiles and roadway control profiles^{9, 17, 20, 27, 28, 30}.

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, 29, 30, 31, 32, 33}. 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 120-L collection tank via PVC pipe (Fig. 4).

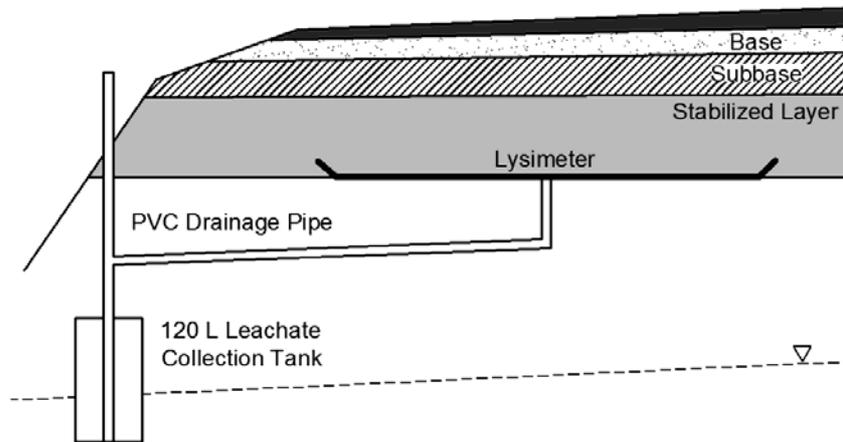


Figure 4. Typical lysimeter detail based on designs reported in O'Donnell²⁶ and Wen et al.³¹.

DATA EVALUATION

The risk imposed by using unencapsulated fly ash in roadway construction was evaluated through direct and indirect assessment according to the flow chart outlined in Fig. 5. Direct assessments were made by comparing concentrations of the elements being monitored in the lysimeters to water quality standards and concentrations obtained from control lysimeters. Indirect assessments were made by modeling concentrations at a point of compliance using maximum measured concentrations from the lysimeters.

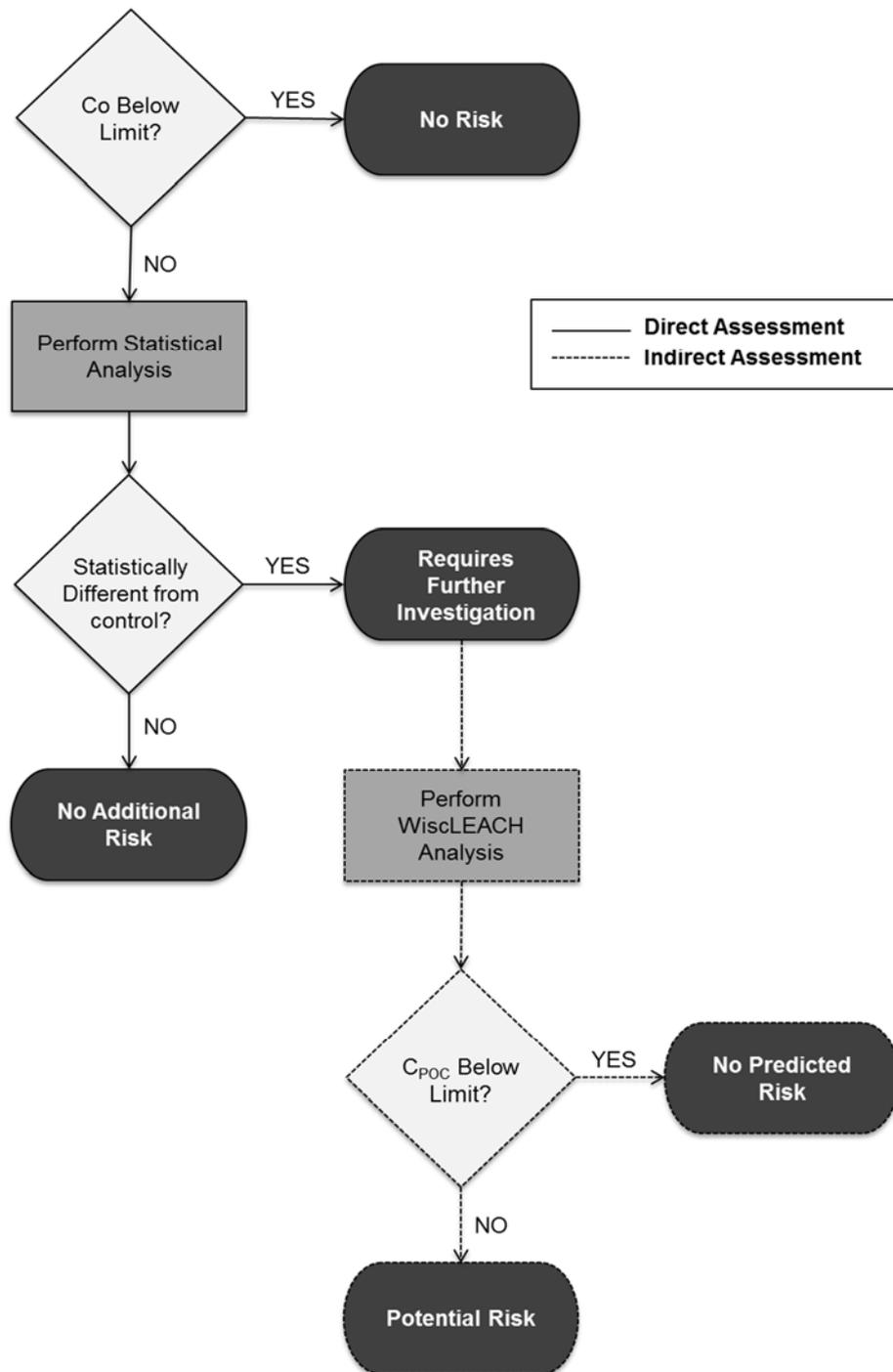


Figure 5. Flowchart depicting the process for categorizing the apparent risk posed by fly ash use in roadway construction based on water quality (leachate) data.

Water quality limits were derived from drinking water limits and surface water limits. Federal drinking water quality limits are referred to as maximum contaminant levels (MCLs)³⁴. Most states also define MCLs that are the same as, or lower than, the federal MCLs. There are 13 elements that were assessed in this study that have MCLs. A summary of the MCLs used in this study can be found in Table 2.

USEPA has established national recommended water quality criteria for different surface water categories under Section 304(a)(1) of the Clean Water Act³⁵. These non-enforceable criteria for freshwater aquatic life^{34,36} 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 Minnesota and Wisconsin were also considered. Standards for Class 2a waters were used for Minnesota³⁷, and the acute toxicity criteria for cold waters were used for Wisconsin³⁸. There are 13 elements that were assessed in this study that have surface water criteria. A summary of the surface water standards is also shown in Table 2.

Table 2. Federal, Minnesota, and Wisconsin drinking water and surface water quality limits. For trace elements where the surface water criterion depends on hardness 100 mg/L CaCO₃ was assumed^{37, 38, 39}.

| Trace Element | Ag | Al | As | Ba | Be | Cd | Co | Cr | Cu | F | Hg | Ni | Pb | Sb | Se | Tl | Zn |
|------------------|---------------------------------------|-----|-----|------|----|-----|-----|------|-------|------|----|-------|-----|----|----|----|-----|
| Authority | Drinking Water Limits (µg/L) | | | | | | | | | | | | | | | | |
| Federal | - | - | 10 | 2000 | 4 | 5 | - | 100 | 1300* | 4000 | 2 | - | 15* | 6 | 50 | 2 | - |
| Minnesota | - | - | 10 | 2000 | 4 | 5 | - | 100 | 1300* | 4000 | 2 | 100** | 15* | 6 | 50 | 2 | - |
| Wisconsin | - | - | 10 | 2000 | 4 | 5 | - | 100 | 1300* | 4000 | 2 | 100** | 15* | 6 | 50 | 2 | - |
| Authority | Surface Water Standards (µg/L) | | | | | | | | | | | | | | | | |
| Federal | 3.2 | - | 340 | - | - | - | - | 570 | - | - | - | 470 | 65 | - | - | - | 120 |
| Minnesota | 2 | 748 | 360 | - | - | 3.9 | 436 | 1737 | 18 | - | - | 1418 | 82 | 90 | 20 | 64 | 117 |
| Wisconsin | - | - | 340 | - | - | 4.4 | - | 1803 | 15 | - | - | 469 | 107 | - | - | - | 120 |

-Denotes elements that do not have water quality limits for that authority.

*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).

**Minnesota and Wisconsin drinking water limits include nickel (Ni).

DIRECT ASSESSMENT

Direct assessment of the field data consisted of comparing concentrations of each trace element monitored in the lysimeter leachate to state and federal drinking water quality standards and surface water quality standards indicated in Table 2 (generally referred to henceforth as water quality limits). Comparisons were also made between concentrations of leachate from roadway sections employing fly ash and roadway sections constructed with conventional materials (controls).

Elements eluted from roadways constructed with fly ash (i.e. STH60, US12-W, US12-E, Scenic Edge, MnROAD, and Waseca) 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 analysis at the point of compliance using WiscLEACH groundwater modeling software.

A summary of the outcomes of the direct assessment is shown in Tables 3 and 4 in terms of field sites where fly ash was used. Most of the elements (11-13 out of 17 elements, depending on field site) fell into the no risk (Table 3) or no additional risk (Table 4) categories. This implies that roadways employing fly ash in stabilizing unbound materials were essentially no different for those elements, in terms of potential impact on the environment, than roadways constructed with conventional unbound construction materials.

Table 3. Elements for which CCP use in roadway applications posed no risk.

| Category | No Risk | | | |
|--------------------|--------------------------------|--------------------------------|------------------------|--|
| | Drinking Water | | Surface Water | |
| | Federal | State | Federal | State |
| STH60 | 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, TI | Ba, Be, Cd, Cr, Cu, Pb, Se, TI | Ag, Al, As, Cr, Ni, Pb | As, Cd, Cr, Ni, Pb |
| MnROAD | Ba, Cd, Cu, Pb | Ba, Cd, Cu, Pb | Al, Ag, Cr, Ni, Pb | Al, Ag, 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, TI, Zn |

Table 4. Elements for which CCP use in roadway applications posed no additional risk relative to controls. Scenic Edge and Waseca field sites did not contain control lysimeters.

| Category | No Additional Risk | | | |
|--------------------|--|--|--|--|
| | Drinking Water | | Surface Water | |
| | Federal | State | Federal | State |
| STH60 | As, Cu, Ni, Pb, Sb, Zn |
| US12-W | As, Be, Cd, Pb, Sb, TI |
| US12-E | Ag, Ba, Be, Cu, TI |
| Scenic Edge | No Control | No Control | No Control | No Control |
| MnROAD | As, Cd, Cr, F, Fe, Mn, Sb, Sn, TI, V, Zn | As, Cd, Cr, F, Fe, Mn, Sb, Sn, TI, V, Zn | As, Cd, Cr, F, Fe, Mn, Sb, Sn, TI, V, Zn | As, Cd, Cr, F, Fe, Mn, Sb, Sn, TI, V, Zn |
| Waseca | No Control | No Control | No Control | No Control |

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.

Direct assessment indicated that concentrations were not below water quality limits or were statistically different from the control for 4-6 of 17 trace elements. Elements requiring further investigation varied per field site, but overall included Ag, Al, As, Be, Cd, Cu, Ni, Pb, Sb, Se, Ti, and Zn. An indirect analysis was conducted on these elements to provide a representative assessment of concentrations that would be realized at a receptor point in ground water. The regulatory point of compliance (POC) for water quality for many roadway applications is the right-of-way of the roadway⁴⁰, and was used as the modeled receptor point.

The analysis 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^{33, 40}. 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, 30, 41}. Input concentration, C_0 , 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} , 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} 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} was reached. It was found that regardless of trace element modeled, C_{POC} was reached by 5 years, which is within the lifetime of a road (typically 20 to 40 years)^{2, 42}. Values of C_{POC} 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 applications⁴⁰, 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 m²/yr. was assumed for elements that had no published values (As, Sn, Ti, and V)⁴³. Dispersivities were taken as one-tenth the domain and recommended grid parameters from Li et al. 2006 were used⁴⁰. A summary of site-specific WiscLEACH model inputs is provided in Table 5.

Table 5. Site-specific WiscLEACH model inputs.

| Field Sites | Point of Compliance (POC) (m) | Width of Pavement (m) | Width of Shoulder (m) | Distance to Groundwater Table (m) | Distance to Top of Stabilized 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 |
| Field Sites | Distance to Bottom of Stabilized Layer (m) | Infiltration Rate (m/yr.) | Hydraulic Conductivity of Aquifer (m/yr.) | Porosity of Aquifer | Regional Hydraulic Gradient |
| STH60 FA | 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 |
| Field Sites | Hydraulic Conductivity of Pavement (m/yr.) | Hydraulic Conductivity of Base (m/yr.) | Hydraulic Conductivity of Stabilized 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 WW | 1.0 | 1.0 | 0.19 | 126.9 | 0.33 |
| US12 EW | 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 |
| Field Sites | Porosity of Base | Porosity of Stabilized Layer | Porosity of Subgrade | Horizontal Dispersion | Vertical Dispersion |
| STH60 FA | 0.33 | 0.41 | 0.16 | 2.0 | 0.20 |
| US12 WW | 0.33 | 0.27 | 0.10 | 2.0 | 0.15 |
| US12 EW | 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 |

All 12 elements modeled (Ag, Al, As, Be, Cd, Cu, Ni, Pb, Sb, Se, Tl, Zn) with WiscLEACH groundwater modeling software had C_{POC} below water quality limits, thus were categorized as imposing “no predicted risk” (see Table 6). Trace elemental concentrations had a minimum 97.5% concentration reduction, with an average reduction of 98.4%. The direct assessment showed that fly ash used in base and subgrade layers posed no predicted risk at the modeled receptor points and thus are suitable beneficial reuse applications with respect to water quality.

Table 6. Elements for which fly ash use in roadway applications posed no predicted risk at POC.

| Category | No Predicted Risk at Point of Compliance (POC) | | | |
|--------------------|--|----------------|---------------|--------|
| | Drinking Water | | Surface Water | |
| | Federal | State | Federal | State |
| STH60 | Cd, Se, Tl | Cd, Se, Tl | Ag | Cd |
| US12-W | Se | Ni, Se | Ag, Al, Zn | Cu, Zn |
| US12-E | As, Pb, Se | As, Ni, Pb, Se | Pb, Zn | Zn |
| Scenic Edge | As, Sb | As, Sb | Zn | Cu, Zn |
| MnROAD | Be, Se | Be, Se | Ag | Ag, Se |
| Waseca | As, Pb, Sb, Tl | As, Pb, Sb, Tl | Pb | Pb |

In order to determine if the C_{POC} 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 Fig. 6. Concentration decreased by 61% in the vadose zone directly underneath the pavement section and 96% as it reached the saturated zone. Concentration reduced an additional 0.1% 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.^{33, 40} the distance to the groundwater table would impact the distance the element travels through the vadose zone, potentially affecting the magnitude of concentration reduction.

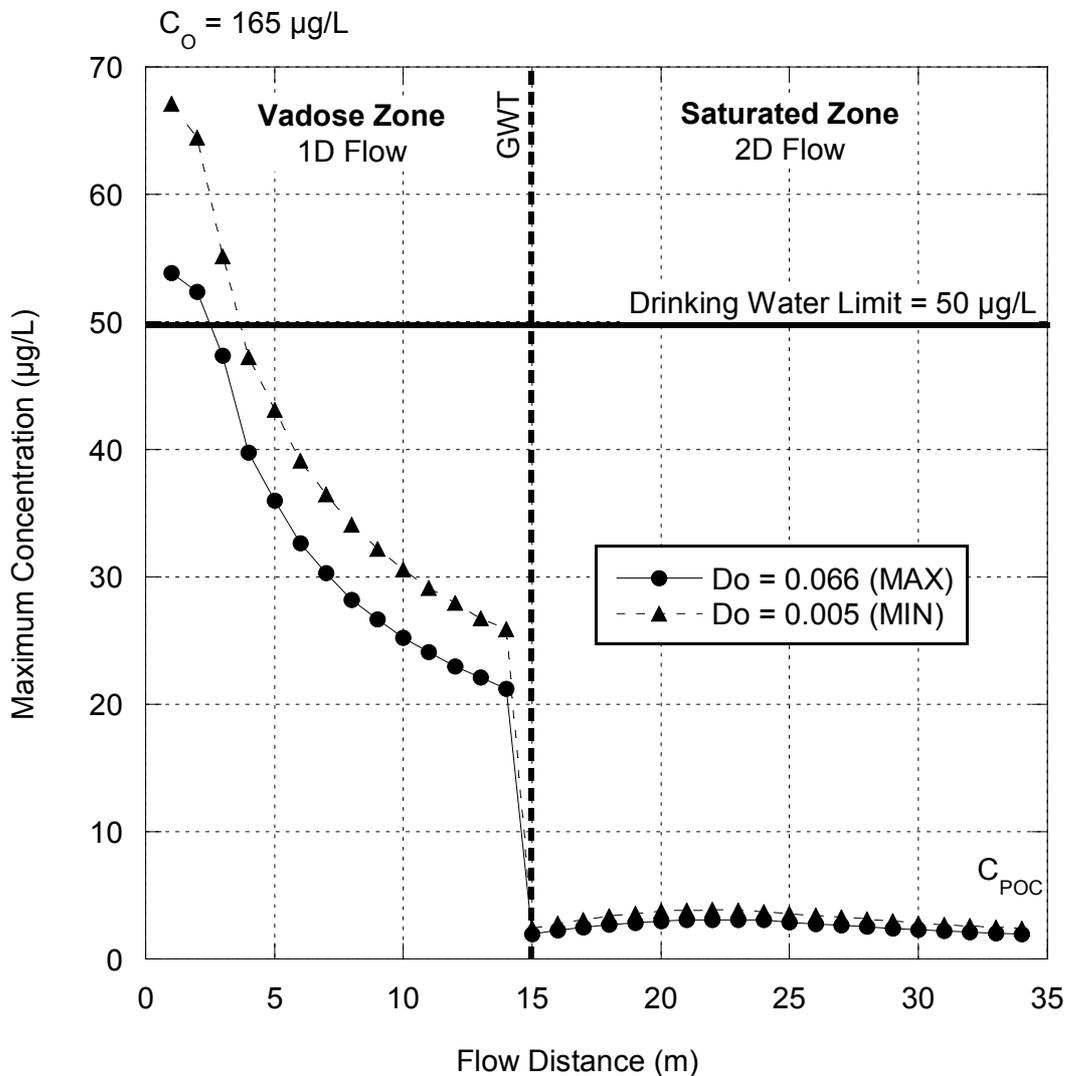


Figure 6. Concentration vs. flow distance for a typical field site in Minnesota and Wisconsin for maximum and minimum molecular diffusion coefficients. Concentration decreases in the vadose zone and drops dramatically after the groundwater table. This example is for selenium and the drinking water limit for selenium is market.

Using the WiscLEACH model, reduction factors (RF) were calculated by dividing C_0 by C_{POC} to give a general sense of the amount of reduction that took place and to facilitate the discussion and ranking of field sites. RFs spanned 45.7-87.9, with increasing RF indicating that more reduction took place during water migration to POC. Percentage of reduction that took place at field sites spanned 97.5% to 98.7%, the small range of which does not facilitate discussion as well as the range of RF. Additionally, RF allow for the quick estimation of C_{POC} given leachate characteristic data (e.g. C_0) or the back-calculation of an allowable C_0 given maximum allowable C_{POC} (e.g. water quality limits).

RF represent the overall concentration reduction that occurred in field conditions and are a function of the input parameters that influence C_{POC} , 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_0 . Z_{GWT} was the most sensitive parameter because it correlates to the length of the flow path and thus the amount of dispersion that took place⁴⁰. Thickness of the stabilized layer was the second because it affected the total mass leached: higher concentrations occurred at the POC when more mass was leached from the fly ash stabilized layer⁴⁰. 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^{33, 40}. Values of C_0 and C_{POC} varied greatly between elements and between field sites, but RF were constant for each trace element at a field site regardless of C_0 input into WiscLEACH because all other factors remained constant and the ADRE used in WiscLEACH was linear.

The RFs for each trace element assessed at a given field site (points) and the average RF per field site (lines) are shown in Fig. 7. The depth to groundwater table and stabilized layer thickness are included for context in Fig. 7. Because all other parameters were the same, the only influence on elemental RF per site was molecular diffusion which differs between elements. Small margins of error (95% confidence interval) suggest that the average of the RF for all elements at a given field site can accurately represent all elements at that field site.

Waseca is the only field site that did not demonstrate a downward trend in RF with decreasing depth to groundwater table (Fig. 7). The other field sites appear to be controlled by depth to groundwater table. The average RF is higher at Waseca because it had a thin (0.15 m) stabilized layer thickness compared to the other field sites, which suggests Waseca was instead controlled by thickness of stabilized layer.

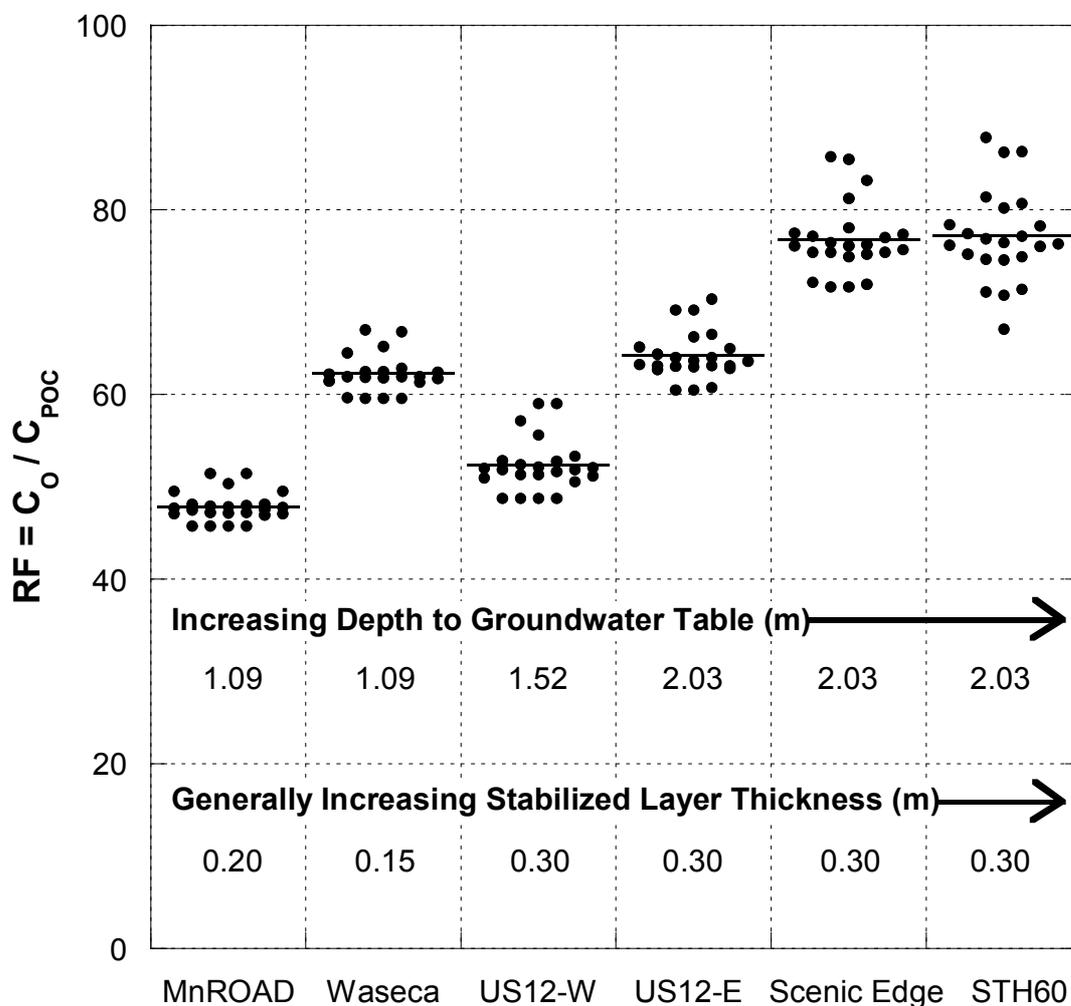


Figure 7. RFs for elements at the field sites (points) and the average RF per field site (line). Depth to groundwater table and stabilized layer thickness are included for context.

RF statistics are presented in Table 7. RF ranged between 45.7 (MnROAD) and 87.9 (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} ^{33, 40}.

Using water quality limits as C_{POC} instead of the predicted C_{POC} to solve for RF effectually back-calculated the minimum required RF that a field site would need to obtain a C_{POC} below water quality limits. Even though STH60 had the maximum average RF (77.2), a RF as low as 37.5 would still reduce C_o to a C_{POC} below the water quality limits. Similarly, RF could be as low as 31.2 at Scenic Edge, 3.5 at US12-E, 6.4

at US12-W, 28.0 at Waseca, and 19.6 at MnROAD. RF from one of the field sites could potentially be used to quickly estimate C_{POC} given leachate characteristic data (C_o) of a similarly constructed and situated field site. RF could also potentially be used to back-calculate an allowable C_o given maximum allowable C_{POC} , such as water quality limits.

Table 7. Reduction factor (RF) statistics.

| Site | Minimum Value | Maximum Value | Average | Standard Deviation | 95% Margin of Error | Percent Reduction |
|-------------|---------------|---------------|---------|--------------------|---------------------|-------------------|
| STH60 | 67.06 | 87.88 | 77.2 | 5.054 | ±2.07 | 98.7% |
| US12-W | 48.75 | 59.02 | 52.4 | 2.025 | ±1.18 | 98.1% |
| US12-E | 60.48 | 70.35 | 64.2 | 1.926 | ±1.07 | 98.4% |
| Scenic Edge | 71.70 | 85.79 | 76.8 | 2.718 | ±1.41 | 98.7% |
| Waseca | 59.62 | 67.03 | 62.3 | 2.092 | ±0.89 | 98.4% |
| MnRD | 45.74 | 51.44 | 47.9 | 1.156 | ±0.64 | 97.9% |

SUMMARY AND CONCLUSIONS

In this study, the potential risk of contaminating ground water and surface water by constituents leaching from fly ash used in roadways was evaluated using field water quality data collected from projects where fly ash has been used in roadway bases and subgrades. Six field sites in Minnesota (MnROAD and Waseca) and Wisconsin (STH60, US12-W, US12-E, and Scenic Edge) were evaluated, which consisted of fly ash stabilizing recycled asphalt pavement base and soft soil subgrades, respectively.

The assessment evaluated field water quality data from leachate collected from field sites where fly ash had been used in non-pavement applications in roadway bases and subgrades. 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 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 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.

Indirect analyses were conducted to more realistically assess field conditions at a point of compliance (POC) using the field data as input to WiscLEACH groundwater modeling software (C_o). When the modeled concentrations at the POC (C_{POC}) 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 field sites.

Additionally, RF could allow for the quick estimation of C_{POC} given leachate characteristic data (e.g. C_O) or the back-calculation of an allowable C_O given maximum allowable C_{POC} (e.g. water quality limits).

Findings include:

1. The direct assessment 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 field sites and were consequently categorized as imposing “no risk” or “no additional risk.” Essentially, the six roadways employing fly ash stabilization of unbound materials were no different, in terms of potential impact on the environment for those elements, than roadways constructed with conventional materials.
2. The direct assessment 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 groundwater modeling determined that C_{POC} 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.
3. For all field sites, the initial concentration at the base of the fly ash stabilized layer (C_O) was reduced by an average of 98.4% at the point of compliance. Most (96%) of the concentration reduction occurs just after vadose-saturated zone boundary underneath the pavement section. This implies that a point of compliance adjacent to the edge of the pavement would result in very little difference in C_{POC} .
4. Reduction factors (RF) for all sites ranged from 45.7-87.9 and the average of all trace elements was found to represent field sites. RF were controlled primarily by depth to groundwater table and secondarily by thickness of stabilized layer. More reduction occurred in field sites with a relatively thicker stabilized layer, deeper Z_{GWT} , lower seepage velocity in the vadose zone, and higher seepage velocity in the saturated zone.
5. The RF actually required to decrease C_O to water quality levels at POC were well below the RF that field sites exhibited in this study. This implies that less reduction could have taken place at the field sites and still imposed “no predicted risk.”

Overall, this study demonstrated that there are no additional risks imposed by using unbound fly ash in roadways than roadways constructed with conventional construction materials, in terms of potential trace element impact on the environment. The unbound fly ash applications described in this study have been concluded to be suitable beneficial reuse applications with respect to water quality. Conclusions and RF can be applied to similar field sites, however roadways with different field conditions than

evaluated in this study (esp. 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.

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