The Laconia, New Hampshire Bottom Ash Paving Project

Volume 1: Environmental Testing Report

*Environmental Research Group
University of New Hampshire
Durham, New Hampshire*

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

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NREL Technical Monitor: Philip Shepherd

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Prepared under Subcontract No. XAE-3-13245

March 1996

SPONSORS

- Concord Regional Solid Waste/Resource Recovery Cooperative (CRSW/RRC)
- Wheelabrator Environmental Systems Inc. (WES)
- City of Laconia, N.H.
- U.S. Department of Energy (U.S. DOE) via the National Renewable Energy Laboratory (NREL)
- U.S. EPA via Rutgers University

PARTICIPANTS

- U.S. Army Corp of Engineers Cold Regions Research and Engineering Laboratory (CRREL)
- New Hampshire Department of Environmental Services (N.H. DES)
- New Hampshire Department of Transportation (N.H. DOT)
- Federal Highway Administration (FHWA)
- New York Department of Environmental Conservation (N.Y. DEC)
- Netherlands Energy Research Foundation (ECN)

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ACKNOWLEDGEMENTS

This research has been supported by contracts between the University of New Hampshire and the (i) Concord Regional Solid Waste/Resource Recovery Cooperative - Wheelabrator Environmental Systems, the (ii) U.S. Department of Energy via the National Renewable Energy Laboratory (XAE-3-13245-01), and the (iii) U.S. EPA via Rutgers University (through CR818178-01-0). The following individuals are thanked for their efforts on behalf of this project:

John Clements, FHWA
Nan Collins, UNH
Kendra Ecton, NREL
Paul Fitzgerald, City of Laconia
Don Fohs, FHWA
Ron Ford, CRSW/RRC
Simon Friedrich, US DOE
Lee Gifford, City of Laconia
Helena Harman, NREL
Vince Janoo, ACOE/CRREL
Matt Killeen, WES
David Kosson, Rutgers University

Teresa Kosson, Rutgers University
Sheldon Landsberger, University of Illinois
Dan McKeever, City of Laconia
Paul Moynihan, City of Laconia
Craig Musselman, CMA Engineers
Alan Perkins, NH DOT
Jim Presher, CRSW RRC
Jeff Schmidt, NY DEC
Phil Shepherd, NREL
Steve Shope, EEA
Mike Sills, NH DES
Hans van der Sloot, ECN
Carlton Wiles, NREL

ABSTRACT

Grate ash from the Concord, N.H. waste-to-energy (WTE) facility was successfully used as an aggregate substitute in an asphalt binder course pavement. The grate ash was used in a New Hampshire Department of Transportation type B binder course as part of an ash utilization demonstration project. A section of Rt. 3 in Laconia, N.H. was reconstructed. As part of the demonstration, a test section and a control section were built. The test section used a binder course containing 50% grate ash and 50% natural aggregate with 7% asphalt cement. The control section used a binder course containing 100% natural aggregate with 5 % asphalt cement. Both sections were placed above a stabilized base course containing soil and recycled asphalt pavement (RAP) from the road rehabilitation. Both sections were overlaid with a wearing course containing natural aggregate. The demonstration involved extensive field and laboratory testing for both physical and environmental performance. The physical performance of the test section over the 1.5 year study period was the same as the control section. No environmental impacts were observed over the 1.5 year study period. Pavements are excellent encapsulating agents. The use of ash in hydrophobic, monolithic pavements prevents any significant migration of ash constituents (e.g. metals) into the polymeric binder and prevents leaching of ash constituents (e.g. salts) from the monolith. Asphalt cement, in both monolithic and granular pavement specimens, acts as a diffusional impediment to the leaching of ash constituents. This promotes diffusional leaching behavior with extremely low diffusional fluxes (ash constituent mass released per unit area of monolith per unit time); even under aggressive laboratory leaching tests. The future behavior of the test binder course was evaluated using both accelerated testing methods and one dimensional diffusion modeling. The conservatively estimated cumulative fluxes (ash constituent cumulative mass released per unit area of monolith per modeled time period) associated with all modeled scenarios were at least 10 to 10,000 times smaller than existing contaminant fluxes (background contaminant mass moving under or applied upon the road per unit area per unit time) associated with road salting, road surface runoff, or preexisting upgradient ground water contamination. The use of grate ash or bottom ash from the Concord WTE facility, or analogous facilities, in asphaltic binder course applications is an acceptable use of this light-weight aggregate substitute.

KEY POINTS

A number of key points about the environmental testing for the Laconia Bottom Ash Paving Project are provided in bullet form to facilitate review. The bullets are sorted by category. The reader may refer to the executive summary or text portions of the report for more detailed discussions of the results.

Summary

- Grate ash was successfully used as an aggregate substitute in an asphaltic binder course pavement for a section of Route 3 in Laconia, N.H. that was reconstructed for the demonstration project.
- The mix design involved the use of 50% aged grate ash, 50% natural aggregate and 7% asphalt cement to meet N.H. DOT type B binder course specifications.
- The reconstruction involved installation of a test section containing ash in the binder course and a control section containing only natural aggregates in the binder course.
- The two year demonstration evaluated both physical and environmental performance using laboratory studies and extensive field work conducted at the demonstration site.
- Excellent physical performance was observed with the test section behaving similarly to the control section. These field data were corroborated by extensive laboratory studies.
- Excellent environmental performance was observed in the field. No environmental impacts were seen during the two year study. These field data were supported by extensive laboratory studies and modeling to predict future environmental behavior.

Background

- Bottom ash and grate ash are widely used in Europe as an aggregate substitute in civil construction projects like road construction.
- The Concord Regional Solid Waste/Resource Recovery Cooperative, the City of Laconia, Wheelabrator Environmental Systems, the U.S. Environmental Protection Agency (via Rutgers University), and the National Renewable Energy Laboratory for the U.S. Department of Energy sponsored an extensive research effort by the University of New Hampshire and the U.S. Army Corp of Engineers

Cold Regions Research and Engineering Laboratory to conduct an ash utilization pavement demonstration project.

- A comprehensive two year field demonstration (from 1993 to 1995) was conducted to evaluate the environmental and physical performance of a pavement material made with grate ash from the Concord, N.H. WTE facility.
- This field demonstration followed an earlier two year project (from 1990 to 1992) that examined the time dependent physical and chemical characteristics of bottom ash from the Concord WTE facility, as well as the physical performance and environmental behavior of pavement monoliths designed as binder course.
- Bottom ash is a uniform material that can be used as an aggregate substitute in asphaltic binder course.

Demonstration Site Characteristics

- The field demonstration site involved rehabilitation of a section of Rt. 3 in Laconia, N.H.
- The site was characterized prior to paving using an extensive hydrogeological investigation involving six monitoring wells and two surface water monitoring stations.
- At the time of paving, subsurface suction lysimeters were installed below the road in the test and control sections to sample vadose zone moisture.
- At the time of paving, road run-off collection storm drains and manholes were installed in both the test and control sections to characterize road surface run-off.

Environmental Performance of the Asphalt Batch Plant During Test and Control Pavement Manufacture

- Air emissions testing was conducted during the manufacture of test and control asphalts.
- Air emission testing was done for HCl, particulates, multimetals, and opacity.
- For all production runs, the plant met all applicable air emission limits.

Grate Ash, Soil and RAP Characteristics

- Grate ash was collected, size separated and aged for six months prior to its use.
- The total element concentration ranges for 46 elements in fresh grate ash, aged grate ash and bottom ash (from the earlier study) are typical and similar except that bottom ash showed more variability from high concentration outliers. This

may be due to (i) the presence of grate siftings in the bottom ash, (ii) artifacts associated when the two ash types were collected, or (iii) artifacts associated with minor differences in the sampling and processing (e.g. sieving, trommeling) of the ash samples.

- The leachability or total available element concentration ranges in fresh grate ash, aged grate ash and bottom ash (from the earlier study) were typical and similar except that bottom ash has high concentration outliers; these relate to the high total element concentration outliers mentioned above.
- Aging did not markedly alter the availability of elements in the grate ash when using the operationally-defined availability leaching tests.
- The aged grate ash was not hazardous according to federal and state regulations.
- Significant preexisting lead and chloride concentrations were present in the roadside soils (Pb from 31 to 269 mg/kg, Cl from 68 to 250 mg/kg) and in the preexisting RAP material used in the road reconstruction (Pb from 32 to 36 mg/kg, Cl from 200 to 204 mg/kg). These were observed in both the control and test sections prior to paving. These contaminants are present from the historical use of leaded gasolines and from the prior and present use of road salt.

Field Environmental Behavior

- At the microscale level (on the order of microns), no significant diffusional migration of grate ash constituents into the asphalt cement binder adjacent to the ash particles was observed for test binder pavements collected after 1.25 years of service. Calculated solid phase diffusivities were extremely low (10^{-16} to 10^{-18} m²/s) and typical for ion diffusion through polymeric systems.
- At the macroscale level (on the order of millimeters), no significant diffusional migration of grate ash constituents into the wearing course or the base course was observed for test section binder pavements collected after 1.25 years of service.
- Monolithic diffusional leaching of road cores collected at the beginning of the pavement service life and after 1.25 years of service showed typical diffusional leaching. Fluxes from the monoliths were extremely low and similar to previously reported values for ash in solidified asphalt monolith products.
- The elements Ca, Fe, Mg, and Mn diffused out of control cores. The elements Ca, Cl, Mg, Mn, Na, SO₄²⁻, Si and Zn diffused out of test cores.

- The observed diffusivities ranged from 10^{-12} m²/s for Cl to 10^{-16} m²/s for Zn. These are typical for diffusional leaching from asphalt products made with natural aggregates and waste materials.
- The asphalt cement acts as an impediment to diffusion and therefore controls diffusional processes.
- Monolith tortuosity is the predominant monolith characteristic controlling diffusional processes; the diffusion pathways in ash/asphalt monoliths are very tortuous.

Prediction of Future Environmental Behavior

- The future behavior of monolithic binder course was evaluated using a statistically designed laboratory experiment that looked at the effects of void change, microcracking, and asphalt cement aging on diffusional monolith leaching behavior. Microcracking was the most significant variable to influence diffusional leaching because it reduces tortuosity.
- The future behavior of grate ash binder course recycled as a RAP base course was evaluated using a granular diffusion leaching test. The granularization of the monolith reduced tortuosity but increased chemical retention. Overall, the RAP materials leached slightly more than the monolith materials. The beneficial influence of the asphalt cement on reducing fluxes compared to ash controls was observed.
- One dimensional diffusion modeling was conducted for a number of binder course and RAP base course scenarios. The modeling effort was very conservative because it neglected interface effects and subsequent geochemical attenuation of leached ash constituents in the vadose zone. An hypothesized wetting phenomena and a wide range of time frames were evaluated. Modeled cumulative fluxes were extremely low. The cumulative fluxes that were relatively the highest were associated with RAP material.

Evaluation of Preexisting Ground Water Contamination

- Significant preexisting lead and chloride contamination was found at the demonstration site in road side soils, ground waters, and surface waters.
- Water quality monitoring during the study period revealed elevated concentrations of lead in ground water, surface water, and road run-off. The elevated levels

occurred in both the test and control sections. They also occurred prior to paving. Lead isotope analysis revealed that the source of the lead was due to atmospheric deposition of lead aerosols from gasoline combustion and industrial activities and not from the grate ash.

- Water quality monitoring during the study period revealed that concentrations of chloride in ground water, surface water, vadose zone moisture, and road run-off samples exceeded State and Federal secondary drinking water standards. These exceedences occurred in both the test and control sections. They also occurred prior to paving. Ion fingerprint analysis and ion ratio analysis revealed that the source of chloride in the test section was due to upgradient contamination and prior road salting practices and not from the grate ash.

The Environmental Behavior of Grate Ash and Bottom Ash From the Concord WTE Facility

- The environmental behavior of grate ash and bottom ash from the Concord WTE facility was found to be similar with regard to ash leaching, monolith leaching and granularized product leaching. Provided that these ashes are used in asphaltic binder course pavements, the environmental behaviors of both these ashes should be similar in future asphalt binder course applications.

The Need for Aging of Grate Ash or Bottom Ash

- From an environmental perspective, aging has no apparent positive or negative influence on the leaching behavior of ash constituents from hydrophobic asphaltic binder course materials.
- From a physical perspective, the future use of bottom ash from the Concord WTE facility in asphalt binder course may require aging to minimize potential expansion or swelling reactions in the monolith. This issue was not studied and warrants further investigation to see if it is an issue.
- From a physical perspective, the future use of grate ash from the Concord WTE facility in asphaltic binder course probably does not require aging.

Suggested Criteria for Analogous Uses of Grate or Bottom Ash from Other WTE Facilities

- The extensive research that has been conducted here on the use of bottom ash and grate ash in asphaltic binder course pavements provides a basis for the

analogous use of bottom and grate ashes from other WTE facilities in asphalt paving applications.

- If grate ash or bottom ash from a mass burn WTE facility with modern grate systems and operating with good combustion practices is to be used in asphaltic binder course pavement applications, then some criteria are suggested for analogous uses that would allow for limited additional investigations to confirm that an analogous use would be acceptable.
- Suggested criteria for ash characteristics, pavement mix design and product environmental behavior are offered.

EXECUTIVE SUMMARY

INTRODUCTION

Bottom ash is the principal waste stream from the combustion of municipal solid waste (MSW). It is comprised of grate ash (97%), the slag material discharged at the end of the grate system, and grate sifting (3%), the material that melts or falls through the grate structure. This project was conducted to demonstrate the feasibility of using municipal solid waste grate ash as an aggregate substitute in the construction of a pavement binder course for a portion of Rt. 3 in Laconia, New Hampshire. The research, sponsored by the Concord Regional Solid Waste/Resource Recovery Cooperative (CRSW/RRC), Wheelabrator Environmental Systems Inc. (WES), the U.S. EPA, and the U.S. DOE, was conducted over a two year period during 1993 and 1994. This study is the culmination of an earlier two year characterization study between 1990 and 1992 that documented the physical and environmental characteristics of the bottom ash as it was produced at the Concord, N.H. waste-to-energy (WTE) facility and used in an asphaltic binder course. Together, these two studies provide a complete evaluation of the potential for using grate ash or bottom ash in asphalt binder course or as recycled asphalt pavement (RAP) in base courses in pavements.

This study included two principal parts: an environmental evaluation and a physical performance evaluation. The environmental component included an evaluation of the potential short term and long term impacts associated with the use of grate ash in pavement construction, including possible future life cycle scenarios for the pavement. The final Environmental Testing Report is comprised of two volumes. Volume 1 addresses environmental performance evaluations and Volume 2 provides appendices containing data. One companion, Volume 3, (Gress et al., 1996) addresses physical performance evaluations.

This Executive Summary includes sections that provide information about the background related to the project, the hydrogeology of the site, the results from asphalt batch plant testing during ash pavement manufacture, the materials used in the demonstration, the evaluation of environmental impacts in the near term, the evaluation of possible environmental impacts in the longer term, the evaluation of ground water quality at the study site, the examination of preexisting contaminants at the site, the comparison of modeled potential releases from the road to the fluxes existing at the site from anthropogenic activity, and conclusions.

BACKGROUND

Bottom ash is comprised of grate ash and grate siftings. The use of both types of ash in civil engineering construction is widely practiced in western Europe. Applications include its use as granular structural fill in wind and sound barriers, road embankments, road subbases, parking lots and bike paths. The uses that are anticipated for the U.S. include the use as aggregate substitutes in bituminous asphalt and their recycled products, Portland cement concrete, stabilized road subbase, granular fill, or as granular cover material at lined MSW landfills.

The Laconia paving project effort consisted of the reconstruction of Rt. 3 in Laconia, New Hampshire. A 2,000 linear foot (610 m) section was reconstructed. Approximately 1,150 feet (350 m) was constructed as a control section using natural aggregate both in the binder and wearing courses. The 850 foot (260 m) test section was constructed using 50% grate ash/50% natural aggregate in the binder course and natural aggregate in the wearing course. Underlying the entire reconstruction project was a soil/recycled asphalt pavement (RAP) mixture comprised of road subbase soils, wearing course RAP from the original pavement surface, and RAP from other locations.

The requirements to establish the use of a waste material as a product in the State of New Hampshire involve defining: (i) the physical and chemical variability of the ash process stream, (ii) a suitable market for the product, and (iii) an evaluation of the performance of the product. The earlier two year characterization study addressed the first two requirements by showing the relative invariability of the chemical and physical properties of the bottom ash as it is produced at the Penacook plant, the successful replacement of bottom ash for aggregate in the establishment of a pavement job mix formula, the successful manufacture of pavement at a batch hot mix asphalt plant, and the role that bituminous polymeric asphalt plays in controlling diffusional leaching behavior. This project addresses the third requirement.

SITE HYDROGEOLOGY

The hydrogeology in the control section is dominated by glacial outwash loamy sands. Hydraulic conductivities (12-28 ft/d or 4.0×10^{-3} - 9.9×10^{-3} cm/sec), shallow gradients (0.008 ft/ft or m/m), and seepage velocities (0.5-1.1 ft/d or 0.15-0.33 m/d) are typical for permeable soils in close proximity to surface waters (Paugus Bay on Lake Winnepesaukee). The hydrogeology in the test section is dominated by thin overlays of glacial till on top of highly fractured metasedimentary pelitic schists of the Rangely Formation. Hydraulic conductivities (0.11-0.4 ft/d or 3.9×10^{-5} - 2.0×10^{-4} cm/sec), steep gradients (0.14 ft/ft or m/m) and seepage velocities (0.18-0.37 ft/d or 0.05-0.11 m/d) are typical for relatively permeable bedrocks. The seasonal ground water table is high in the test section and is partially controlled by the use of a French drain adjacent to the roadway. To facilitate site characterization, five monitoring wells and a preexisting dug well were used to characterize ground water. Two sets of suction lysimeters (three lysimeters per set) were used to characterize vadose zone moisture below the road, two

road run-off storm drains were used to characterize road run-off, and two sampling stations were used to characterize surface waters.

ASPHALT BATCH PLANT TESTING

The asphalt batch plant was evaluated for HCl emissions, particulate emissions, metals emissions and visible emissions during the production of control and test asphalts. The plant is regulated for particulate and visible emissions. Stack testing showed that the plant met all applicable air emissions limits during production of both the control and test asphalts. The average HCl emissions were higher during test asphalt production (0.09 vs 0.14 lb/h). The average particulate emissions were moderately higher during the test asphalt production (1.66×10^{-2} versus 6.49×10^{-3} grains/dry standard cubic foot) but less than the applicable limit of 4×10^{-2} grains/dry standard cubic foot. The average particulate metals content was higher during the control run for the metals Cd, Cr, Ni and Se. The average particulate metals content was higher during the test run for the metals Cu and Zn. Opacity was higher during the test asphalt run (0 to 15% compared to 0 to 10%) but less than the 20% limit.

GRATE ASH, SOIL AND RAP CHARACTERISTICS

The grate ash was obtained from the Wheelabrator-Concord L.P. WTE facility. This is the same facility that provided the bottom ash for the earlier study. The facility is a 500 ton per day (454 metric tonnes per day) modern mass burn system with von Roll reciprocating grates. Only grate ash was collected. The residues were trommeled to remove oversize material prior to aging for about six months at the Franklin, N.H. secure ash monofill.

Grate ash was evaluated in both its fresh form and its aged form for total element composition and total available composition. These data were then compared to the

bottom ash total element composition and total available composition data obtained in the earlier two year study (Eighmy et al., 1992; Whitehead, 1992).

For the total composition data, data ranges overlap for all elements for each ash type. However, the bottom ash usually has high concentration outlier values. For the total available composition data, data ranges overlap for all elements for each ash type. However, the bottom ash usually has high concentration outlier values that coincide with the high total composition data. Some of the high outlier elements are those traditionally associated with grate siftings (Al, Pb, Zn). Some of the high outlier elements are not associated with grate siftings (Ca, Cl, Ti). The high outliers in bottom ash may be associated with the presence of grate sifting in the bottom ash, artifacts associated with the way the two ash types were collected or artifacts associated in the sampling and processing (i.e., sieving and trommeling) of the ash samples.

The influence of aging on grate ash element total availability was statistically evaluated. There were slight differences in availability between the fresh and the aged grate ash as determined by Student's t-test (95% probability, pooled variances, two tailed comparison). Na and Si availabilities were significantly higher in the fresh grate ash. Al and Fe availabilities were significantly higher in the aged grate ash. These differences are attributed to robust changes in ash mineralogy during aging. More subtle changes (e.g. carbonation) would not be detected because of the aggressive nature of the Dutch Total Availability Test that was used.

The aged grate ash was evaluated for its TCLP characteristics and was determined to be not hazardous according to federal and state regulations.

The characteristics of the road side soils and RAP show that significant anthropogenic Pb and Cl were present at the site prior to the paving demonstration. Soil lead values ranged from 31 to 269 mg/kg. Soil chloride values ranged from 68 to 250 mg/kg. RAP lead values ranged from 32 to 36 mg/kg. RAP chloride values ranged

from 200 to 204 mg/kg. The lead comes from long term deposition of anthropogenic lead in the environment (e.g. from the use of tetraethyl lead in leaded gasoline). The chloride comes from road salting and other sources of contamination in the local drainage basin.

PAVEMENT MICROSCALE MIGRATION

Pavement samples removed after 1.25 years of service life were subjected to scanning electron microscopy/x-ray microanalysis (SEM/XRM) studies to determine if ash constituents were migrating, via molecular diffusion, from ash particles into the surrounding bituminous polymer matrix. Studies were conducted at the microscale level (on the order of tens of microns). If significant migration from the ash particle into the polymer matrix had occurred, then high concentrations of the element would be detected in the matrix. Profiles were established for Al, Cu, and Zn because of their larger particle size and the relative ease wherein they could be identified and located with SEM/XRM x-ray spatial mapping. No evidence was seen of significant microscale migration from ash particles containing Al, Cu and Zn after 1.25 years of service life. These particles could be easily identified and probed with SEM/XRM. Effective diffusion coefficients for molecular diffusion ($D_{e,m}$) were calculated. Values of 10^{-16} to 10^{-17} m²/sec range were observed; these values are extremely low and are typical for molecular diffusion in polymeric solids. These values are also one to three orders of magnitude less diffusive than those observed with monolith leaching tests, as described below, where aqueous diffusion is promoted.

PAVEMENT MACROSCALE MIGRATION

Pavement samples removed after 1.25 years of service life were subjected to total elemental composition analysis using neutron activation analysis (NAA) and x-ray

fluorescence (XRF) analyses. Road cores from the test and control sections were disassembled into their wearing course, binder course and RAP base course components. If large scale migration had occurred simultaneously up into the wearing course and down into the RAP base course from the test binder course, then the concentrations of elements in these courses would be higher in the test section when compared to controls. With the exception of Mn and Al, statistical evaluations using Student's t-test (95% probability, pooled variances, two tailed comparisons) showed that no significant differences existed in the elemental composition of test and control sample populations for the wearing course and RAP base course. Thus, no evidence was seen of macroscale migration after 1.25 years of service life.

MONOLITH DIFFUSIONAL LEACHING BEHAVIOR OF ROAD CORES

Road cores taken from the road right after pavement construction ($t=0$ years) and after a 1.25 year service life ($t=1.25$ years) were subjected to the Dutch NEN 7345 Tank Leaching Test. Effective diffusion coefficients (D_e) for leaching from monoliths were determined for Ca, Fe, Mg, Mn, Si, Na, Zn, Cl and SO_4^{2-} because these were the only constituents exhibiting diffusive behavior. Generally, Ca, Fe, Mg, and Mn diffused from control section cores. Generally, Ca, Cl, Mg, Mn, Na, SO_4^{2-} , Si, and Zn diffused from test section cores. Values ranged from 10^{-12} m²/sec (Cl) to 10^{-16} m²/sec (Zn). Such values are typical for ion diffusion under aqueous situations in tight, hydrophobic polymeric monoliths like intact pavements. Values of chemical retention (R) were less important than tortuosity (τ) in reducing diffusivity. With the exception of Ca, no significant differences were seen using Student's t-test (95% probability, pooled variances, two tailed comparison) between test section cores taken immediately after pavement construction and those taken after 1.25 years of service life.

EVALUATION OF EFFECTS OF PAVEMENT VOID CHANGE, BITUMINOUS POLYMER AGING AND MICROCRACKING ON MONOLITH DIFFUSIONAL LEACHING BEHAVIOR

In an effort to predict how the test road might behave 20 or more years into its service life, a statistically-based factorially designed experiment using analysis of variance (ANOVA) was utilized to evaluate voids, bitumen aging, and monolith microcracking on leaching behavior. Three levels of pavement voids (5%, 7.5% and 10%), three levels of bituminous polymer aging (none, medium and high) and three levels of monolith microcracking (none, medium, and high) were used. These were selected to predict how traffic-induced densification (void decreases), atmospheric oxygen and UV light aging (polymer oxidation), and monolithic integrity (stress microcracking) might influence the diffusional leaching process. The results show that microcracking, and to a lesser extent aging and the interaction term between cracking and aging, are the only statistically significant processes at the 95% confidence level that affect diffusional leaching. High levels of microcracking reduced tortuosities (τ) from 8,000 to 10,000 down to 200 to 400. Such reductions can increase fluxes at the monolith surface by factors of 20 to 40. The results show that monolithic microcracking can influence monolith leaching behavior.

EVALUATION OF GRAIN SIZE AND THE PRESENCE OF BITUMINOUS ASPHALT CEMENT ON GRANULAR DIFFUSIONAL LEACHING BEHAVIOR

The granular diffusion leaching test was used in an attempt to predict how the test road materials might behave in a compacted form either as a RAP base course pavement (ground to $<3/4$ " or 1.9 cm and recompact) situated beneath a pavement, or as a compacted material disposed in a landfill ($<3/4$ " or 1.9 cm granular material), or as a compacted product of road grinding (fine granular material). This test produces effective diffusion coefficients (D_e), chemical retentions (R) and tortuosities (τ) for compacted granular material. The results showed a decrease by a factor of 10 to 1,000

in effective diffusion coefficients when granular behavior is compared to monolithic behavior. Tortuosities (τ) were significantly reduced (10,000 down to 50) while chemical retention (R) increased by a factor of 10. Of the three granular materials, 3/4" (1.9 cm) minus pavement with asphalt cement was the least diffusive, followed by 3/4" (1.9 cm) minus grate ash, then <300 μm (0.012") grate ash. The results also show that asphalt cement still reduces leachability even in non-monolith, granular material. This occurs because asphalt cement is incorporated in the internal pores of the grate ash particles, dramatically reducing the effective surface area of the ash particles. The use of binder course containing grate ash as a RAP material in subsequent pavement reconstructions is also a viable use.

OUTDOOR LYSIMETER STUDIES

In the earlier two year characterization study (Eighmy et al., 1992), two large outdoor lysimeters were constructed to evaluate the long term, percolation-based, leaching behavior of the bottom ash from the Concord facility and the monolithic diffusional leaching of large, broken pavement materials made with bottom ash (25% substitution). The lysimeters have been in operation for four years. The constituents Ca, SO_4^{2-} , Cl, Na, and K leached in the greatest concentration from both lysimeters. NH_4^+ -N, Br, PO_4^{3-} -P, B, Fe, Mg, Mn, Sr and Si leached, but at much lower levels. The asphalt monolith reduced leachability by factors of 10 to 100. Cumulative release plots presented in the report show the leaching history of these materials. The data are useful for evaluating leaching behavior for utilization scenarios (granular fill) or disposal scenarios that are not presently under consideration in this project.

MODELING OF CONSTITUENT FLUXES FOR VARIOUS TIME PERIODS AND DEGREES OF WETTING

A one dimensional diffusion model was used to estimate potential constituent release for the test pavements using a number of life cycle scenarios (new pavement, 10 year old pavement, 20 year old pavement, RAP base course pavement), a number of conservative estimates of wetting (5, 10, 20% of the time because of condensation/evaporation) and three reference leaching periods (1.5 years, 20 years, 100 years). The approach estimates what would be released at the lower binder course/soil interface for a binder course pavement containing grate ash or at the RAP/soil interface for a RAP base course containing grate ash. It assumes that an intact pavement would exist above either ash-containing course. It does not take into account any subsequent extensive attenuation that would occur in soils below the interface. The wetting percentages are estimates of the time where the interface would be wetted by ephemeral condensation from soil water vapor. Appropriate pD_e , R , and availability values from the road cores were used for all elements exhibiting diffusional leaching behavior (Ca, Cl, Fe, Mg, Mn, Na, Si, SO_4^{2-} , Zn). As an example, chloride (a mobile constituent) is discussed. Modeled fluxes at the interface for chloride ranged from $1.41 \text{ g/m}^2/1.5 \text{ years}$ to $104 \text{ g/m}^2/100 \text{ years}$. These fluxes are considered extremely low and do not reflect any subsequent attenuation that would occur for many constituents if subsequent migration were to take place downwards towards the water table.

GROUND WATER QUALITY

An extensive program was undertaken to characterize the ground water, surface water, vadose zone moisture, and road run-off at the site prior to and after placement of the pavement. The ground water quality was compared to existing State and Federal drinking water quality standards. Lead was the only analyte to exceed primary drinking

water standards maximum contaminant levels (MCLs). The standard was exceeded in both the control and test sections prior to pavement reconstruction as well as after the placement of pavement. No other primary drinking water standards were exceeded. As discussed below, the source of the lead detected in the ground water in the test section was from historical anthropogenic inputs (atmospheric deposition of lead aerosols, combustion of leaded gasoline) and not from the grate ash. Comparisons were also made for secondary drinking water standards; exceedences occurred for Cl, Fe, Mn and Na. However, like lead, they occurred in both the test and control sections prior to pavement reconstruction, as well as after the placement of pavement.

Trend analyses were conducted for lead and chloride data for all sampling locations; no statistically significant increasing or decreasing trends were seen in either the control or test section for lead; increasing trends for chloride were seen at two locations in the control section. Evaluation of lead isotope ratios ($^{207}\text{Pb}/^{204}\text{Pb}$) and of conservative ion ratios (K/Cl versus Ca/Cl, Na/SO₄ versus Ca/Cl, Na/SO₄ versus K/Cl) unequivocally show that the lead and chloride in the ground water are not originating from the grate ash. They are preexisting anthropogenic contaminants.

COMPARISON OF MODELLED CONSTITUENT FLUXES TO PREEXISTING BACKGROUND CONTAMINATION FLUXES

The results of one dimensional diffusional modeling of potential release from the binder course/soil interface were compared to fluxes of contaminants coming from road run-off, road salting, or ground water flow under the road. The presence of upgradient background ground water contamination or anthropogenic activity produced fluxes that were factors of 10 to 10,000 times higher than potential signals at the binder course/soil interface over the 1.5 year evaluation period.

ENVIRONMENTAL BEHAVIORS OF BOTTOM ASH AND GRATE ASH FROM THE CONCORD WTE FACILITY

The total elemental composition, total available composition, monolithic leaching behavior, and behavior of granular RAP material was compared for fresh bottom ash and fresh and aged grate ash. The elements Ca, Si, Cl and Pb were compared. Bottom ash was found to have high outlier concentrations for total elemental composition and total available composition. However, ranges overlapped for all three ash types. Monolith leaching behavior was similar for all ash types. Similar availabilities, fluxes, diffusivities, tortuosities, and leaching mechanisms were observed for each ash type in each element category. The leaching behavior of granularized monoliths made with either fresh bottom ash or fresh grate ash was similar with respect to the influence of asphalt cement on the reduction of leaching (release or flux). The data show that there are no apparent differences between the environmental behavior of bottom ash and grate ash in asphaltic products.

AGING REQUIREMENTS

If bottom ash (with grate siftings) from the Concord WTE facility is to be used in asphaltic pavements without aging, then its environmental behavior will be similar to grate ash and would not be problematic. From a conservative materials performance perspective, aging should be considered to stabilize the material. A minimum time period of one to three months would provide a conservative approach. Further studies may show that aging may not be needed or that these times can be reduced.

If grate ash (without grate siftings) is used in asphaltic pavement without aging, its environmental behavior will be acceptable. From a materials performance perspective, aging should be less important because grate siftings are absent. A conservative

approach would be to have grate ash generators or users evaluate the need for grate ash aging as needed.

APPLICATION OF THESE RESULTS TO ANALOGOUS USES

The transferability of these results to analogous uses in hot mix asphalt pavement binder courses has been discussed for a scenario involving a similar combustor using a modern grate system and good combustion practices. A number of criteria have been suggested. The grate ash or bottom ash must be processed for grain size considerations. It may also be necessary to control the moisture content of the ash during storage. Aging requirements related to physical performance must be determined by the user. The ash total Si, Cl, and Pb concentrations should have similar distributions and measures of central tendency to the Concord grate or bottom ash. These elements are indicative of slag chemistry and leaching behavior. Additionally, the ash loss on ignition should be controlled as values less than 10% are deemed to be acceptable for use in asphaltic pavements. The mix design for the binder course should involve state- or user-specified mix designs with ash loading less than 50%. The environmental performance of the product should involve the use of tests to verify monolithic leaching behavior or the encapsulating effect of the asphalt cement.

CONCLUSIONS

The use of grate ash from the Concord WTE facility as an aggregate substitute has had no measurable impact on the environmental quality at the study site over the 1.5 year study period. Like natural aggregates, the ash has defined chemical characteristics and physical characteristics. Its fundamental leaching behavior and its diffusive leaching behavior in monolithic and granular form are well understood. Models can be used to predict long term leaching behavior for all of the life cycle scenarios of the pavement.

Modeling efforts show that future behavior as a pavement or as a RAP material will also have negligible impacts. Its behavior is virtually indistinguishable from standard pavements from both an environmental and physical standpoint. Grate or bottom ash from a modern mass burn WTE facility such as the Concord WTE facility, when used in binder course asphalt pavement or in its subsequent use as a RAP base course below a pavement, are acceptable uses for this light weight aggregate substitute.

CHAPTER 1

INTRODUCTION

INTRODUCTION

This is the first volume of a two volume report titled "The Laconia, N.H. Bottom Ash Paving Project". This volume addresses environmental testing and evaluation regarding the project. The second volume contains the raw data in numerous appendices. Companion volumes (Gress et al., 1995a,b) provide information on physical performance and evaluation.

The two volumes of this report contain information relative to grate ash chemical characterization, evaluation of micro-scale and macro-scale diffusion in pavement materials, evaluation of monolithic diffusional leaching behavior of laboratory and road specimens, modeling of contaminant release behavior, and evaluation of ground water and surface water quality data from the study site. Companion volumes (Gress et al., 1995a,b) contain information relative to grate ash physical characteristics, mix design, pavement testing and performance, and pavement design.

This research was sponsored by the Concord Regional Solid Waste/Resource Recovery Cooperative (CRSW/RRC), Wheelabrator Environmental Systems (WES), the City of Laconia, N.H., the U.S. Department of Energy (U.S. DOE) via the National Renewable Energy Laboratory (NREL), and the U.S. Environmental Protection Agency (U.S. EPA) via Rutgers University. Numerous state, federal, and foreign governmental agencies have participated in this project as observers who received progress reports for comment and review. The research was conducted by the Environmental Research

Group (ERG) of the University of New Hampshire and the Cold Regions Research and Engineering Laboratory (CRREL) of the U.S. Army Corps of Engineers (U.S. ACOE).

BACKGROUND

The CRSW/RRC is a consortium of 27 New Hampshire municipalities, including the City of Laconia. The cooperative presently sends its municipal solid waste (MSW) to the Concord, N.H. waste-to-energy (WTE) facility located in the village of Penacook. The facility is owned and operated by WES. Combined bottom ash and scrubber residues are presently disposed in a double-lined ash monofill in Franklin, N.H. The CRSW/RRC owns the landfill and is responsible for its operation.

The CRSW/RRC was interested in securing longer term disposal capacity for the residue that it must manage. The extension of the operational life of the landfill via bottom ash separation and utilization was seen to be an interesting opportunity, hence the CRSW/RRC has actively evaluated bottom ash utilization. WES, as owners or operators of over 16 WTE facilities nation-wide, was also interested in evaluating ash utilization.

In 1990, CRSW/RRC and WES embarked on a two year characterization study to carefully evaluate: (i) the time-dependent chemical and physical properties of the bottom ash waste stream generated at the Concord waste-to-energy facility and (ii) the proper asphalt mix design needed to make a high quality pavement. This study, conducted by ERG, resulted in a report (Eighmy et al., 1992), numerous graduate student theses and dissertations (Whitehead, 1992; Tarr, 1993; Zhang, 1993), and

numerous scientific papers (Gress et al., 1991; Gress et al., 1992; Whitehead et al., 1993; Tarr et al., 1994; Zhang et al., 1994) addressing the suitability of municipal waste combustor bottom ash as an aggregate substitute in the manufacture of asphaltic pavement material.

Near the end of the two year characterization project, plans were made to identify a suitable location within the 27 communities of the CRSW/RRC to pave a test road with grate ash used as an aggregate substitute in a binder course. A number of criteria were established for site selection. These included the desire (i) to pave a road which was otherwise scheduled for reconstruction and which carried a high volume of traffic, (ii) to construct a pavement with excellent physical performance capabilities, (iii) to construct a pavement with environmentally protective characteristics, and (iv) to design a project addressing all New Hampshire Department of Environmental Services (N.H. DES) regulatory requirements for ash utilization.

A site was identified in Laconia, N.H. The selection process involved numerous public meetings, publicity in the press, and meetings with abutters. A request was submitted to the New Hampshire Department of Environmental Services, using an R&D permitting process, to conduct the demonstration. Approval was obtained on November 6, 1992.

In May, 1993, a 2,000 linear foot (610 m) section of US Route 3 was reconstructed in Laconia, N.H. Approximately 1,150 feet (350 m) was constructed as a control section using natural aggregate in the binder course. The 850 foot (260 m) test section was constructed using a 50% grate ash/50% natural aggregate blend in the

binder course. A wearing course, using 100% natural aggregate, was applied over both sections. Therefore, in this demonstration, the test binder course was not directly exposed to traffic or the environment. Route 3 was originally the main highway between Boston and Montreal and was designed and constructed in the 1930's to high construction standards. The road was originally built above a macadam pavement. Excellent subbase materials were used. The road surface was originally concrete; it was periodically resurfaced with an asphalt wearing course. During the 1993 reconstruction, the existing asphalt wearing course was removed from the road to be used later as a recycled asphalt pavement (RAP) base course for the reconstruction. The underlying concrete road surface was excavated and removed.

From October, 1992 through December, 1994, data have been gathered on the study site and on the environmental and physical performance of the road. This has involved extensive field and laboratory testing. This two volume environmental testing report summarizes this information and provides documentation required to obtain an approval for direct reuse pursuant to EnV-Wm 2602.06 from N.H. DES. The approval process will involve the modification of the Concord facility's residuals management plan.

BOTTOM ASH UTILIZATION WORLD-WIDE

A modern, mass burn waste-to-energy (WTE) facility is comprised of a tipping floor (or pit), a crane to load MSW to the combustor, MSW feed hoppers, a furnace with grates, a boiler, heat exchanger, air pollution control system, and stack. Figure 1.1 depicts a typical layout of a WTE facility.

1. Receiving Hall/Tipping Floor
2. MSW Bunker/Pit
3. Grapple Crane
4. Charging Hopper
5. Reciprocating Grates With Underfire Air (Grate Ash and Grate Siftings)
6. Combustion Zone With Overfire Air
7. Superheater
8. Boiler and Economizer (Economizer Ash)
9. Ram Discharge With Quench (Grate Ash, Grate Siftings, Economizer Ash)
10. Dry Lime Scrubber Venturi
11. Fabric Filters (Dry Scrubber Residue)
12. Induced Draft Fan
13. Stack
14. Combined Ash Roll-Off

Figure 1.1: Schematic of a Typical WTE Facility

Figure 1.2 depicts a materials balance in a combustion facility. In a modern mass-burn municipal WTE facility, about 80 to 95% of the total weight of the residues that are produced are bottom ashes (IAWG, 1994). Bottom ash is comprised of grate ashes and grate siftings that remain on the grate (or sift through the grate) during the combustion process. Typically, bottom ash is comprised of 95 to 97% by weight of grate ash and 3 to 5% grate siftings. Grate ash and grate siftings contain slags, unmelted or partially melted metallic materials, and uncombusted MSW. Frequently, economizer ash from the boiler section of the furnace is added to the bottom ash; though this represents a small fraction of the bottom ash (<1%). In the earlier two year characterization study, bottom ash was characterized. In this study, only grate ash was used in the demonstration. These distinctions are maintained throughout the report.

The bottom ash is about 60-80% by weight of aggregate-size slag particles. The intended use of the particles and the required size [e.g. < 3/4" (1.9 cm)] influences the weight fraction that can be utilized. Traditionally, in western Europe, these residues are utilized as aggregate substitutes in granular fill, road bases, wind barriers, sound barriers, Portland cement, and bituminous asphalt pavements (IAWG, 1994).

A fair amount of research has been conducted on the process of slag formation and the petrology of the grate ash slags (Eusden et al., 1994; Eusden and Eighmy, 1995). Grate ash slag particles consist of non-melted or partially melted waste products (30-45%) and melt products (55 to 70%). The non-melted waste products include bottle glass, metallic material, soil particles, and uncombusted waste. The melt products consist of glasses formed in the combustor which are divided into three types: isotropic silicate

Figure 1.2: Mass Balance of Residuals from a WTE Facility (from LAWG, 1994)

glasses, schlieren, and opaque metallic glass and crystalline minerals formed in the combustor which consist of two major groups: complex silicate and complex oxide minerals. The complex silicate minerals include melilite-like ($\text{Ca}_2\text{Al}_2\text{SiO}_7$) and akermanite-like ($\text{Ca}_2(\text{Mg},\text{Fe}^{2+})\text{Si}_2\text{O}_7$) minerals. The complex oxides include iron oxides (Fe_3O_4) and lime (CaO). The texture and mineralogy of the isotropic and schlieren glasses and silicate minerals is similar to alkaline volcanic rock materials subjected to fractional crystallization at a melt temperature of about 2,200°F (1,200°C). Trapped gas vesicles, which are sometimes expelled from the melt as it cools, give the slag particles a high degree of porosity; making the grate ash a light weight aggregate.

As shown in Table 1.1, grate ash and bottom ash are widely used as a granular fill or road base material in the Netherlands, Denmark, Switzerland, and the western portion of Germany. To a lesser extent, bottom ash is utilized in Japan after it is vitrified and converted into a fine-grain frit (Sakai and Hiraoka, 1994). The frit is used in various applications; largely as a fine aggregate in road construction applications.

In many of the European jurisdictions, grate ash is used after the material has been processed and aged. Aging reactions are conducted by maintaining a moist residue usually after trommeling or sieving to remove oversized material. The presence of moisture allows for a variety of aging reactions to occur (IAWG, 1994). These include (i) $\text{CO}_2(\text{g})$ uptake into the alkaline residue coupled with metal carbonate formation which neutralizes the ash to pH values around 8 and minimizes metal leaching, (ii) elemental metal oxidation and water reduction resulting in $\text{H}_2(\text{g})$ evolution, (iii) metal

Table 1.1: Grate Ash/Bottom Ash Utilization in Europe and Japan

Country	MSW Generated (10 ⁶ tonnes/yr) ^a	MSW Combusted (10 ⁶ tonnes/yr)	Ash Produced (10 ⁶ tonnes/yr)	Percent Used	Application	Reference
Netherlands	8.57	3.00	0.75	60	Subbase, embankments	Van der Sloot, 1991
Denmark ^b	5.74	1.80	0.43	72	Subbase, embankments, land reclamation	Hjelmar, 1991
France		8.40	2.52	64	Road base	
Western Germany	22.30	7.36	3.00	50	Subbase, embankments	Vehlow, 1991
Switzerland	3.70	2.30	0.60	>50 ^c	Subbase, embankments	Stämpfli, 1991
Sweden	2.50	1.25	0.40	75	Subbase, embankments	Hartlen, 1990
Japan	42.96	30.86	-	5	Civil construction ^d	Sakai and Hiraoka, 1994

^a Some caution should be used in interpreting these numbers as definitions of MSW vary between countries

^b The data for Denmark include the use of oversize ferrous in the listed percentage, the other countries do not specify if ferrous recycling is included in the percentage.

^c Reflects anticipated usage, not presently used.

^d Ash used after vitrification.

oxide hydrolysis reactions, (iv) slag weathering to clays, (v) simple salt dissolution and solid phase respeciation and (vi) organic carbon biodegradation. In some jurisdictions, grate siftings are removed from the bottom ash primarily to minimize the potential for $H_2(g)$ generation resulting from the oxidation of elemental metals found in the siftings.

A number of recent studies have examined the environmental impact of MSW bottom ash use as road subbase or structural fill material. These include test roads in Sweden (Hartlén and Fallman, 1991), structural fill embankments in the Netherlands (DHV Milieu en Infrastructuur BV, 1992a,b,c), large scale road bases constructed in lysimeters in the Netherlands (Mulder and Gerritsen, 1990; Mulder, 1991), and historical evaluation of a ten year old road subbase constructed with bottom ash in the Netherlands (van der Sloot and Hoede, 1994a,b). The Swedish study (Hartlén and Fallman, 1990) involved using bottom ash as a granular base course material. The study has shown that after perforation of the asphaltic wearing course to allow infiltration, leachates collected from rain water contacted with the bottom ash were similar to bottom ash leachates from column leaching studies at low liquid to solid (L/S) ratios. The leachates contained dissolved salts (Na, Cl, SO_4^{2-} , K) and some low concentrations of metals (Ca, Cu, Mg, Mn, Pb, Zn). Similar data were seen by Mulder and coworkers in Dutch lysimeter studies where bottom ash was placed below standard pavement materials and road run-off was allowed to infiltrate the ash base courses (Mulder and Gerritsen, 1990; Mulder, 1991). The Highway 15 study in the Netherlands and the lysimeter study in the Netherlands (DHV Milieu en Infrastructuur BV, 1992a,b,c) have shown that bottom ash use as granular fill in bridge approaches also produces typical

bottom ash leachates. The historical analysis of the use of compacted bottom ash as a base course for the service road in Rotterdam, the Netherlands (van der Sloot and Hoede, 1994a,b) has shown that accumulation of metals in the underlying soils over a ten year period takes place in the first few centimeters of soil below the pile, demonstrating significant attenuation when ashes directly overlie soils and leachates migrate downwards into the soil.

The use of bottom or grate ash as an aggregate substitute in bituminous asphaltic materials has been more prevalent in North America. Electrostatic precipitator (ESP) ash is used as a mineral filler in asphaltic materials in the Netherlands (IAWG, 1994) and some fundamental leaching studies on the behavior of metals from ESP ash in asphalt monoliths have been conducted (de Groot et al., 1990). As shown in Table 1.2, a number of demonstrations on the use of bottom ash in pavement material were conducted in the 1970's and early 1980's. Generally, these studies utilized residues from facilities that are not now considered as state-of-the-art. They focused on the use of bottom ash as an aggregate substitute in asphaltic mixtures; particularly on the physical properties of the materials and not on the environmental performance of the materials. These earlier studies, do, however, differ from European directions in that the ash was used in an encapsulated form. Such encapsulated materials are considered more likely for utilization scenarios in the U.S. The use of ash as granular material in landfill cover within the footprint of lined landfills or as a subbase below paved roads is also being considered in the U.S.

Table 1.2: Earlier Bottom Ash Use Studies in Bituminous Applications in the United States

Project	Date	Residue %	Asphalt %	Lime %	Length m	Thickness cm	Performance	(Reference)
Houston, TX	1974	100 ^a	9.0	2.0	60	15 BC ^c	Excellent	(e,f,g)
Philadelphia, PA	1975	50 ^a	7.4	2.5	30	WC ^d	Acceptable	(h)
Delaware Co., PA	1975	50 ^a	7.0	2.5	20	3.8 WC	Acceptable	(h)
Harrisburg, PA	1975	50 ^a	7.0	2.5	80	3.8 WC	Poor	(h)
Washington, DC	1977	70 ^a	9.0	2.0	130	11.3 BC	Good	(i)
Lynn, MA	1979	50 ^a	6.5	2.0	1500	3.8 WC	Excellent	(j)
Harrisburg, PA	1976	100 ^a	6.7	0.0	60	3.8 WC	Excellent	(k)
Tampa, FL	1987	15 ^b	7.0	-	400	2.5 WC	Excellent	(l)

^a Largely bottom ash; possibly some economizer ashes.

^b Bottom ash and fly ash.

^c BC = base course.

^d WC = wearing course.

^e Haynes and Ledbetter, 1976.

^f Teague and Ledbetter, 1978.

^g Ederly and Ledbetter, 1981.

^h Collins et al., 1977.

ⁱ Pavlovich et al., 1979.

^j Bastanza, 1982.

^k Snyder, 1980.

^l Mehan and Hooper, 1991.

Several studies have looked at using fused (Snyder, 1980) or treated (Mehan and Hooper, 1991) bottom ashes as aggregate substitutes. Work by Chesner et al. (1988) has shown that bottom ash from the Southwest Brooklyn, New York combustor can be used as an aggregate substitute. They found a 30% bottom ash substitution to physically perform as well as controls in batch Marshall testing for pavement design. Recent evaluations of bottom ash use by Chesner (1991) and by the Long Island Regional Planning Board (1994) have examined economic, regulatory, and environmental issues associated with the use of bottom ash. It appears that institutional issues may be the largest impediment to bottom ash use in the United States despite the fact that its use is technically feasible.

OVERVIEW OF APPROACH TO EVALUATE ENVIRONMENTAL PERFORMANCE

The life cycle stages for bottom ash utilization have different potential environmental impacts. Different control measures are needed in each stage. As shown in Table 1.3, the life cycle of grate ash or bottom ash utilization in a road involves at least seven stages including processing, aging, production, paving, utilization, extensive reuse, and disposal. Each are described here with respect to the stage and the control measure. The processing of grate ash or bottom ash to produce an aggregate with specific grain size distribution could involve magnetic separation/sieving/tromelling operations at the WTE facility or scrubber residue/bottom ash rejects landfill facility. Standard dust control procedures using water would allow for maintenance of optimum

Table 1.3: Life-Cycle Health and Environmental Issues

Life-Cycle Stage	Potential Human Health or Environmental Contamination Issue	Comment
<ul style="list-style-type: none"> ● Processing 	<ul style="list-style-type: none"> ● Fugitive Dust 	<ul style="list-style-type: none"> ● Dust Control Measures Should Control
<ul style="list-style-type: none"> ● Aging/Storage with Leachate Control 	<ul style="list-style-type: none"> ● Ground Water Contamination 	<ul style="list-style-type: none"> ● Proper Storage Practices are Available and Should Control
<ul style="list-style-type: none"> ● Asphalt Batching 	<ul style="list-style-type: none"> ● Emission of More Volatile Elements or Fugitive Dust 	<ul style="list-style-type: none"> ● Proper Asphalt Batching Plant Operation Should Control. Most Batch Plants Utilize Bag Houses for Particulate Control, Filter Bags Should Collect Particulates and Condensates
<ul style="list-style-type: none"> ● Paving 	<ul style="list-style-type: none"> ● None 	<ul style="list-style-type: none"> ● None
<ul style="list-style-type: none"> ● Aging/Cracking/Wearing During 20 Year Life History 	<ul style="list-style-type: none"> ● Fugitive Particles (Wearing Course Only) ● Ground Water Contamination 	<ul style="list-style-type: none"> ● Mass Loading to Road Soils and Environs is Low ● Duration-Dependent, Site-Specific, Job Mix-Specific, and Ash-Specific, Release Should Not be Problematic
<ul style="list-style-type: none"> ● Recycling for Reuse in RAP Base Course (Perpetual) 	<ul style="list-style-type: none"> ● Fugitive Particles ● Ground Water Contamination 	<ul style="list-style-type: none"> ● Method Dependent, and Controllable ● Duration-Dependent, Site-Specific, Job Mix-Specific, and Ash-Specific, Release Should Not be Problematic
<ul style="list-style-type: none"> ● Disposal 	<ul style="list-style-type: none"> ● Ground Water Contamination 	<ul style="list-style-type: none"> ● If Disposal is Needed, Then Proper Disposal Practices are Available and Should Control

moisture levels to control dusting. Aging is frequently employed to geochemically stabilize the ash before use. The aging and storage of processed grate ash or bottom ash prior to its use in pavement manufacturing could be managed at temporary locations at the landfill facility where leachate collection and treatment systems are in place. The manufacture of pavement materials at an asphalt plant would involve the traditional air pollution control of volatile elements or particulate metals emissions. The use in pavement wearing course in its 20 year service life or subsequently in RAP base course during recycling for reuse is the most lengthy, potentially uncontrolled aspect of the life cycle. Although continued reuse of the pavement as a RAP material is preferred, the eventual disposal of the RAP could take place in standard construction/demolition landfills.

Factors Affecting Leaching

An understanding of factors that affect element leachability is important in the context of bottom ash utilization. The L/S ratio (the mass of liquid to the mass of dry bottom ash, unitless) that the residue is exposed to over time, the permeability of the residue (in granular or monolith form), and a variety of equilibrium-driven reactions occurring at the pore water/solid phase interface influence leaching. Such reactions include precipitation, dissolution, ion exchange, and specific adsorption. Solution pH, redox (Eh), ionic strength, and ligand concentration influence these reactions. Temperature, reaction kinetics, and mass transfer resistances affect reaction velocities. The factors influencing leaching are depicted schematically in Figure 1.3. The schematic,

Solution Phase Reactions

- Proton + Conjugate Base = Protonated Conjugate Base
- Metal + Hydroxide = Metal Hydrolysis Specie
- Metal + Salt = Ion Pair
- Metal + Organic Acid = Metal Ligand

Precipitation Reactions

- Metal + Salt = Metal Salt Precipitate

Sorption Reactions

- Metal + Oxyhydroxide Surface Site = Sorbed Metal
- Metal + Carbon Surface Site = Sorbed Metal

Figure 1.3: Schematic of Factors Influencing Leaching Behavior

developed by Kirkner et al. (1987), denotes a multiphase/multisolute system where the surface of the solid phase is the source of and potentially controls the concentrations of leachable constituents in the interstitial pore water. A low L/S ratio and interstitial fluid velocity are assumed. Kinetic constraints may rate-limit fast species interactions.

In major element composition, both grate and bottom ash are nearly identical to basaltic material (Stämpfli et al., 1990). However, the composition of minor and trace elements is enriched relative to basalt. If the ash can be managed so that the mass flux of the elements of concern in the bottom ash can be controlled to make them behave as natural materials over the timeframe for utilization, then there would be no incremental impact to human health or the environment associated with the utilization scenario.

For any element of potential concern in the ash, only a certain mass fraction is environmentally available for leaching over a geologic time-scale. The mineralogical speciation and major element composition control this phenomenon; metals that are weakly adsorbed, coprecipitated in soluble phases, and/or present as soluble phases are generally available. Depending on the element, leachable fractions comprise less than 0.001% to 95% of total element fraction in the waste (Eighmy et al., 1989). Metals in very insoluble phases or present in aluminosilicate phases are considered to be unavailable for leaching (Eighmy et al., 1990; deGroot and van der Sloot, 1991). Figure 1.4 schematically depicts this relationship for a divalent metal cation such as copper. It shows that 75% of the metal is unavailable for leaching because it is associated with insoluble phases (glasses, aluminosilicates, spinels, waste minerals). The remaining 25%

Figure 1.4: Schematic of Total Availability

is available for leaching because it is speciated as or associated with soluble phases (oxides, hydroxides, carbonates, sulfates, chlorides, sorbed).

Particle size also plays an important role in controlling leaching (Stegemann and Schneider, 1991). Small particles of high surface area to volume leach more of their available fraction (when pH is controlled) than larger particles or particles made into monoliths through the use of solidification/stabilization processes (e.g. asphalt cement, Portland cement). The use of bitumen as an asphalt cement is particularly effective because the hydrophobic, cementing nature of the binder makes a monolith out of granular material and "blinds" the particle surfaces so that leaching mechanisms are attenuated. deGroot and van der Sloot (1992), deGroot et al. (1990), and Gress et al. (1991, 1992) have shown how asphalt controls fluxes of elements out of bottom ash and blinds the particle surface. The manufacturing of hot mix asphalt also allows for the polymer to be absorbed inside the pores and vesicles in the slag particles. Provided that the nature of the bonding between the bitumen and ash is resilient, asphalt can make an excellent encapsulant.

Near the end of the road's life cycle, grate ash or bottom ash and asphalt could be subjected to a wide range of leaching scenarios. These can range from intermittent to continuous exposure to leachant. The monolith may shrink and crack, and the voids will decrease due to traffic-induced densification, but the monolith will still be the dominant mechanism controlling fluxes of constituents out of the material. For certain unlikely scenarios, the road may physically fail and produce a loose granular material containing

ash, aggregate, and asphalt cement. These scenarios are highly unlikely from a pavement management perspective.

The Role of Solubility, Percolation and Diffusion

It is important to understand the nature of the physical interaction between a leaching solution and a waste material. The leachant can flow through a loose granular material or around a tight monolith containing the waste material. It can also flow around a tightly compacted granular material. This distinction is important because of how constituents are mobilized from the waste material. In flow-through scenarios, the movement of the leachant through the waste means that advection is the dominant mass transfer mechanism. In flow-around scenarios, the constituents in the waste must diffuse from regions of high concentration in the waste form to regions of lower concentration outside the form before the leachant can effectively carry the constituents away. The rate of release is many orders of magnitude lower when diffusion, rather than advection, is the dominant process. The use of waste materials in monoliths is one way of controlling the leaching rate or flux from a waste. These principles are depicted in Figure 1.5. Because of the prevalence of monolithic applications in this project, more emphasis is placed on the discussion of monolith leaching or compacted granular leaching. This is the basis for much of the subsequent modeling of fluxes from the pavement for various utilization scenarios and timeframes.

As depicted in Figure 1.5, diffusional leaching behavior can predominate when monolithic or compacted granular material are present. Percolation and solubility

Figure 1.5: Schematic of Diffusional Control or Percolation/Solubility Control

control of leaching can occur when loose granular material are present. Solubility control occurs when the solution in contact with a waste is at chemical equilibrium with respect to the mineral phases in the waste for the constituent of interest. This condition is prevalent at low L/S ratios when percolation dominates (Kosson et al., 1995). Highly soluble constituents (e.g., sodium, chloride, etc.) are considered to be released up to their availability. Sparingly soluble constituents are considered to be released at the concentration determined to correspond to the anticipated field pH and the pH-dependent equilibrium dissolution of mineral phases. The anticipated L/S is determined by:

$$L/S = \frac{(\text{inf})(0.001)(t_{\text{yr}})}{\rho H_{\text{fill}}} \quad (1)$$

where inf is the annual infiltration (m^3/m^2 year), t_{yr} is time (years), ρ is the fill density (kg/m^3) and H_{fill} is the height or depth of fill (m). The estimated cumulative release is

$$M_{\Sigma} = (L/S)(S_x) \quad (2)$$

where S_x is the concentration of constituent X at field pH (mg/L) and is determined by solubility or availability, as appropriate. Diffusion control occurs when the permeability of the granular material is low ($<10^{-6}\text{cm}/\text{s}$) or when the waste is present in monolithic form.

Figures 1.6 and 1.7 depict the fundamental processes involved in diffusional leaching from monolithic or compacted granular specimens, respectively. The figures

Figure 1.6: Schematic of Monolithic Diffusional Leaching Behavior

Figure 1.7: Schematic of Granular Diffusion Leaching Behavior

depict the diffusive release of constituents via pathways of varying tortuosity, long term dissolution of solid phase material at the monolith surface, and initial wash-off of soluble material from the monolith surface. These phenomena exhibit different cumulative release behaviors (see Figure 1.8), as evidenced by plot slopes, on log-log cumulative release versus time plots.

Diffusion occurs by the random movement of individual molecules or ions. It is driven by the difference in chemical potential between the solid and the leachant. In a slightly porous solid, the ion flux of a soluble contaminant in the pore water system is defined by Fick's Second Law, which relates the concentration of a diffusing substance to both space and time:

$$\frac{dC}{dt} = L \frac{d^2C}{dx^2} \quad (3)$$

where C is the concentration of the diffusing ion, and L is the leach constant, with units of a diffusion coefficient (m^2/s). In the case of one dimensional diffusion, the leach constant, L , is obtained by applying the following relationship:

$$L = \frac{f^2 \cdot D_o}{R \cdot \tau} \quad (4)$$

where f is the available leachable fraction of the element in the material, D_o is the diffusive mobility of the element in water (m^2/s), R is the chemical retention factor of the element (unitless), and τ is the physical retardation or tortuosity factor (unitless).

Figure 1.8: Cumulative Release Plots for Monolith or Compacted Granular Leaching

When the leachable amount of the element equals the total amount of the element present in the material (i.e., $f=1$), the leach constant L equals the effective diffusion coefficient, which is modified for retention and tortuosity.

If Equation 4 is transformed to logarithmic values and using the relationship $pD_o = -\log D_o$, then the new relationship is as follows:

$$pL = pD_o + 2pf - pR - p\tau \quad (5)$$

Since the available fraction of the element may be obtained from analytical data and remains as a constant, Equation 5 may be simplified to:

$$pD_e = pD_o - pR - p\tau \quad (6)$$

where D_e is the effective diffusion coefficient (m^2/s) of a constituent in a waste form contacted by water. This equation allows for the determination of the relative contributions of D_o , R , and τ to the magnitude of D_e .

The mobility of an element within the monolithic pore space may be compared to its free mobility in water by determining the physical and chemical retardation factors of the product and the element, respectively. To calculate the physical retardation factor it is necessary to choose an ion which does not chemically interact with the matrix (i.e., $R=1$). In most studies, sodium is chosen and the physical retardation is calculated with the formula:

$$\tau = D_{Na}/D_{e,Na} \quad (7)$$

where D_{Na} is the diffusion coefficient of sodium in water ($pD_{Na} = 8.88 \text{ m}^2/\text{sec}$ at 25°C) and $D_{e,Na}$ is the effective diffusion coefficient of sodium in the monolith (m^2/s). The chemical retardation factor for the element is determined using the following formula:

$$R = D_x / (D_{e,x} \tau) \quad (8)$$

where D_x is the diffusion coefficient for the element in water (m^2/s) and $D_{e,x}$ is the effective diffusion coefficient for the element in the monolith (m^2/s).

In monolith leach testing, the material is considered homogeneous and is immersed in a leachant which is renewed at regular intervals. The concentration of the element is uniformly distributed and the surface is maintained at a constant concentration. The solution to Equation 3 under such conditions is presented by Crank (1975):

$$\frac{C - C_1}{C_o - C_1} = \text{erf} \frac{x}{2\sqrt{(D \cdot t)}} \quad (9)$$

where C is the element's concentration in the monolithic material as a function of place and time, C_1 is the constant concentration at the surface of the monolith, C_o is the initial concentration of the element in the material, D is the diffusion coefficient and erf is the standard error function. Since the leachant is regularly renewed during the leaching experiment, the surface concentration, C_1 , is assumed to be zero (Crank, 1975), and the solution to Equation 9 under this assumption is:

$$D_e = \frac{\pi B_t^2}{4t(U_{\max}d)^2} \quad (10)$$

where B_t is the cumulative release of the element at time t (mg/m²), $U_{\max}$ is the maximum leachable quantity of the element from the monolith (mg/kg) and d is the bulk density of the monolithic material (kg/m³).

By plotting the cumulative release of an element leaching from the monolith as a function of time, it can be determined whether matrix diffusion or other leaching mechanisms, such as dissolution or surface wash-off, are occurring. The solubility of certain elements in the solid material can be significantly high, such that longer term dissolution of the element at the surface proceeds faster than diffusion through the pores of the solid matrix.

To determine which leaching mechanism is controlling release of the element from the monolith, Equation 10 is rearranged to yield the following:

$$B_t = U_{\max} d \sqrt{(4D_e/\pi)} \sqrt{t} \quad (11)$$

After log transformation, Equation 11 becomes:

$$\log(B_t) = 1/2 \log(t) + \log[U_{\max} d \sqrt{(4D_e/\pi)}] \quad (12)$$

From the monolith leach test results, the release of the element per time interval may be calculated using the formula:

$$B_i = \frac{c_i V_i}{1000 A} \quad (13)$$

where B_i is the release of the element per unit area in period i (mg/m^2), c_i is the concentration of the element in the i th period ($\mu\text{g}/\text{L}$), V_i is the volume of the leachant (L), and A is the surface area of the monolithic material (m^2).

The cumulative release of the element for all N periods ($N=8$) is calculated from:

$$B_{t,i} = B_i \frac{\sqrt{t}}{\sqrt{t_i} - \sqrt{t_{i-1}}} \text{ for } i = 1 \text{ to } N \quad (14)$$

where $B_{t,i}$ is the cumulative release of the element for all periods (mg/m^2), t_i is the contact time after period i (seconds), and t_{i-1} is the contact time after $i-1$ periods (seconds). Eight leaching periods are usually used (0.25, 1, 2, 4, 8, 16, 32, and 64 days). This conforms to a time series relationship (renewal time of the n th period is equal to the square of the period sequence number times the renewal time of the first period) that is based on both leaching behavior and on data distribution in $\log(B_{t,i}) - \log(t_i)$ plots.

If the logarithm of the cumulative release, $B_{t,i}$, is plotted versus the logarithm of time, t_i , for the eight periods, the slope of the resulting graph indicates the mechanism controlling the release of the element. Since the slope may change over different time intervals, the slope is examined over the following ranges:

- i) Total Range $i = 1$ to 8
- ii) Initial Range $i = 1$ to 3
- iii) Middle Range $i = 3$ to 6
- iv) Final Range $i = 5$ to 8

The relevance of the change in slope at the different intervals is summarized below.

Range	Slope		
	< 0.35	$0.35 - 0.65$	> 0.65
Initial	Surface Washoff	Diffusion	Lag Time/Dissolution
Middle	Depletion	Diffusion	Dissolution
Final	Depletion	Diffusion	Dissolution

The effective diffusion coefficient for the element is then calculated from each period for the release per period (B_i) using the data points where the slope is 0.50 ± 0.15 by:

$$D_{e,i,x} = \frac{\pi B_i^2}{4(U_{\max}d)^2 \cdot (\sqrt{t_i} - \sqrt{t_{i-1}})^2} \quad (15)$$

where $D_{e,i,x}$ is the effective diffusion coefficient of element x calculated from the release in the i th period (m^2/s), and the other terms are as previously described.

The cumulative release of a diffusing constituent from a solid matrix, e.g. a monolithic solid or a compacted granular material, can also be described by (Kosson et al., 1996; Crank, 1975):

$$M_t = 2\rho C_o \left(\frac{D_e t}{\pi} \right)^{0.5} \quad (16)$$

where M_t is the cumulative release per geometric surface area of product (mg/m^2), ρ is density (kg/m^3), C_o is availability (mg/kg), D_e is effective diffusivity (m^2/sec), and t is time (sec). Equation 16 assumes that the concentration of the diffusing constituent remains dilute at the surface boundary and that the concentration of the diffusing constituent at some distance from the surface boundary within the material does not change, e.g., depletion does not occur. Depletion occurs when the cumulative release of a very soluble component approaches the maximum leachable quantity, as determined by the availability leach test. The initial concentration of the diffusing element or species is equal to the availability of that component because the availability is the concentration which serves as the chemical "driving force" for mass transfer.

For field scenarios, it may be necessary to adjust the D_e value in Equation 16 for temperature (Kosson et al., 1996). This can be accomplished using the following:

$$D_{e,T2} = \frac{D_{e,T1} T_2}{T_1} \quad (17)$$

where T values are absolute temperature in $^{\circ}\text{K}$ for the experimental temperature (T_1) and the field temperature (T_2).

For situations where wetting of the product is not continuous, the cumulative release in Equation 16 can be modified by (Kosson et al., 1996):

$$M_{t,w/d} = M_t \left(\frac{t}{t_{w/d}} \right)^{-0.5} \quad (18)$$

where $M_{t,w/d}$ is the cumulative mass released under reduced wetting (when wetting and drying may be occurring), t is the period of interest (sec), $t_{w/d}$ is the time where wetting has occurred (sec). Equation 18 can be simplified so that (Kosson et al., 1996):

$$M_{t,w/d} = M_t F_{w/d} \quad (19)$$

where $F_{w/d}$ is the time fraction wherein wetting occurred (0.10 for 10%, etc.).

It can be seen that laboratory-derived pD_e values, along with measures of availability and product density, can be used to estimate cumulative release behavior from monolithic or compacted granular materials for predictive purposes describing future leaching behavior.

THE LACONIA, N.H. BOTTOM ASH PAVING PROJECT

The Laconia, N.H. Bottom Ash Paving Project has involved over five years of effort. This effort has consisted of two major parts. The first part was an earlier two year characterization study involving the careful evaluation of the time-dependent physical and chemical properties of the bottom ash process stream as it is produced at the Concord WTE facility, the design of a suitable pavement, and the fundamental evaluation of environmental leaching behavior of the bottom ash and bottom ash/asphalt materials. The second part is this demonstration project.

Earlier Two Year Characterization Study

One of the principal objectives of the earlier research was to design a systematic and comprehensive sampling program to characterize the bottom ash process stream as it was generated at the Concord plant. This effort was a quality assurance (QA) program to confirm that the bottom ash has known properties with characterized bounds of variability. Such assurance is needed if the process stream is to replace a natural material in the views of regulators, end-users, and transportation engineers.

As shown in Table 1.4, 18 different sampling events were conducted from October, 1990 through April, 1992. The sampling dates were distributed on the days of the week as follows: Monday, 3; Tuesday, 4; Wednesday, 4; Thursday, 3; Friday, 4. Sampling was not conducted on Saturday or Sunday because of staffing requirements at the plant. The sampling data had the following monthly distribution: January, 1; March 2; April, 2; June, 1; August, 1; October, 5; November, 4; December 2. This was done to provide a balanced distribution between months, seasons, and times when incoming MSW to the plant was intermittently wet and more difficult to burn. All sampling was conducted over a four to five hour consecutive period usually beginning on the morning of the sampling day.

Figure 1.9 depicts the sampling protocol that was used for each of the sampling visits. The four hour period was separated into four consecutive hourly sampling events. For each hourly sampling event, plant personnel randomly collected 40 to 60 lbs (18 to 27 kg) of bottom ash off of the drag chain conveyor during the first 3 to 4 minutes of a ten minute period. This was repeated for the second, third, fourth, fifth, and sixth ten

Table 1.4: Sampling Events for the Earlier Two Year Characterization Study

Sampling Event Number	Date	Day of Week	Time of Sampling	Combustor Unit Sampled	Total Sample Collected lbs (kg)
1	10/3/90	Wed.	1045-1450	1	1,510 (685)
2	10/11/90	Thur.	0935-1345	1&2	1,051 (477)
3	10/19/90	Fri.	1150-1550	1	1,080 (490)
4	10/29/90	Mon.	0945-1415	2	1,058 (480)
5	11/5/90	Mon.	0920-1320	1	705 (321)
6	11/29/90	Thur.	1000-1400	2	813 (369)
7	12/7/90	Fri.	1000-1400	2	887 (403)
8	1/29/91	Tues.	0930-1330	2	1,045 (474)
9	3/26/91	Tues.	1130-1600	2	937 (425)
10	4/24/91	Wed.	0900-1300	2	939 (426)
11	6/17/91	Mon.	1045-1445	2	956 (434)
12	8/2/91	Fri.	1430-1730	2	1,280 (581)
13	10/1/01	Tues.	0930-1410	1	1,006 (456)
14	11/5/91	Tues.	0930-1340	2	1,039 (472)
15	11/20/91	Wed.	1100-1400	2	1,047 (475)
16	12/18/91	Wed.	1120-1520	2	1,050 (477)
17	3/20/91	Fri.	0840-1240	2	1,750 (794)
18	4/2/92	Thur.	0915-1305	2	810 (367)

Figure 1.9: Sampling Protocol for the Earlier Two Year Characterization Study

minute periods of the hour. A spade was used to randomly collect material off the flights as they moved past the sampling station. Objects larger than the spade were not collected.

For each of the six increments during the hour, the material was sieved as received through a 3/4" (1.9 cm) sieve over a large barrel, producing a stream passing the sieve and a stream being rejected from the sieve. At the end of the hour, 240 to 360 lbs (109 to 163 kg) were sieved, producing approximately 200 lbs (91 kg) of wet <3/4" (<1.9 cm) bottom ash which were made into an hourly composite and approximately 150 lbs (68 kg) of rejects. Scales were used to weigh both the passed and rejected material. In effect, approximately 4% of the bottom ash process stream from the combustor was collected each hour for sieving.

This process was repeated again for the second, third, and fourth hours. Table 1.4 describes the total amount of wet <3/4" (<1.9 cm) bottom ash that was collected for each of the eighteen days. For each sampling event, combustor operation was monitored. This included evaluation of combustion temperature; air preheat temperature; over and underfire airflow; economizer outlet temperature; and economizer outlet opacity, CO, and O₂.

As indicated in Figure 1.9, the four hourly composites were combined to generate a daily composite. Approximately 30 lbs of wet bottom ash (13.6 kg) was collected from the four to five sample buckets from each hourly composite, added to a concrete mixer, and blended to make a daily composite containing approximately 120 lbs (54.5 kg) of bottom ash. Large subsamples of the hourly and daily composites were collected and

dried in a large drying oven for subsequent analysis. The remaining hourly and daily composites were stored wet as archived samples that were susceptible to aging processes.

Table 1.5 describes the physical tests that were conducted on the bottom ash collected during the 18 sampling events or on the bottom ash used in the test paving work. The methods were selected to: (i) conform to testing conducted in previous studies (e.g. Chesner et al., 1988; VEABRIN, 1988), (ii) develop a data base to justify the substitution of bottom ash for natural aggregate in asphalt paving from a physical performance perspective, and (iii) help develop a data base to support the use of bottom ash as an aggregate substitute in other applications (e.g. granular fill, Portland cement concrete, stabilized bases, and granular road subbase). Table 1.5 briefly explains the purpose of each method.

Table 1.6 provides the ASTM reference method for each analysis; it also describes the frequency of analysis. The majority of the methods were conducted on each hourly composite (72 analyses) and each daily composite (18 analyses). Some of the more intensive analyses were conducted on selected daily composites. Some level of replication was employed with each method to verify precision and accuracy.

Table 1.7 summarizes the mean values for all the physical testing parameters that were conducted in the earlier study. Ranges are also provided. The data show (Eighmy et al., 1992; Tarr, 1993; Zhang et al., 1993) the time dependent physical property variability of the bottom ash over a two year period. While these variabilities are slightly larger than what is encountered with natural aggregates that are mined or produced from

**Table 1.5: Physical Testing Requirements for the Earlier
Two Year Characterization Study**

	Parameter	Purpose
1.	Mass <3/4" (1.9 cm)	- Measure of Material Suitable for Base or Binder Course
2.	Moisture Content	- Measure of Water Content for Handling, Drying
3.	Bulk Specific Gravity, Fine	- Mix Design, Weight - Volume Conversions
4.	Bulk Specific Gravity, Coarse	- Mix Design, Weight - Volume Conversions
5.	Bulk SSD ^a Specific Gravity, Fine	- Mix Design, Weight - Volume Conversions
6.	Bulk SSD Specific Gravity, Coarse	- Mix Design, Weight - Volume Conversions
7.	Apparent Specific Gravity, Fine	- Mix Design, Unit Weight
8.	Apparent Specific Gravity, Coarse	- Mix Design, Unit Weight
9.	Absorption, Fine	- Tendency to Absorb Asphalt
10.	Absorption, Coarse	- Tendency to Absorb Asphalt
11.	Loss on Ignition	- Tendency to Absorb Asphalt
12.	Ferrous Content	- Measure of Metallic Content, Corrodible Material
13.	Passing #4 Sieve	- Grain Size Distribution
14.	Passing #200 Sieve	- Grain Size Distribution
15.	Uniformity Coefficient	- Cohesive Soil Property
16.	Effective Size	- Cohesive Soil Property
17.	Los Angeles Abrasion (Grading B)	- Material Strength, Friability
18.	Los Angeles Abrasion (Grading C)	- Material Strength, Friability
19.	Soundness, Fine	- Material Durability
20.	Soundness, Coarse	- Material Durability
21.	California Bearing Ratio @ 0.1 Inch	- Material Strength
22.	California Bearing Ratio @ 0.2 Inch	- Material Strength
23.	Optimum Proctor Moisture	- Material Compactability
24.	Maximum Proctor Density	- Material Compactability
25.	Unit Weight	- Compacted Volume-Density Relationships
26.	Marshall Stability	- Asphalt Paving

^aSaturated, surface dry.

**Table 1.6: Physical Testing Methods and Frequencies for
the Earlier Two Year Characterization Study**

	Parameter	Method	Frequency ^a
1.	Mass < 3/4"	3/4" Wet Sieve	H
2.	Moisture Content	ASTM D2216	H
3.	Bulk SG, Fine	ASTM C128	H,D
4.	Bulk SG, Coarse	ASTM C128	H,D
5.	Bulk SSD ^b SG, Fine	ASTM C128	H,D
6.	Bulk SSD SG, Coarse	ASTM C127	H,D
7.	Apparent SG, Fine	ASTM C128	H,D
8.	Apparent SG, Coarse	ASTM C127	H,D
9.	Absorption, Coarse	ASTM C128	H,D
10.	Absorption, Coarse	ASTM C127	H,D
11.	Loss on Ignition	ASTM C114	H,D
12.	Ferrous Content	Hand Magnet	H,D
13.	Passing #4 Sieve	ASTM C136	H,D
14.	Passing #200 Sieve	ASTM C136	H,D
15.	Uniformity Coefficient	ASTM C136	H,D
16.	Effective Size	ASTM C136	H,D
17.	Los Angeles Abrasion Grading B	ASTM C131	S
18.	Los Angeles Abrasion Grading C	ASTM C131	S
19.	Soundness, Fine	ASTM C88	S
20.	Soundness, Coarse	ASTM C88	S
21.	California Bearing Ratio @ 0.1 inch	ASTM D1883	D
22.	California Bearing Ratio @ 0.2 inch	ASTM D1883	D
23.	Optimum Proctor Moisture	ASTM D1557	D
24.	Maximum Proctor Density	ASTM D1557	D
25.	Unit Weight	ASTM C29	D
26.	Marshall Stability	ASTM D1559	D

^aH - every hourly composite, D = every daily composite, S = selected daily composites.

^bSaturated, surface dry.

**Table 1.7: Upper and Lower Limits of Physical Properties of Bottom Ash
From the Earlier Two Year Characterization Study**

Property	Mean	Range
Mass Rejects, %	32.9	20.8 - 50.1
Mass < 3/4", %	67.01	49.8 - 79.1
Water Content, %	37.8	22.3 - 60.5
Uniform Coefficient	21.7	8.3 - 34.0
Effective Size	0.29	0.11 - 0.52
BSG ^a , Fine	1.86	1.55 - 2.22
BSG, Coarse	2.19	1.92 - 2.43
BSG SSD ^b , Fine	2.13	1.893 - 2.40
BSG SSD, Coarse	2.32	2.11 - 2.58
Apparent SG ^c , Fine	2.56	2.20 - 2.98
Apparent SG, Coarse	2.51	2.31 - 2.76
Absorption, Fine	14.7	6.81 - 24.7
Absorption, Coarse	5.69	1.79 - 12.2
Loss on Ignition, %	6.36	3.16 - 9.99
Iron Content, %	25.8	11.8 - 39.6

^aBulk specific gravity

^bSaturated, surface dry

^cSpecific gravity

crushing operations, their general characteristics are quite good as a lightweight aggregate substitute (Eighmy et al., 1994). Gress et al. (1995a,b) provide more details.

Pavement mix designs involving the Marshall Test Procedure and the Gyratory Test Method (GTM) were used to evaluate suitable mix designs. As shown in the companion volumes to this report (Gress et al., 1995a,b), the GTM provided for an excellent mix design when compared to the Marshall method. At a 50% substitution of bottom ash for natural aggregate, a mix with excellent strength and resistance to flow was produced. The GTM was used in the actual design of the binder course for the paving demonstration because it more closely approximates the compactive effort of large rollers.

Table 1.8 describes the environmental tests that were conducted on the bottom ash produced during the 18 sampling events or on the bottom ash used for conducting comprehensive environmental leaching studies. As with the physical testing, the environmental testing was conducted to: (i) conform to data from other studies (e.g. de Groot et al., 1990), (ii) develop a data base to justify the substitution of bottom ash for natural aggregate in asphalt paving from an environmental perspective, and (iii) develop a comprehensive leaching study on the leaching of metals and anions from bottom ash and bottom ash/asphalt materials. Table 1.8 briefly describes the purpose of each analysis.

Table 1.9 provides the appropriate reference for each of the tested environmental parameters. It also discusses the frequency with which these parameters were applied to

**Table 1.8: Environmental Testing Requirements for the Earlier
Two Year Characterization Study**

Parameter		Purpose
1.	% Ground to < 300 μ m	- Sample Grinding Effectiveness
2.	Acid Neutralizing Capacity	- Bottom Ash Buffer Capacity
3.	Total Elemental Composition	- Elemental Composition
4.	Total Available Composition	- Elemental Composition Available for Leaching
5.	pH-Dependent Leaching	- Influence of pH on Leaching
6.	TCLP Extraction	- Regulatory Leaching Test
7.	Method 3050 Digestion	- Standard Digestion Method
8.	Batch Leach Test (Hot Mix)	- Granular Leaching After Size-Reduction
9.	Field Lysimeter (Bottom Ash)	- Field Leaching
10.	Field Lysimeter (Ash/ Aggregate/Asphalt Pavement)	- Field Leaching
11.	Monolith Leaching Test	- Laboratory Monolith Leaching

Table 1.9: Environmental Testing Methods and Frequencies for the Earlier Two Year Characterization Study

Parameter	Method	Frequency ^a
1. % Ground < 300 μm	UNH Method	SH,D
2. ANC	Environment Canada, 1990	SH,D
3. Total Composition	NAA	SH,D
4. Total Available Composition	Dutch NEN 7341	SH,D
5. pH-Dependent Leaching	UNH Method	SD
6. TCLP	EPA	SD
7. 3050	EPA 3050	SD
8. Batch (Hot Mix)	UNH Method	SD
9. Field Lysimeter (Bottom Ash)	UNH Method	SD
10. Field Lysimeter (Pavement)	UNH Method	SD
11. Monolith Leach Test	Dutch NEN 7345	SD

^aD = daily composite, SH = selected hourly composite, SD = selected daily composite.

bottom ash samples. The majority of the parameters were applied to all of the ash samples that were collected.

Table 1.10 summarizes the mean values for all the elemental total concentrations in the ash samples that were collected during the earlier characterization study. The values that are shown, and their ranges, can be compared to values for typical soils. As can be seen, all of the major constituents in the bottom ash (Si, Fe, Al, Ca, etc.) are similar in composition to soil minerals. Trace elements like Cr, Cu, Zn, Pb, Cd and Hg are enriched.

As an example of the type of comprehensive environmental leaching data generated in the earlier two year characterization study, information for chloride is presented in Figures 1.10 and 1.11. As shown in Figure 1.10a, chloride exhibited very little pH-dependent solubility. The causes for this behavior are related to the speciation of chloride in the bottom ash; typically NaCl and KCl are the predominant phases for chloride. The solubilities of NaCl and KCl are so great and these solid phases dissociate so readily that they are not influenced significantly by solution pH.

Figure 1.10b shows the regranularized hot mix material data for chloride. Concentrations in the ash/aggregate/asphalt mixes were usually between 500 and 1000 mg/kg. The patterns described for chloride are very similar to those found for other elements; % asphalt cement (AC) appeared to have a greater influence on solution phase chloride concentrations than % bottom ash. Typically, the bottom ash/aggregate/asphalt mixtures leached 25-50% of the chloride compared to that of the 100% bottom ash control. Results from statistical analyses showed that the differences

Table 1.10: Upper and Lower Limits for Bottom Ash from the Earlier Characterization Study and Soil Elemental Composition (mg/kg)

	Bottom Ash ^a		Soils ^b	
	Range	Average	Range	Average
Al	34,400-64,800	52,530	10,000-300,000	71,000
Ca	51,200-102,900	78,275	7,000-500,000	13,700
Fe	56,400-114,950	82,940	7,000-550,000	38,000
Si	182,500-274,000	233,000	230,000-350,000	320,000
Na	20,200-48,000	37,200	750-7,500	6,300
K	7,200-11,600	9,330	400-30,000	8,300
Ba	785-1,480	978	100-3,000	430
Mg	1,900-10,700	7,555	600-6,000	5,000
Cl	1,105-4,190	2,289	20-900	100
Br	16.65-126	45.5	1-10	5
Mn	605-1,560	1,033	20-3,000	600
Ti	3,490-9,500	7,085	1,000-10,000	4,000
Sr	0.0-1,000	581	50-1,000	200
As	17.9-189	42.0	1-50	5
Sb	60-283	118.0	-	-
V	31.6-123	57.5	20-500	100
Mo	20-161	45.4	0.2-5	2
Co	21-43	29	1-40	8
Cr	867-2,005	1,419	2-100	100
Cu	1,140-6,980	2,414	2-100	30
Ni	249-855	610	5-500	40
Zn	2,198-7,640	3,500	10-300	50
Pb	1,200-6,600	2,855	2-200	10
Cd	2.62-70.6	18	0.01-0.70	0.06
Hg	0.0-2.25	0.95	0.01-0.30	0.03

^aData based on 18 daily composites collected to date.

^bData based on compilation by Lindsay (1979) for a wide variety of soils.

Figure 1.10: Fundamental Leaching Behavior of Chloride in Bottom Ash and Bottom Ash/Aggregate/Asphalt. (a) pH-Dependent Leaching for Cl from Bottom Ash, (b) Cl Leaching from Regranularized Pavement Materials Made with Various Percentages of Asphalt Cement, (c) Cumulative Release Plots for Cl from Monoliths, and (d) Determination of the Role of Physical Retardation and Chemical Retention on Diffusive Leaching Behavior of Cl

Figure 1.11: Unified Leaching Plot for Chloride

in concentrations between the bottom ash and bottom ash/aggregate/asphalt mixtures were significantly lower at the 95% confidence level when chloride concentrations from the nine bottom ash/aggregate/asphalt mixtures were pooled and compared to duplicate analyses of the 100% bottom ash control.

The Monolith Leach Test was conducted to determine the leaching mechanisms (diffusion, dissolution, or depletion) controlling elemental release from intact Marshall specimens. In those cases where it was determined that diffusion was the controlling mechanism, effective diffusion coefficients and chemical retardation factors were calculated. A plot of the log of the calculated cumulative release (B_n) for chloride versus the log of time (t_i) for $i = 1$ to 8 time periods is presented in Figure 1.10c. Since the slope for each of the monolith samples, 25B, 50B, 50C, and 75B, and the control C3 were within the 0.35-0.65 range, diffusion was the mechanism controlling chloride leaching.

The effective diffusion coefficient (pD_e) and chemical retention values were calculated for chloride. pD_e values ranged from 11.67 to 12.20 and were similar to those reported by de Groot et al. (1990). These values were compared to those calculated for sodium, which is considered to be an inert and mobile element to which elemental release is compared. Since these values were only slightly higher than those for sodium, chloride can also be considered to be a relatively mobile component. Chemical retention values (1.39 - 2.12) indicate little chemical attenuation by the asphalt matrix. de Groot et al. (1990) reported values slightly lower than those obtained in this study, suggesting even less attenuation.

Figure 1.10d shows the contributions of free mobility, tortuosity, and chemical retention to the overall mobility (m^2/s) of chloride. Tortuosity is the most dominant mechanism controlling diffusion in asphalt pavement monoliths. No definitive information regarding the overall mobility of chloride in similar asphaltic products was found in the literature.

The unified plot for chloride, which includes all of the time-dependent and leaching data except from the 3050 Digestion and the TCLP tests, is presented in Figure 1.11. [The 3050 Digestion uses HCl in the leachant, and thus Cl was not measured; Cl was omitted during TCLP analyses because it is not a tested analyte]. As shown, the lack of pH-dependency for chloride was evident by the clustering of the individual data points around the total availability asymptote. Additionally, the hot mix data indicates that asphalt was effective in decreasing Cl release even when the material was regranularized. Releases from the bottom ash/aggregate/asphalt lysimeter were approximately two orders of magnitude lower than the bottom ash control lysimeter. Finally, good continuity was seen between the bottom ash/aggregate/asphalt lysimeter and the Monolith Leach Test data in terms of the slopes of the respective plots and the relative linear continuity between the plots. This trend is encouraging and suggests that the release mechanisms in the laboratory are accurate indicators of release in larger, field leaching scenarios.

The reader may refer to Eighmy et al. (1992), Whitehead et al. (1993), Whitehead (1992), Tarr (1992), and Zhang (1993) for a more thorough evaluation of the data from the earlier two year characterization study.

Present Study

The overall goal of the present study is to document that processed grate ash can be used in paving applications as an acceptable substitute for natural aggregates from both a physical and an environmental performance standpoint. Specific demonstration goals included: (i) successful utilization of 50 percent aggregate substitution of grate ash in an asphalt binder course; (ii) development of American Association of State Highway and Transportation Officials (AASHTO) pavement design layer coefficients for the asphalt binder course; (iii) evaluation of the environmental performance of the pavement; and (iv) the development of a data set for field performance to allow for a request for a modification of the Concord WTE facility's residual management plan for bottom ash utilization in binder course and subsequently in RAP base course.

Project Chronology

An abbreviated project chronology, starting in 1990 and ending in 1995 is provided in Table 1.11. Major chronological events are shown. The chronology shows the earlier two year characterization study, the process to select a site, the public and regulatory approval process, and salient dates for the present study.

Site Plan and Pavement Construction

A plan view of the site is shown in Figure 1.12. The site consists of a control section and a test section. In May, 1993, 2,000 linear feet (610 m) of US Route 3 in the City of Laconia, New Hampshire was reconstructed using, in part, grate ash aggregate in

Table 1.11: The Chronology of the Laconia, N.H. Bottom Ash Paving Project (1990-1995)

Date	Event
April, 1990	- Discussions Amongst CRSW/RRC, WES and UNH-ERG About Ash Utilization
August, 1990	- Earlier Two Year Study Initiated
October, 1990	- First Test Patch at Franklin, N.H. Monofill
April, 1991	- Discussion with N.H. DES About Demonstration Project
June, 1991	- Letter to CRSW/RRC Members Requesting Candidate Roads
August, 1991	- Meeting in Laconia, N.H. to Visit U.S. Route 3
September, 1992	- Meeting in Laconia, N.H. with N.H. DES About Route 3
March, 1992	- Meeting with N.H. DES Regarding Site Hydrogeology, Permit Issues
April, 1992	- Letter to Route 3 Abutters
	- First Neighborhood Abutters Meeting
	- Second Letter to Route 3 Abutters
	- Second Neighborhood Abutters Meeting
	- Laconia, N.H. City Council Meeting
	- Articles in <u>Laconia Citizen</u> , <u>Manchester Union Leader</u>
May, 1992	- Interim Report (Eighmy et al., 1992) Issued
June, 1992	- Public Meeting with Laconia, N.H. City Council Public Works Subcommittee
September, 1992	- Notification Letter Sent to Abutters
	- R&D Application Sent to N.H. DES
October, 1992	- Second Test Patch at Franklin, N.H. Monofill
October, 1992	- Monitoring Wells Installed; Surface Soils Collected
November, 1992	- N.H. DES Request for Additional Information
	- Monitoring Wells Installed, Surface Soils Collected
November 20, 1992	- Sampling of Ground Waters, Surface Waters
December, 1992	- N.H. DES Air Resources Division Approval Request Submitted
	- Laconia, N.H. City Council Approval
January, 1993	- <u>Concord Monitor</u> Article

Table 1.11: The Chronology of the Laconia, N.H. Bottom Ash Paving Project
(1990-1995) (Continued)

Date	Event
	- Present Research Project Starts
January 29, 1993	- Sampling of Ground Waters, Surface Waters
February, 1993	- N.H. DES Air Resources Division Approval
February 25, 1993	- Sampling of Ground Waters, Surface Waters
March, 1993	- N.H. DES Waste Management Division Approval
	- Public Hearing on Bond Issue
April 1, 1993	- Sampling of Ground Waters, Surface Waters
April 10, 1993	- Route 3 Reconstruction Initiated
April 29, 1993	- Lysimeter Trenches Constructed, RAP, Shallow Soils, Deep Soils, MW 5 Surface Soils Collected
May 7, 1993	- Binder Courses Paved
May 15, 1993	- Wearing Courses Paved, t=0 Year Pavement Slabs Removed, Road Run-Off Systems Constructed
July 7, 1993	- Sampling of All Locations
September 24, 1993	- Sampling of All Locations
December 7, 1993	- Sampling of All Locations
April 6, 1994	- Sampling of All Locations
May 12, 1994	- Sampling of All Locations
June 28, 1994	- Sampling of All Locations
July 29, 1994	- t=1.25 Year Pavement Slabs Removed
September 8, 1994	- Sampling of All Locations
October 14, 1994	- Sampling of All Locations
December, 1994	- Present Research Project Completed
January, 1996	- Residuals Management Plan Modification Application Submitted to N.H. DES

NOTES:

- 1) ELEVATIONS TAKEN FROM PLAN TITLED, "TOPOGRAPHIC SURVEY, CITY OF LACONIA, BELKNAP CO., N.H. PAUGUS BAY AREA". CONTOUR INTERVAL 5', SCALE 1"=100' BY GORDON E. AINSWORTH & ASSOC. BY PHOTOGRAMMETRIC METHODS (FROM PHOTOGRAPHY DATED APRIL, 1957). HORIZONTAL CONTROL BY POLARIS. VERTICAL CONTROL BY U.S.C. & G.S.
- 2) UTILITIES SHOWN ARE VERY APPROXIMATE LOCATIONS SCALED FROM PLAN ENTITLED, "CITY OF LACONIA, N.H. PAUGUS INTERCEPTOR AND FORCE MAIN" BY METCALF & EDDY, BOSTON, MA. DATED AUGUST, 1985. LABELED RECORD DRAWING.
- 3) EXISTING SEWER IS 18" REINFORCED CONCRETE PIPE
- 4) EXISTING WATER MAIN NOT SHOWN ON THIS PLAN.

Approximate Scale: 1" = 200'

Figure 1.12
The Laconia, NH Bottom Ash
Paving Demonstration

- SITE PLAN -

CMA ENGINEERS, INC.
CIVIL/ENVIRONMENTAL ENGINEERS

a binder course pavement. US Route 3 in this area is a two lane secondary roadway having an average daily traffic which varies seasonally from about 5,000 to 20,000 vehicles per day.

Of the 2,000 linear feet (610 m) of reconstruction, 1,150 linear feet (350 m) was reconstructed in the control section using natural aggregate both in the 2" (5.0 cm) binder course and the 1" (2.5 cm) wearing course. The 850 linear foot (260 m) test section was constructed using a 50% bottom ash/50% natural aggregate blend in the 2" (5.0 cm) binder course pavement. A 1" (2.5 cm) wearing surface of 100% natural aggregate was applied over the bottom ash asphalt binder course such that, in this demonstration, the bottom ash asphalt is not exposed to traffic or the environment. The transition point from the control to the test section occurs near the intersection of White Oaks Road with Rt. 3. Figure 1.13 shows a road cross-section schematic for the transition and standard sections. The transition point was located so that, jurisdictionally, the test section remained solely within the City of Laconia.

The binder course pavement for the first 100 feet (30.5 m) on either side of the transition point between the two pavements was constructed to a 4" (10.1 cm) depth to allow for collection of road cores of sufficient thickness for physical testing purposes (Gress et al., 1995a). The installation of strain gauges; moisture, resistance and temperature probes; and traffic counters occurred in this section as well. The wearing course remained at a 1" (2.5 cm) thickness through this 200' (61 m) transition section.

The land use in the control section is commercial, including a resort/conference center, several smaller motels, a restaurant, and retail businesses. In the test section,

Figure 1.13: Pavement Construction Details. (a) Transition Section for Test and Control Sections, (b) Remaining Sections for Test and Control Sections

abutting properties were largely undeveloped. Paugus Bay, a part of the Lake Winnepesaukee system, is in close proximity to the test section.

Scope of Work

Table 1.12 briefly identifies the major aspects of the environmental testing for the present study. A scope of work for physical testing can be found in the companion volume (Gress et al., 1995a) to this report.

The scope addresses characterization of the grate ash used in the project, characterization of the soils, pavement, and RAP at the site, evaluation of ground water and surface water characteristics during the course of the project, and evaluation of the environmental behavior of the ash/asphalt materials. This involved conducting laboratory studies to predict long-term environmental behavior and evaluation of the constructed pavements.

A number of papers have been recently published regarding this present project. They include papers by Musselman et al. (1994a,b) and Eighmy et al. (1995). Readers can refer to these papers for general overviews of various aspects of the project.

Utilization Approval Process

According to the New Hampshire Solid Waste Rules, under Env-WM 318.03, Criteria for Direct Re-Use, a certificate for direct reuse can be obtained on the basis of demonstration that (i) the ash is produced by a process which is consistent and uniform, (ii) the ash is characteristically and analytically consistent, and (iii) there is a use or a

Table 1.12: Environmental Testing Scope of Work

<u>Environmental Testing</u>	
1.	Bottom Ash Pile Testing <ul style="list-style-type: none"> - Ash Elemental Composition - Ash Element Availability - Ash Aging Effects - Ash Regulatory Testing
2.	Asphalt Batch Plant Air Testing <ul style="list-style-type: none"> - Stack Testing
3.	Demonstration Site Soil Testing <ul style="list-style-type: none"> - Soil Element Composition - Soil Element Availability
4.	Ground Water/Surface Water Sampling <ul style="list-style-type: none"> - Sampling of Dug Well, MW 1, MW 2, MW 3, MW 4, MW 5, SW 2, SW 3 over a Two Year Period
5.	Road Run-Off Sampling <ul style="list-style-type: none"> - Sampling of Control, Test Section Run-Off Over a 1.5 Year Period
6.	Suction Lysimeter Sampling <ul style="list-style-type: none"> - Sampling of Control, Test Section Suction Lysimeters Over a 1.5 Year Period
7.	Pavement and RAP Characterization <ul style="list-style-type: none"> - Pavement, RAP Elemental Composition - Pavement, RAP Element Availability
8.	Laboratory Monolith Diffusion Study <ul style="list-style-type: none"> - Evaluate Effects of Voids, Microcracking, Aging
9.	Laboratory Granular Diffusion Study <ul style="list-style-type: none"> - Evaluate Effects of Particle Size, Asphalt Cement Content
10.	Pavement Monolith Leaching <ul style="list-style-type: none"> - Evaluate Monolith Leaching of Road Cores at $t = 0$ years and $t = 1.25$ years
11.	Pavement Microscale Migration <ul style="list-style-type: none"> - Evaluate Migration (via Molecular Diffusion) from Ash Metallic Particles Into the Asphalt Cement
12.	Pavement Macroscale Migration <ul style="list-style-type: none"> - Evaluate Migration (via Molecular Diffusion) of Ash Constituents Into the Wearing Course or RAP

market for the waste product where its use will not pose a risk to human health or the environment that is greater than the risk of secure disposal. The information contained in Eighmy et al. (1992) for the earlier two year study addresses criteria (i) and (ii). This report is designed to address criterion (iii). The formal approval of the direct reuse of the residue in the U.S. Route 3 reconstruction is intended to be sought under the provisions of Env-Wm 2602.06 as part of the Concord facility's residuals management plan, and not under the terms of Env-Wm 318.

CHAPTER 2

MATERIALS AND METHODS

The materials and methods chapter provides a brief overview of the procedures employed to conduct the environmental scope of work. The chapter is broken down into sections describing the hydrogeological investigations; the WTE facility; methods for stack testing at the asphalt plant during the manufacture of the demonstration pavements; procedures to characterize the ash, soils, and pavement materials at the site; procedures to conduct diffusional leaching tests; procedures to evaluate pavement element migration behavior; data quality assurance/quality control (QA/QC), and statistical methods.

SITE HYDROGEOLOGICAL INVESTIGATIONS

Site hydrogeological investigations were conducted by Exeter Environmental Associates, Inc. Appendix 1 in Volume 2 of this report contains the hydrogeological report. As shown in Figure 1.12, five ground water monitoring wells (MW) were installed; two (MW 1, MW 2) in the control section and three (MW 3, MW 4, MW 5) in the test section. A preexisting dug well with a stone and mortar casing was retrofitted with a PVC well casing to facilitate sampling. In the control section, an upgradient well (dug well) and two wells adjacent to the roadway (MW 1, MW 2) were present. In the test section, an upgradient well (MW 4) and two wells adjacent to the roadway (MW 3, MW 5) were present. Hydrologically, MW 1, MW 3 and MW 5 are all downgradient from the road centerline.

Soil borings and well installations occurred on October 29, 1992 and November 18, 1992. The wells were installed by Capital Environmental Drilling. Truck- and track-mounted drilling rigs were used. MW 1 and MW 2 were advanced using 8" (20.3 cm) O.D. by 4.25" (10.8 cm) I.D. hollow stem augers. The soil borings for the other wells were advanced using a 3" (7.6 cm) diameter steel drive and wash casing. All soil samples were collected using split spoon sampling techniques. During well borings, collected soil samples were evaluated for the presence of preexisting volatile organic compounds using a Photovac MicroTIP photoionization detector equipped with a 10.6 eV lamp. The instrument was calibrated to a mixture of 100 ppm isobutylene in air.

Each well was constructed of 2" (5.1 cm) diameter schedule 40 PVC well screen [0.010" (0.25 mm)] and 2" (5.1 cm) diameter riser pipe. Table 2.1 describes well construction details. The PVC sections were threaded together. The annuli around the well pipes were filled with sand up to the well screen height. A hydrated bentonite pellet seal was placed above the top of the sand. All wells except MW 4 were finished with permanent, locking, flush mounted road boxes that were cemented into place. MW 4 was finished with a steel protective casing [3' (0.91 m) stick up]. All wells were developed by pumping until the extracted waters were free of sediment. The top of PVC elevations for all the wells was determined by surveying.

Well water elevations were determined using electronic water level indicators. Additional surface water station sampling staff gages (SW 1, SW 2) in the brook and in Paugus Bay (SW 3) were surveyed for surface water elevations and locations for further sampling efforts (SW 2, SW 3).

Table 2.1: Well Construction Details

Monitoring Well	Top of PVC Elevation (ft/m)	Well Depth (ft/m)	Screen Length (ft/m)
MW 1	91.17/27.79	20/6.10	10/3.05
MW 2	92.95/18.33	20/6.10	10/3.05
MW 3	96.20/29.32	19/5.79	10/3.05
MW 4	117.13/35.70	23.5/7.16	13/3.96
MW 5	94.27/28.73	16.5/5.03	13/3.96
Dug Well	97.47/29.71	10/3.05	10/3.05
Surface Water Stations			
SW 1	84.96 ^a /25.90	-	-
SW 2	83.37 ^a /25.41	-	-
SW 3	82.88 ^a /25.26	-	-

^aTop of marker stake.

Hydraulic conductivity testing was conducted at each of the 5 well locations using the rising head test method (Hvorslev, 1951). Grain size distributions of bore hole sand samples from MW 1 and MW 2 were used to confirm conductivity in the control section using the method of Hazen (Freeze and Cherry, 1979).

WTE FACILITY DESCRIPTION

The Wheelabrator-Concord L.P. WTE facility is a 500 ton per day (454 metric tonnes per day) mass burn facility located in the Penacook Village of the City of Concord, New Hampshire. It serves the 27 member communities of the CRSW/RRC. The plant, in operation since 1989, presently disposes its various ash residue streams as a combined ash in a secure, dedicated ash monofill in Franklin, New Hampshire.

The WTE facility consists of two combustor and air pollution control trains; each consisting of crane-fed ram loaders, von Roll reciprocating stoker grates with primary underfire and secondary overfire combustion control, Babcock and Wilcox superheaters, boilers, and economizer heat-exchangers, dry lime scrubbers, and pulse-cleaned Wheelabrator Air Pollution Control fabric filter modules in bag houses. Each combustion unit has a quench tank and drag chain conveyor to quench the bottom ash stream (containing grate ash, grate siftings, and economizer ash).

The plant produces approximately 170 tons per day (154 metric tonnes per day) of wet bottom ash and oversize ferrous, non-ferrous, and uncombusted material. During grate ash collection for this project and the earlier two year characterization study, the economizer double door was always kept closed to prevent economizer ash from entering

the grate ash process stream. For this demonstration, the grate siftings hopper doors were also kept closed so that only grate ash was collected. Prior to collection, the quench tank was cleaned so that only representative grate ash from the Unit #1 combustor was collected.

ASPHALT BATCH PLANT STACK TESTING

ROJAC Environmental Services, Inc. was retained by Pike Industries, Inc. of Tilton, New Hampshire to conduct the stack air emission testing program. The Pike 700 asphalt drum mixer plant is located in Pembroke, New Hampshire. Testing occurred on May 7, 1993. The air emission testing report is contained in Appendix 2 of Volume 2 of this report.

Stack testing was conducted while the facility was processing both natural aggregate (control asphalt) and ash/natural aggregate (test asphalt) mixtures. The two asphalt materials produced at the plant during the emissions testing program were: (i) control binder course asphalt, and (ii) test binder course asphalt that contained 50% (by weight) processed grate ash substituted for natural aggregate. This was accomplished using four separate sampling runs during asphalt production: runs 1 and 2 when the control asphalt was produced and runs 3 and 4 when the test asphalt was produced.

Emissions measured at the facility consisted of total particulate matter (TPM), multiple metals (including As, Be, Cd, Cr, Cu, Pb, Hg, Ni, Se, and Zn), hydrochloric acid (HCl), and opacity. Outlet emissions were tested in accordance with the methods and procedures approved by the U.S. EPA and N.H. DES Air Resources Division. The

particulate emissions and opacity measurements for each run were compared to the standards applicable to asphalt batch plants. Pike Industries, Inc., was responsible for operating the asphalt batch plant and associated pollution control devices, and ROJAC conducted all emission measurements.

The Pike 700 plant is an H&B asphalt batch plant which was constructed in 1970. The facility is a 4 ton (3.63 metric tonne) batch plant. The burner is a Genco AF-40 with a maximum firing rate of 70.0 million BTU per hour using #4 fuel. The plant's rated capacity is 320 tons per hour (TPH), but the average typical capacity is 240 TPH.

The asphalt plant is equipped with an H&B baghouse Model No. 756 for dust control. The baghouse system collects particulate matter released from the mixer along with fugitive particulate matter from the weigh hopper and associated conveyors. The baghouse contains 756 Nomex fabric filters. Fabric filter cleaning is performed by pulsed air jets.

The baghouse exhaust stack sampling location is located in a 35" by 35" (89 x 89 cm) square section of the steel stack. Five horizontal sampling ports in a horizontal plane provide access to the particulate laden gas stream. The ports are 144 inches (0.36 m or 4.1 duct diameters) downstream of an induced draft fan and 36 inches (0.91 m or 1.0 duct diameters) upstream from the top of the stack. EPA Method 1 requires the use of twenty-five sampling points. Five traverse sampling points were located through each of the five ports to meet this requirement.

Particulate matter and multiple metals sampling were accomplished by using the EPA Modified Method 5/Multimetals (proposed Method 29) sampling train. The train

consisted of a glass nozzle, glass lined probe, six impingers, vacuum pump, dry gas meter, and an orifice flowmeter. Complete sampling train calibrations were performed before and after the compliance test. Quadruple tests were performed for this program. Sampling duration for each test run varied, due to asphalt dump truck availability, and ranged from 40 to 75 minutes during plant operation.

A glass nozzle was attached to a stainless steel glass lined probe which was heated to prevent condensation. Pallflex quartz filter paper supported in a 4 inch (10.2 cm) glass filter holder was used as the collection media. The filter assembly was enclosed in a heated box to maintain temperatures at $248^{\circ}\text{F} \pm 25^{\circ}\text{F}$ (120°C). An ice bath containing six impingers was attached to the back end of the filter. The first impinger was empty, the second and third impingers contained 100 ml of a mixture of 5% nitric acid (HNO_3) and 10% hydrogen peroxide (H_2O_2) solution, the fourth and fifth impingers contained 50 ml of a mixture of 4% KMnO_4 /10% H_2SO_4 solution, and the sixth impinger contained silica gel to remove any remaining moisture. A piece of flexible tubing, vacuum gauge, needle valve, leakless vacuum pump, bypass valve, dry gas meter, calibrated orifice and inclined manometer comprised the sampling train.

The stack velocity pressure was measured using a pitot tube and inclined manometer. The stack temperature was monitored by a thermocouple that was attached to the pitot and connected to a potentiometer. A check valve was not used in the ROJAC sampling train.

Multiple metal sample analyses were performed. Samples were prepared by microwave digestion, as required by the method. The elements Be, Cd, Cr, Cu, Ni, Zn,

As, Se, and Pb were determined by direct aspiration atomic absorption spectrophotometry (AAS). Mercury analysis was performed by cold vapor atomic absorption spectrophotometry (CVAA).

The composition of the gas stream at the sampling location was analyzed for oxygen and carbon dioxide during each test run. To make an accurate assessment of the flue gas composition, redundant Orsat analyses were conducted. During each particulate matter test run at least one multipoint integrated sample of flue gas was taken for Orsat analyses.

Visible emissions measurements were performed in accordance with U.S. EPA Method 9 procedures by a certified observer. Opacity observations were recorded at 15 second intervals on field data sheets. A minimum of 24 observations were recorded per test run.

Hydrochloric Acid (HCl) sampling was accomplished by using U.S. EPA Method 26 procedures. The sampling train consisted of a heated glass probe, three-way glass valve, four midjet impingers, vacuum pump, and dry gas meter. The first two impingers contained 15 ml of 0.1N H_2SO_4 absorbing solution, the third impinger contained 15 ml 0.1N NaOH (scrubbing solution), and the fourth contained silica gel to remove any remaining moisture. The sample was collected at a rate of two liters per minute. Before and after each HCl test run the sampling train was leak checked.

GRATE ASH COLLECTION AND AGING

During the period of November to December 1992, approximately 400 wet tons (363 metric tonnes) of grate ash were collected and delivered to the Franklin landfill. The residues were trommeled through a 3/4" (1.9 cm) trommel to remove oversize material as the ash was delivered to the storage area at the landfill. The trommeled material was then piled and aged for about 6 months prior to its delivery to the Pike Asphalt Plant in Pembroke, New Hampshire.

After the first few loads of grate ash were delivered and trommeled, seven grab samples of fresh grate ash were randomly removed from the pile using a spade and a 3 dimensional grid coordinate and randomizing process. After two months, the large pile was sampled to collect fourteen samples for TCLP testing. At the end of the six month aging process, the large pile was again sampled using a backhoe and spade to collect fourteen aged grab samples. Table 2.2 describes the tests applied to the grate ash.

MONITORING WELL SURFACE SOIL COLLECTION

Roadside surface soils were collected for characterization. Table 2.2 describes the tests that were used to characterize these surface soils. The samples were collected on October 20, 1992. A spade was used to collect the soils in locations adjacent to MW 1, MW 2, MW 3 and MW 5. These locations are shown in Figure 1.12. The samples were stored in Whirl-Pak® bags prior to and after drying at 140°F (60°C) for 48 hours. Samples were stored under desiccation in a vacuum prior to processing and analysis.

Table 2.2: Solid Sample Characterization Methods
and Number of Analyses

Sample	Total Elemental Composition (NAA, XRF)	Total Available Elemental Composition (NEN 7341)	TCLP Regulatory Testing
Fresh Grate Ash	7	7	-
Aged Grate Ash	14	14	14
Roadside Surface Soils			
MW 1, MW 2	3	3	-
MW 3, MW 5	3	3	-
Control Section Soils			
Deep	1	1	-
Test Section Soils			
Deep	1	1	-
Control Section RAP Composite	1	-	-
Test Section RAP Composite	1	-	-

SUCTION LYSIMETER CONSTRUCTION

Ceramic tip suction lysimeters were installed in both the control and test sections on April 29, 1993, 8 days prior to placement of the pavement. Three lysimeters were installed in each road section. The locations of the lysimeters are shown in Figure 1.12. Figures 2.1 and 2.2 depict construction details for the control and test sections, respectively.

A backhoe was used to excavate a 3' (0.91 m) wide by 5' (1.52 m) deep by 25' (7.62 m) long trench running from the center of the road to the road margin. The ceramic lysimeters were embedded in hydrated washed silica sand to allow wicking to occur. PVC pipes and risers were used to protect the polyethylene vacuum/pressure lines and sample return lines running from the lysimeters. An electric vacuum/compressor was developed to maintain high vacuums in the lysimeters during sample collection.

During construction of the lysimeter system in the control section, an old macadam roadway was encountered approximately 4' (1.22 m) below grade. Because of requirements to prevent moisture freezing in the ceramic lysimeter tip, which can cause cracking and failure, the lysimeters had to be installed at 5' (1.52 m) below grade to maintain them below the frost penetration depth. This resulted in their placement, after excavation of the macadam, below the plane of the macadam layer.

During construction of the lysimeter system in the test section, bedrock and fractured bedrock were encountered at the 5' depth (1.52 m) below grade. Some fractured material was excavated. The lysimeter was installed in saturated silica in a

Figure 2.1: Schematic of Suction Lysimeter Construction in Control Section

Figure 2.2: Schematic Depiction of Suction Lysimeter Construction in Test Section

region close to a fracture location. While it was desired to avoid sampling ground water, the presence of an impenetrable bedrock stratum and the requirement for location below the frost penetration depth resulted in its placement where ground water could be sampled during periods of high ground water tables.

DEEP SOIL AND RAP SAMPLE COLLECTION

At the time of suction lysimeter construction, recycled asphalt pavement (RAP) materials and deep soils (4'-5' [1.22-1.52 m]) were collected from the lysimeter trenches during trench construction. Table 2.2 describes the tests that were used to characterize these materials. A spade was used to collect the samples. The locations are depicted in Figure 1.12. The samples were stored in Zip-Lock bags prior to and after drying at 140°F (60°C) for 48 hours. Samples were stored under desiccation in a vacuum prior to processing and analysis.

SURFACE RUN-OFF COLLECTION SYSTEM CONSTRUCTION

Roadside asphalt swales and storm drains were constructed in both the control and test sections to facilitate the collection of road run-off from precipitation events. Figure 2.3 schematically depicts plan views and cross-sections for both sections. Standard storm drains were used. Wearing course asphalt was used to pave the road side swales to allow run-off to flow to the storm drain. PVC buckets were suspended under the storm drain grates to collect run-off. During scheduled sampling visits, a peristaltic pump was used to collect the run-off that had collected since the previous visit.

Figure 2.3: Schematic Plan View and Cross Section of Roadside Run-Off Collection Systems

GROUND WATER, SURFACE WATER, SUCTION LYSIMETER, AND ROAD RUN-OFF SAMPLING AND ANALYSIS

An extensive program was undertaken to sample the monitoring wells (MW 1, MW 2, MW 3, MW 4, MW 5, dug well), the two surface water stations (SW 2, SW 3), the suction lysimeters (control, test), and the road run-off collection systems (control, test) prior to and after the paving event. The sampling events that took place prior to paving were meant to establish baseline levels and identify preexisting contaminants. Table 2.3 lists the sampling dates that were used. Samples collected on the sampling dates prior to pavement placement (11/20/92, 4/23/93) were analyzed for all analytes stipulated in the project scope of work. Samples collected on the remaining three sampling dates (1/29/93, 2/25/93, 4/1/93) were analyzed only for chloride. These latter sampling events were not stipulated in the R&D permit, however, they were conducted to better describe road salting impacts prior to pavement reconstruction.

After pavement placement, eight sampling events occurred between July, 1993 and October, 1994 (see Table 2.3). All analytes were tested except volatile organic compounds via EPA Method 624 and base neutral and acid extractable organic compounds via EPA Method 625. These had been analyzed for prior to paving; the levels of these compounds in the samples was negligible so these methods were dropped in accordance with the scope of work.

Table 2.4 describes the selected analytes as stipulated in the scope of work, the method used for these analytes, the number of samples analyzed by sample type, and the required detection limit. The analyses were conducted by PACE Inc. (formerly Resource

Table 2.3: Sampling Dates for Sampling Monitoring Wells, Surface Water Stations, Suction Lysimeters, and Road Run-Off

Prepaving Sampling Dates (Prior to May 7, 1993 Paving)	
November 20, 1992	All Locations, All Analytes
January 29, 1993	All Locations, Chloride Only
February 25, 1993	All Locations, Chloride Only
April 1, 1993	All Locations, Chloride Only
April 23, 1993	All Locations, All Analytes
Postpaving Sampling Dates (After May 7, 1993 Paving)	
July 7, 1993	All Locations, All Analytes ^a
September 24, 1993	All Locations, All Analytes ^a
December 7, 1993	All Locations, All Analytes ^a
April 6, 1994	All Locations, All Analytes ^a
May 12, 1994	All Locations, All Analytes ^a
June 28, 1994	All Locations, All Analytes ^a
September 8, 1994	All Locations, All Analytes ^a
October 14, 1994	All Locations, All Analytes ^a

^a All analytes except VOCs and BN/As.

Table 2.4: Required Analytes, Methods, Sample Number and Detection Limits for Aqueous Samples

Analyte (Analytical Method)*	Sample Type and Number				
	Monitoring Wells	Surface Water Stations	Suction Lysimeters	Road Run-Off	Detection Limits (ppm)
	MW1, MW2, MW3, MW4, MW5, Dug	SW2, SW3	Control, Test	Control, Test	
Total Phenols (420.1, 510A)	10	10	10	10	0.01
NH ₄ ⁺ (350.2)	10	10	10	10	0.05
NO ₃ ⁻ (353.2)	10	10	10	10	0.05
NO ₂ ⁻ (353.2)	10	10	10	10	0.05
PO ₄ ³⁻ (365.3)	10	10	10	10	0.02
SO ₄ ²⁻ (300.0)	10	10	10	10	10
Cl ⁻ (325.1)	13	13	13	13	1
Br ⁻ (300.0)	10	10	10	10	1
Al (6010)	10	10	10	10	0.1
As (7060)	10	10	10	10	0.01
Ba (6010)	10	10	10	10	0.1
B (6010)	10	10	10	10	0.5
Cd (6010)	10	10	10	10	0.005
Ca (6010)	10	10	10	10	0.1
Cr (6010)	10	10	10	10	0.01
Cu (6010)	10	10	10	10	0.02
Fe (6010)	10	10	10	10	0.03
Pb (7421)	10	10	10	10	0.005
Mg (6010)	10	10	10	10	0.1
Mn (6010)	10	10	10	10	0.005
Hg (7470)	10	10	10	10	0.0003
Mo (6010)	10	10	10	10	0.1
K (6010)	10	10	10	10	3
Se (7740)	10	10	10	10	0.01
Si (6010)	10	10	10	10	0.2
Na (6010)	10	10	10	10	1.0
Sr (6010)	10	10	10	10	0.1
Zn (6010)	10	10	10	10	0.02
VOCs (624)	2	2	2	2	std
BN/As (625)	2	2	2	2	std

* EPA (U.S. EPA, 1979) or Standard Methods (APHA, 1989).

Analysts, Inc.) of Hampton, N.H. or Eastern Analytical Inc. of Concord, N.H. The laboratories are both EPA contract laboratories.

During monitoring well sampling, standard procedures for sample collection were employed including the use of electronic water level indicators, temperature and pH probes, dedicated stainless steel bailers, and well purging techniques (3 well volumes). Certain wells, particularly in the test section, contained high concentrations of iron precipitate. The wells were allowed to settle after purging and before collection of samples. Samples were not filtered after collection. Table 2.5 describes sample bottle requirements and preservation techniques.

During surface water sampling, samples were collected at the station stakes in the prescribed bottles. Sample preservatives were added after sample collection.

During suction lysimeter sampling, long vacuum times were required to allow for sample collection (1-2 hours). After vacuum operation, the vacuum/pressure lines were pressurized and the samples were pushed out of the sample line into a 1000 ml glass sample bottle to make a composite sample. Samples were difficult to obtain from the control section. Samples were sometimes difficult to obtain in the test section during dry periods. During spring run-off conditions, the test suction lysimeters were frequently submerged below the seasonally high ground water table. Table 2.5 describes the sample bottle requirements and preservation techniques. Despite the limited sample volume that was frequently obtained, efforts were made to analyze for anions and metals.

During surface run-off sampling, a peristaltic pump was used to collect samples from the PVC buckets. The buckets were maintained in place throughout the project.

Table 2.5: Sample Bottle Types and Preservation Techniques

Sample Type	Bottle Type	Preferred Volume	Actual Volume	Preservative
Metals	HDPE	200 ml	250 ml	HNO ₃
Anions	HDPE	100 ml	125 ml	None
Ammonia/COD	Glass	200 ml	250 ml	H ₂ SO ₄
Total Phenols	Glass	500 ml	500 ml	H ₂ SO ₄
VOCs	Glass	2x40 ml	2x40 ml	HCl
BN/As	Glass	1000 ml	1000 ml	None
TOC	Glass	100 ml	125 ml	H ₂ SO ₄

During rain events, the buckets would fill and overflow. They were not emptied between sampling visits. Consequently, sample quality reflects a weighted composite of the rain events that occurred between sampling dates. Samples were pumped into a 1000 ml glass sample bottle to make a composite sample. Table 2.5 describes the sample bottle requirements and preservation techniques.

PAVEMENT SLAB AND ROAD CORE COLLECTION

To facilitate physical testing of pavements and the evaluation of monolithic leaching behavior of road specimens, pavement slabs were removed from the road on May 15, 1993 and July 27, 1994. Figures 2.4-2.6 schematically depict the approximate location of these slabs. Slabs were removed from the 4" (10.2 cm) thick binder course section in the region near the transition from the control to test sections. A pavement saw was used in both instances to cut the pavement. This saw requires the use of water to lubricate the saw blade. Slabs collected at $t=0$ years were stored at the Laconia Department of Public Works for six months prior to delivery to UNH. Slabs collected at $t=1.25$ years were immediately transported to UNH. A cylindrical coring press (Model 4054 Milwaukee Electric Tool Corp., Brookfield, Wisconsin) was used to cut 4" (10.2 cm) cores from the pavements. This device also requires the use of water to lubricate the coring bit. Extracted cores were rinsed, dried, and stored prior to analysis.

Figure 2.4: Schematic Showing Location of Pavement Slabs Removed on May 15, 1993 (t=0 years) from the Control Section

Figure 2.5: Schematic Showing Location of Pavement Slabs Removed on May 15, 1993 (t=0 years) from the Test Section

Figure 2.6: Schematic Showing Location of Test and Control Pavement Slabs Removed on July 27, 1994 ($t=1.25$ years)

ELEMENT TOTAL COMPOSITION

Grate ash, various soils, pavement road core materials, and various RAP materials were subjected to total elemental analysis. All samples were ground to less than $300\text{ }\mu\text{m}$ (0.012") using a Weber Brothers & White (Hamilton, MI) rotary hammermill, then stored under mild vacuum desiccation until analysis.

Total elemental composition analyses of the $<300\text{ }\mu\text{m}$ (0.012") material for each of the samples were performed by the Department of Nuclear Engineering at the University of Illinois at Urbana-Champaign (Urbana, Illinois). Concentrations of Al, As, Ba, Br, Ca, Cd, Cl, Co, Cr, Cu, Fe, Hg, K, Mg, Mn, Mo, Ni, Na, Sb, Si, Ti, V, Zn and other trace elements found in the grate ash were determined using thermal and epithermal neutron activation analysis (NAA). Each sample was analyzed in triplicate using a 1.5 MW TRIGA reactor.

Al, Ca, Cl, Mn, Na, and Ti were analyzed using short-lived NAA and a 10 second irradiation at a neutron flux of $4 \times 10^{12}\text{ n cm}^{-2}\text{sec}^{-1}$ (500 KW) followed by a 10 minute decay and a 10 minute counting time. Si and In were determined using short-lived epithermal NAA with a flux of $2.1 \times 10^{11}\text{ n cm}^{-2}\text{ sec}^{-1}$ at 500 KW for neutrons between 0.5 eV and 0.5 MeV and a flux of $4.5 \times 10^{11}\text{ n cm}^{-2}\text{ sec}^{-1}$ at 500 KW for neutrons greater than 1.8 MeV. An irradiation time of 30 seconds was used, followed by a decay time of eight minutes and a counting time of 15 minutes. Medium-lived epithermal NAA and Compton suppression methods were used for Cd, Au, and Mo, which irradiates for one hour at 1.5 MW, followed by a decay time of 6-8 days. A counting time of three hours was also used. Sb, As, Br, La, and Sm were determined using thermal NAA, with an

irradiation time of one hour at a flux of $3.3 \times 10^{12} \text{ n cm}^{-2} \text{ sec}^{-1}$ at 1.5 MW and a decay time of 5-10 days. One hour was used for a counting time. An additional 3-4 week decay was used for Ce, Cs, Cr, Co, Fe, Hg, Ru, Se, Sc, Ag, Ta, Th, and Zn. In addition, an ORTEC high purity germanium detector was used to measure the γ -ray spectra of the samples and standards. Lead and copper were analyzed by x-ray fluorescence (XRF). XRF was conducted on a Phillips PW-1450 automatic sequence spectrometer, also at the University of Illinois. Table 2.6 provides information on typical detection limits for the methods.

ELEMENT TOTAL AVAILABLE COMPOSITION

Grate ash, surface soils, pavement road core materials, and select RAP materials were analyzed for total available compositional analyses. The procedure, based on the Dutch Total Availability Leaching test NEN 7341 (van der Sloot et al., 1991), was used to quantify the element mass fraction potentially available for leaching. Two sequential extractions were used; the first was conducted at a pH of 7.0 for 3 hours at a liquid to solid (L/S) ratio of 100:1 (L/kg) to extract anions. 5.0 g of unfractionated residue was added to 500 mls of Nanopure water and stirred in an open beaker. 1.0 N Ultrex II Ultrapure HNO_3 was used to control pH throughout the leaching period. At the end of the three hours, the leachant was filtered (0.45 μm polycarbonate filter) and combined with the remaining residue and filter to undergo a second extraction at an L/S of 100:1 (L/kg) at pH 4.0 for four hours to extract metal cations. 1.0 N Ultrex II Ultrapure

Table 2.6: NAA and XRF^a Element Detection Limits

Element	Detection Limit mg/kg	Method	Element	Detection Limit mg/kg	Method
Ag	0.80	NAA	Mn	11.00	NAA
Al	1000	NAA	Mo	2.70	NAA
As	0.50	NAA	Na	190	NAA
Au	0.005	NAA	Nd	2.60	NAA
Ba	350.00	NAA	Ni	27.00	NAA
Br	20.00	NAA	Pb	5.00	XRF
Ca	1500	NAA	Rb	5.30	NAA
Cd	3.50	NAA	Sb	0.11	NAA
Ce	0.95	NAA	Sc	0.02	NAA
Cl	180.00	NAA	Se	0.80	NAA
Co	0.18	NAA	Si	15000	NAA
Cr	2.00	NAA	Sm	0.03	NAA
Cs	0.20	NAA	Sr	500	NAA
Cu	5.00	XRF	Ta	0.095	NAA
Dy	1.20	NAA	Tb	0.115	NAA
Eu	0.065	NAA	Th	0.13	NAA
Fe	170	NAA	Ti	950	NAA
Hf	0.165	NAA	U	0.45	NAA
Hg	0.44	NAA	V	7.00	NAA
In	65.00	NAA	W	0.90	NAA
I	7.50	NAA	Yb	0.28	NAA
K	5000	NAA	Zn	6.95	NAA
La	0.72	NAA	Zr	95.00	NAA

^aPb and Cu by XRF, all others by NAA.

HNO₃ was used to control pH throughout the leaching period. After filtration, the pH 7.0 and pH 4.0 leachants were combined for analysis. pH was measured using gel combination electrodes and two point standardization. Table 2.7 describes the analytes, the analytical methods, the number of samples analyzed, and the detection limits for element total available leach testing.

REGULATORY TESTING

Fourteen selected grate ash samples from the ash storage pile were evaluated for their leaching behavior using the Toxicity Characteristics Leaching Procedure (TCLP). Testing was conducted by Eastern Analytical Inc. The procedure involved two stages. First, a 5 g portion of the sample was mixed with deionized water. After 5 minutes, 1.0 N HCl was added and the mixture was heated to 50°C for 10 minutes. Depending on the final pH upon cooling, one of two extraction fluids, a buffered or non-buffered acetic acid solution, was used in the second stage which involved mixing 100 g of the sample with 2000 ml of extraction fluid. Table 2.7 describes the analytes, the methods, the number of samples analyzed, and the analytical detection limits.

MONOLITH LEACHING TESTS

The monolith leaching test procedure is based on the Dutch Tank Leaching test NEN 7345 (van der Sloot et al., 1991). Each monolithic specimen was placed in nylon netting and suspended in a 3 L Rubbermaid polypropylene container. The container was filled with approximately 2 L (5 times the calculated volume of the specimen) of Milli-Q

Table 2.7: Required Analytes, Methods, Sample Number and Detection Limits for Leachate Samples

Analyte (Analytical Method) ^a	TCLP ^b	Element Total Availability						Monolith Diffusion		Granular Diffusion	Detection Limit, ppm
		Fresh Ash	Aged Ash	Surface Soils	Laboratory Monoliths	Road Core Monolith	Granular Diffusion	Laboratory	Road Core		
NH ₄ ⁺ (350.2)	-	7	14	12	1	4	2	14 (112) ^c	16 (128) ^c	6 (48) ^c	0.01
NO ₃ ⁻ (353.2)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.05
NO ₂ ⁻ (353.2)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.05
PO ₄ ³⁻ (365.3)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.05
SO ₄ ²⁻ (300.0)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.02
Cl ⁻ (325.1)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	10
Br ⁻ (300.0)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	1
Ag (6010)	14	-	-	-	-	-	-	-	-	-	0.02
Al (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	1
As (7060)	14	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.1
Ba (6010)	14	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.01
B (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.1
Cd (6010)	14	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.5
Ca (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.005
Cr (6010)	14	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.01
Cu (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.01
Fe (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.02
Pb (7421)	14	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.03
Mg (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.005
Mn (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.0003
Hg (7470)	14	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.1

Table 2.1: Required Analytes, Methods, Sample Number and Detection Limits for Leachate Samples (Continued)

Analyte (Analytical Method) ^a	TCLP ^b	Element Total Availability						Monolith Diffusion		Granular Diffusion	Detection Limit, ppm
	Aged Ash	Fresh Ash	Aged Ash	Surface Soils	Laboratory Monoliths	Road Core Monolith	Granular Diffusion	Laboratory	Road Core		
Mo (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	3
K (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.01
Se (7740)	14	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.2
Si (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	1.0
Na (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.1
Sr (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	0.02
Zn (6010)	-	7	14	12	1	4	2	14 (112)	16 (128)	6 (48)	std

^aBased on EPA (U.S. EPA, 1979) or Standard Methods (APHA, 1989).

^bTCLP was done for all TCLP analytes only.

^cThe unbracketed numbers represent total number of tests conducted; the bracketed numbers reflect the total number of analyte determinations made for each test (the diffusion tests produce 8 leachates per test).

type II water, initially prepared at a pH of 4 using 6N Ultrex II Ultrapure nitric acid. The container was then placed in a constant temperature room, set at $25 \pm 0.5^{\circ}\text{C}$. After 0.25, 1, 2, 4, 8, 16, 32 and 64 days, the specimen was removed and immersed in a new container filled with the same volume of prepared pH 4 type II water. This results in the production of eight leachates over the course of the experiment for each monolith. After each time period, the pH and conductivity of the leachant was recorded. The leachant was then filtered and samples were taken for elemental and anionic analyses. Elemental subsamples were acidified to a pH of less than 2.0 using concentrated Ultrex II Ultrapure nitric acid. All subsamples were stored at 4°C until analysis. Table 2.7 describes the analytes, methods, number of samples analyzed, and detection limits that were used.

ROAD CORE LEACHING

For the $t=0$ year slab, ten 4" (10.2 cm) cylindrical monoliths consisting of the wearing course and binder course were removed from both the control and test section slabs. The individual cores were hand manipulated to separate the binder course. The binder course samples, 4" (10.2 cm) in diameter and 4" (10.2 cm) in height, were used in the monolith leaching test.

A similar procedure was used for the $t=1.25$ year slabs. Five 4" (10.2 cm) cylindrical monoliths were removed. The excised binder course was cut into 1" (2.54 cm) thick pucks for use in the leaching test.

In all instances, the binder course monoliths consisted of cut surfaces from the coring device (the outer cylindrical surface) and asphalt saw (top surface) and bitumen covered surfaces (bottom). Table 2.7 describes the analytes, the methods, the number of samples analyzed, and the detection limits that were used.

MONOLITH CONSTRUCTION WITH VARIABLE VOIDS, BITUMEN AGING, AND MONOLITH MICROCRACKING FOR MONOLITH LEACHING

The purpose of this laboratory test was to evaluate the effects of void content, aging, and microcracking on monolith specimens generated from the paving job mix formula using the monolith leach test procedure. Figure 2.7 depicts how the laboratory specimens could be used to predict long term behavior. A partial $3^3 + 6$ factorial design experiment was conducted on 14 gyratory compacted specimens. Figure 2.8 depicts the experimental design. The material used to make the specimens came from the actual production run for the full-scale demonstration (50% grate ash, 7% asphalt content). Three degrees of voids (low, medium, high), aging (none, medium, high), and microcracking (none, medium, high) were integrated into the experimental design. Voids (5%, 7.5%, 10%) were created during the compaction of the specimens using a gyratory testing method (GTM). Aging was simulated by heat treatment in the presence of forced air (107°C [225°F] for 5 days for moderate aging, 107°C [225°F] for 10 days for severe aging). The regimen was based on methods compiled by von Quintus et al. (1991). An Instron machine was utilized to subject some of the samples to cyclical loading parallel to the direction of compaction to produce microcracking (i.e. moderate and high levels). A load of 8.8 MPa (1,158 psi) at 2 cycles per second was used.

PAVEMENT AGING SCENARIO			
	Voids	Cracking	Bitumen Aging
New (t= 0 y)
10 %	None	None
Moderately Aged (t= 10 y)
7.5 %	Moderate	Moderate
Aged (t=20 y)
5 %	High	High
Non-Monolithic (t>> design life, compacted RAP or dsiposed material)
None	None	None

Figure 2.7: Schematic Showing Variables to be Tested for Voids, Microcracking and Aging Monolith Leach Test

EXPERIMENTAL DESIGN

Figure 2.8: Schematic Showing Factorial Design Experiment for Voids, Microcracking and Aging Monolith Leach Test

Moderate microcracking was produced after $1,250 \pm 250$ cycles. High microcracking was produced after $1,750 \pm 250$ cycles. The cylinders were kept frozen during the cracking process to facilitate brittleness and straining.

GRANULAR LEACHING TESTS

The granular leaching tests were conducted to evaluate granular diffusional leaching behavior in crushed pavement materials. These tests were developed as part of an EPA-sponsored ash solidification/stabilization project (Kosson et al., 1993). Scenarios depicting crushed pavement, crushed grate ash without asphalt cement, and very finely divided grate ash ($< 300 \mu\text{m}$) were used. The granular leaching test was conducted in a manner identical to the monolith leach test except the granular specimens were compacted in HDPE beakers to densities of 96.8 to 104.6 lbs/ft³ (1,550-1,675 kg/m³) and then suspended in the leachant. These densities represent typical values for materials that would be compacted to manufacture a RAP base course or represent compacted disposed pavement or pavement grindings. A liquid to volume ratio of 20 was used. The available area from which a diffusive flux could occur was the open (but submerged) surface of the beakers. A layer of glass beads (1" or 2.54 cm thick) was placed over the material in the beakers to render the surface less susceptible to agitation. Table 2.7 describes the analytes, methods, sample number, and detection limits for this test.

GRANULAR MATERIAL CONSTRUCTION WITH VARIABLE GRAIN SIZE AND BITUMEN CONTENT FOR GRANULAR LEACHING

Spare monoliths constructed for the laboratory monolith tests were used to produce size-reduced monolithic material for the granular diffusion leaching tests. A proctor hammer was used to produce material less than 3/4" (1.9 cm) in diameter with adhering bituminous material. Composite grate ash from the batch run on May 7, 1993 was used to produce 3/4" (1.9 cm) material without asphalt. These specimens were run in duplicate. Composite grate ash was also used to produce <300 μm (0.012") material. These samples were also run in duplicate.

PAVEMENT MICROSCALE MIGRATION

Figure 2.9 depicts the approach used to examine if microscale migration of elements such as Al, Zn, and Cu was occurring from grate ash particles containing these elements into the surrounding bituminous polymer matrix. The hypothetical gradient that is shown is relatively shallow, suggesting diffusion from the particle into the polymer. Selected road cores from the test section slab taken at $t=1.25$ years were cut with a pavement saw into thin cylinders. Subsamples were then cut that contained defined ash particles (e.g. Al, Cu, Si). A diamond blade circular wet saw was used (MK Diamond Products model 101, Hawthorne, California). These subsamples were cut to conform to approximate 0.5" x 0.5" x 1.0" (0.15 mm x 0.15 mm x 0.3 mm) dimensions. Samples were dried and stored under vacuum until analysis. Samples were then mounted onto sample holders and carbon coated for analysis using scanning electron microscopy/X-ray

Figure 2.9: Schematic of SEM/XRM Analysis of the Interface Between Grate Ash Particles and the Bituminous Polymeric Matrix

microanalysis (SEM/XRM). X-ray dot maps, secondary, and back-scattered electron images were taken to facilitate the location of the ash particles of interest.

A Link AN-10,000 energy dispersive XRM workstation was used in conjunction with a Pentafet atmosphere-thin window detector (lithium-drifted silicon crystal) and an AMR 1000 SEM. Elemental concentrations (weight %) were determined using an accelerating voltage of 20 keV and acquisition time of 240 live seconds. The weight % calculations were normalized because of variable beam current associated with the SEM. Spectra were corrected for drift using the Cu $K\alpha$ peak obtained from Cu tape attached to each sample. The quantification package provided by the manufacturer was completely modified to create profiles for 25 elements. A variety of primary standards were used. Back scattered electron, secondary electron and x-ray spatial images were routinely generated. These images helped determine element associations and locate hot spots or particles containing high elemental concentrations. During quantification work or dot-mapping, a spot size of 3 was used for controlling beam diameter. At this spot size, the beam width is 800 angstroms. The interaction volume producing characteristic x-rays has a diameter and depth of about 1.0 μm . For elastic back-scattered electrons, the interaction volume has a diameter of 0.6 μm and a depth of about 0.3 μm . For secondary electrons, the interaction volume has a diameter of 1,000 angstroms and a depth of 10 nm. Radial distances were calculated using micron bars generated by the LINK workstation. These bars were calibrated using a standard reference 10 μm grid (SPI Supplies, West Chester, PA). SEM/XRM has detection limits around 1,000 to 5,000 mg/kg.

PAVEMENT MACROSCALE MIGRATION

Macroscale migration of elements in ash particles into the surrounding bituminous polymeric matrix was evaluated using pavement materials extracted from the road slabs at $t=1.25$ years. Road cores from the test and control section taken at $t=1.25$ years were separated into their binder and wearing course components by simple manipulation. RAP material situated under the slabs was also sampled. Ten cores and 10 RAP samples were collected from the test section as well as the control section. Four of the ten were used for macroscale migration experiments. The wearing, binder, and RAP materials were ground to pass $300\text{ }\mu\text{m}$ and analyzed for total element composition using NAA and XRF.

OUTDOOR LYSIMETERS

The field lysimeter sampling program is a continuation of the earlier two year study of this project (Eighmy et al., 1992). A bottom ash lysimeter and bottom ash/aggregate/asphalt lysimeter have been in place since November, 1990. The outdoor lysimeters were exposed to the atmosphere and designed to collect rainwater infiltration that percolated down through the residues and generated a leachate. Sampling has been conducted over four years from November, 1990 through November, 1994.

For the bottom ash lysimeter, approximately 6,606 kg (14,555 lbs) of bottom ash was collected at the Concord plant and transported to the Franklin Landfill on October 11, 1990. The ash was stored for one week while exposed to the atmosphere and then trommeled. About 4,591 kg (10,112 lbs) of the $<1.9\text{ cm}$ ash (dry weight) was placed in a

double-lined lysimeter and transported to the UNH Field Lysimeter facility. For the bottom ash/aggregate/asphalt lysimeter, a hot mix containing 9% asphalt, and a blend of 75% natural aggregate and 25% bottom ash was batched and transported to the Franklin Landfill. The hot mix was placed in a 5 cm (2") lift on a prepared sand base, compacted, allowed to age for one week, and subsequently excavated using a backhoe. About 7,239 kg (15,960 lbs) of broken pavement chunks containing 2,015 kg (4,443 lbs) of <1.9 cm bottom ash (dry weight) were placed in the second double-lined lysimeter and transported to the UNH Field Lysimeter facility.

Both lysimeters are identical in design. Each container is a steel, roll-off dumpster, manufactured by MM Solid Waste Equipment, Inc. (Lee, NH), and equipped with a leachate collection system installed by Resicon Containment, Inc. (Sunapee, NH).

The liner system consists of primary and secondary flexible membrane liners of 0.203 cm high density polyethylene. Six layers of geofabric were placed beneath the secondary liner to cushion it from the floor of the roll-off. A layer of geonet/geofabric was placed in between the two membrane liners and above the primary liner. A 15.2 cm sand drainage layer was placed on top of the primary liner geonet/geofabric system.

The primary leachate collection system consisted of two schedule 80 PVC pipe risers, placed below the sand layer, in between the geonet/geofabric and the primary liner. The secondary leachate collection system consisted of two schedule 80 PVC pipe risers placed on the opposite end of the roll-off, in between the primary and secondary liners. Flexible tubing was placed inside each riser.

The lysimeters were sampled over a 7 month period (May-November) for each year. The leachate from each lysimeter was pumped by attaching the flexible tubing to a Masterflex 6-600 rpm variable speed peristaltic pump (Cole-Palmer Instrument Co., Chicago, IL) for the first two years, and to a standard high speed centrifugal pump the last two years. Leachate was collected by pumping leachate from the drainage layer in the lysimeter into four designated 227 L containers, which were connected together with garden hose. Once the leachate was completely mixed about 4 L were sampled from each container and combined to form a composite sample. For each leachate collection, the total volume of leachate was recorded so as to obtain a cumulative liquid to solid (L/S) ratio for the sampling period.

Two extra liters were collected for the measurement of pH, conductivity and alkalinity at UNH. This analysis had to occur within 48 hours of the sampling period. Duplicate analyses were performed for both leachate types for all three parameters. The alkalinity was determined with the potentiometric titration method. A Beckman® Altex Φ^m 71 pH meter with Beckman Futura Plus gel-fitted combination electrode and a Beckman thermo-compensator was used with both of these tests. The conductivity measurements were made using a Myron® LDS Meter (Model EP).

Standard protocol, including the use of chain-of-custody procedures, was followed in the collection, preserving, and delivering of the samples to Pace or to UNH.

LEAD ISOTOPE ANALYSES

Lead isotope analyses of selected solid samples and aqueous samples were conducted by Dr. Henri Gaudette of Biogeochemical Systems Center in the Institute for the Study of Earth, Oceans and Space at UNH.

Solid samples included four replicate aged grate ash samples from the storage pile at the Franklin Landfill, a shallow and deep roadside soil from both the test and control sections (collected prior to paving), binder material from the control and the test section (removed after 1.25 years of service), and RAP material from the control and test section (removed after 1.25 years of service). These solid samples were ground to pass 300 μm prior to analysis.

Aqueous samples were collected on the last sampling day of 1994 (October 14, 1994) along with standard ground water, surface water, and road run-off. This included samples from MW 1, MW 2, MW 3, MW 4, MW 5, SW 2, and SW 2. MW 2 was run in duplicate for quality control purposes. An HNO_3 blank was also run as a control.

An aliquot of the dry solid samples (e.g., ash, soil, road materials), normally about 3 grams, was carefully weighed into a clean plastic bottle and mixed with 10 ml of ultraclean 3 N nitric acid for 24 hours at room temperature. After 24 hours, the sample was filtered in a class 100 filtered air enclosure, and the filtrate was retained for analysis.

An aliquot of the filtrate was then weighed and spiked with a pure ^{207}Pb spike. After equilibration, the total Pb (sample + spike) was separated by an anion column procedure in a class 100 filtered air enclosure and the column elutriate dried down for mass spectrometric analysis for Pb concentration.

A second aliquot of the filtrate from the solid sample was weighed, dried down, taken up in 1.1 N HBr where the Pb was separated by a similar anion column procedure. This was then analyzed by mass spectrometry for its Pb isotopic composition.

The solutions which were received for analysis (e.g., monitoring wells, surface waters) were treated in a similar fashion. An aliquot of the solution as received was weighed, spiked with ^{207}Pb , and the Pb was separated by column procedures. This sample was then analyzed by mass spectrometry for Pb concentration.

A second weighed aliquot of the solution sample was dried down, taken up in 1.1 N HBr acid, and the Pb was separated by the exchange column. This sample was analyzed for its Pb isotopic composition.

Mass spectrometric analysis was performed using a 23 cm, 60° sector thermal ionization mass spectrometer at the Biogeochemical System Laboratories at UNH. The sample was loaded on rhenium filaments, and the intensities of the ion beam for masses 204, 206, 207, 208, and background were measured repetitively for a minimum of 200 ratios. From the background corrected intensities, the ratios of $^{204}\text{Pb}/^{206}\text{Pb}$, $^{207}\text{Pb}/^{206}\text{Pb}$, and $^{208}\text{Pb}/^{206}\text{Pb}$ were calculated. From these ratios, other Pb isotropic ratios are determined.

Fractionation during mass spectrometric analysis of Pb is 0.012% per atomic mass unit as determined from the analysis of NIST 981 lead standard reference material. Errors of the mass spectrometric analysis of Pb in this laboratory are less than 1%.

QUALITY ASSURANCE/QUALITY CONTROL

A comprehensive quality assurance/quality control (QA/QC) program was utilized for this project. These procedures pertain to all of the work conducted under the direction of UNH; the hydrogeological investigation and asphalt batch plant testing was conducted by outside contractors who adhered to their own prescribed levels of QA/QC (see Appendices 1 and 2 in Volume 2 of this report).

A summary of the QA/QC program is provided in Table 2.8. The table identifies the various QA/QC measures that were applied and methods for which these measures are applicable. At the instrumentation level, instrument calibration and continuing calibration verification procedures were used for all instrumentation that was applied in this project. These measures were implemented by staff at PACE Inc., Eastern Analytical Inc., the University of Illinois, and UNH personnel. At the sample analysis level, basic provisions to analyze sample trains consisting of calibration standards, blanks, samples, sample duplicates, and matrix spikes were used. The complexity of the sample train depends on the analytical method. The use of these measures allows for continuing calibration verification and assessment of precision, accuracy, and background contamination. These measures were also implemented by staff at all four institutions. At the sampling program level, UNH personnel submitted National Institute of Standards and Technology (NIST) certified standards and replicate samples as checks on the external laboratories. These measures provided for an additional level of verification of QA/QC for method precision and accuracy. In all cases, data were evaluated for quality. Where necessary, samples were reanalyzed.

Table 2.8: QA/QC Program General Description

QA/QC Measure	Method ^a :	GC/MS	IC	ICAP-AES	CVAA	NAA	XRF	SEM/XRM	TMS	IR	Colorimetric ^b	Potentiometric ^c
Instrument Level^d												
- Instrument Calibration		X	X	X	X	X	X	X	X	X	X	X
- Continuing Calibration Verification		X	X	X	X				X	X	X	X
Sample Analysis Level^e												
- Blanks		X	X	X	X				X	X	X	
- Duplicates		X	X	X	X				X	X	X	
- Spikes		X	X	X	X				X	X	X	
- Precision		X	X	X	X	X	X		X	X	X	
- Accuracy		X	X	X	X	X	X		X	X	X	
Sampling Program Level^f												
- Blind NIST Standard Reference Analysis			X	X	X	X	X		X	X	X	
- Blind Sample Replicate Analysis			X	X	X	X	X		X	X	X	
- Results Evaluation/Reanalysis		X	X	X	X	X	X		X	X	X	

^a GC/MS = gas chromatography/mass spectrometry, IC = ion chromatography, ICAP-AES = inductively coupled argon plasma-atomic emission spectrometry, CVAA = cold vapor atomic absorption spectrometry, NAA = neutron activation analysis, XRF = X-ray fluorescence, SEM/XRM = scanning electron microscopy/X-ray microanalysis, TMS = thermal ionization mass spectrometry, IR = infrared spectroscopy.

^b Wet chemical colorimetric methods using spectrophotometry (e.g. NO₃⁻-N, NO₂⁻-N, Cl⁻, PO₄³⁻-P, NH₄⁺-N, total Phenols).

^c Potentiometric for pH, conductivity.

^d Implemented by PACE Inc., Eastern Analytical Inc., University of Illinois, or UNH staff.

^e Generally involves the use of sample trains with calibration standards, blanks, samples (plus duplicates), and matrix spikes.

^f Implemented by UNH staff as check on external laboratories.

At the instrumentation and sample analysis levels, each of the laboratories (PACE Inc., Eastern Analytical Inc., University of Illinois, UNH) was required to generate data reports describing adherence to method-prescribed calibration, precision, and accuracy standards.

At the sampling program level, results from the analysis of blind NIST samples and blind replicate samples were evaluated for additional evaluation of precision and accuracy. Results from these efforts are presented here.

Table 2.9 shows the precision of various analyses of water samples for select elements in NIST 1643b "Trace Elements in Water". The certified standard does not contain all of the elements, anions, or components that were analyzed for in the various aqueous samples. Nevertheless, the precision, as determined by an average of the percent relative standard deviation (RSD) was less than 14% and usually less than 10%. These are analytes present in the certified standard at very low concentrations. The precision values fall within typical limits ($\% \text{ RSD} < 15$).

Table 2.10 shows the accuracy of various analyses of water samples for selected elements in NIST 1643b. The mean values from the four analyses were compared to the true certified value in the standard. Student's t-test was used to determine if significant differences existed between the measured value and the true value. Ca and Mg were the only elements that were significantly different; Ca was off by 7%, Mg was off by 42%. However, these elements are present in the standard reference material at concentrations around the detection limit of the method and are not certified, but approximate concentrations.

**Table 2.9: Laboratory Precision Based on Replicate Analysis of NIST 1643b
Trace Elements in Water**

Element ^a	Average % RSD ^b
As	0.000
Cd	4.728
Ca	2.666
Cr	0.000
Cu	0.000
Fe	5.128
Pb	10.163
Mg	3.808
Mn	4.027
Mo	0.000
Na	6.060
Sr	0.000
Zn	6.897
SO ₄	14.301

^a Certain elements not included due to their BDL concentrations in the standard reference material.

^b RSD = relative standard deviation (standard deviation/mean) in percent.
Average values are shown based on analyses from 10/93, 4/94, 8/94, and 9/94.

Table 2.10: Laboratory Accuracy Based on Replicate Analysis of NIST 1643b
Trace Elements in Water^a

Element	Mean Value of 10/93, 4/94, 8/94, 9/94 (mg/L)	True Value (mg/L)	Significance ^c
Cd	0.0203	0.0203	NSD
Ca ^b	37.500	35.000	SD
Cr	0.020	0.0189	NSD
Cu	0.020	0.0223	NSD
Fe	0.0975	0.1007	NSD
Pb	0.0233	0.0241	NSD
Mg ^b	8.675	15.000	SD
Mn	0.0313	0.0285	NSD
Mo	0.100	0.0864	NSD
Se	0.010	0.0099	NSD
Na ^b	8.250	8.000	NSD
Sr	0.200	0.2309	NSD
Zn	0.0725	0.0671	NSD

^a Certain elements not included due to their BDL concentrations in the standard reference material.

^b Values are not certified and are approximate.

^c NSD = no significant difference, SD = significant difference based on Student's t-test (two tailed, 95% probability).

Table 2.11 shows the precision of NAA and XRF analyses of solid samples for select elements in NIST 1633a "Trace Elements in Coal Fly Ash". The certified standard does not contain all of the elements that were analyzed for in the various solid samples. Nevertheless, the precision, as determined by an average of the percent RSD was less than 34% and usually less than 10%. The elements Ca, Cr, and Mn had high % RSD values. However, these elements are present at very low concentrations in the certified standard. Better precision would be expected at higher concentrations.

Table 2.12 shows the accuracy of NAA and XRF analyses of solid samples for select elements in NIST 1633a. The mean values for the three analyses are compared to the true certified value in the standard. Statistical t-test procedures were used to determine the t statistic. For all comparisons, there were no significant differences between the mean measured value and the true value at the 95% confidence level (two tailed). Thus excellent accuracy was observed.

STATISTICAL ANALYSES

A number of statistical procedures were utilized in this research effort. Table 2.13 generally describes the various purposes for which statistical tests were needed, the methods that were employed to evaluate the data, and the appropriate reference for the statistical method.

Frequently, compositional data from the analysis of ash are not normally distributed. Instead of a gaussian, or normal bell-shaped distribution, the data are positively skewed with a tail and outliers on the high side of the central distribution.

Table 2.11: NAA and XRF Precision Based on NIST 1633a Coal Fly Ash Standard Reference Samples^a

Element	Average % RSD ^b
Al	1.13
As	9.58
Ca	20.66
Cr	34.17
Cu	0.911
Fe	15.44
K	4.89
Mn	16.42
Na	6.65
Ni	8.86
Pb	4.97
Rb	7.01
Se	2.36
Si	2.02
Sr	9.38
Th	7.00
U	17.92
V	5.97
Zn	2.677

^a Certain elements not included due to their BDL concentrations in the standard reference material.

^b RSD = relative standard deviation (standard deviation/mean) in percent. Average values are shown based on analyses from 8/93, 10/93 and 1/95.

Table 2.12: NAA and XRF Accuracy Based on NIST 1633a Coal Fly Ash Standard Reference Samples^a

Element	Mean Value of 8/93, 10/93, 1/95 (%)	True Value (%)	Significance ^b
Al	14.576	14.3	NSD
As	0.0143	0.0145	NSD
Ca	1.210	1.11	NSD
Cr	0.0163	0.0196	NSD
Cl	0.0115	0.0118	NSD
Fe	9.22	9.4	NSD
K	1.950	1.88	NSD
Mn	0.0165	0.0179	NSD
Na	0.184	0.170	NSD
Ni	0.0132	0.0127	NSD
Pb	0.00716	0.00724	NSD
Rb	0.0142	0.0131	NSD
Se	0.000980	0.00103	NSD
Si	21.976	22.800	NSD
Sr	0.1002	0.0830	NSD
Th	0.0026	0.00247	NSD
U	0.00101	0.00102	NSD
V	0.0305	0.0297	NSD
Zn	0.0217	0.022	NSD

^a Certain elements not included due to their BDL concentrations in the standard reference material.

^b NSD = no significant difference, SD = significant difference based on Student's t-test (two tailed, 95% probability).

Table 2.13: Statistical Methods

Purpose	Method	Reference
Data Distribution	Boxplots	Mason et al., 1989
Comparison of Two Populations of Data	Student's t-test	Miller and Miller, 1988
Multiple Comparisons of Data	ANOVA	Miller and Miller, 1988
Trend Analysis	Mann-Kendall Analysis for Trend	Gilbert, 1987

When data are distributed as such, statistical methods relying on normal distributions cannot be directly employed. The boxplot (Mason et al., 1989) can be used to examine the type of distribution of data. The boxplot is based on the percentile evaluation of data. The median value (located where 50% of the data are above the value and 50% are below the value) is used as a measure of central tendency. It is graphically located in a box with upper and lower boundaries being the 75th and 25th percentiles (or third and first quartiles), respectively. The length of the box is the interquartile range (third quartile minus first quartile) where 50% of the data values lie. Whiskers are drawn horizontally up and down from the box depicting the 90th and 10th percentiles, respectively. Values falling outside of the whiskers are termed outliers. Ash compositional data plotted on a linear scale produce boxplots with characteristics of positive skewness and high outliers. When these same data are plotted on log scales, the data are normally distributed in the boxplot and conform to a log normal distribution. Comparisons between data sets frequently utilize only boxplots to graphically depict the data rather than conducting statistical comparisons on transformed data.

Significance testing can be used to compare populations of data (Miller and Miller, 1988). The test allows for determination that two data sets are either significantly different or not different because of random variation. The null hypothesis is used to stipulate that the variation is not due to systematic error. The approach assumes that the observed difference between a sample mean, $\bar{x}$, and the true value, μ , is due to significant differences in the data sets at some probability level (usually 95%). The methods require normal distributions, evaluation of homogeneity of variances, and

various uses of Student's t-statistic to compare either two populations of data, one population of data to a specific value, or confidence intervals for a data set.

Analysis of variance (ANOVA) is used for comparison of several populations of data simultaneously (Miller and Miller, 1988). The use of experimental design (Mason et al., 1989) allows for multiple comparisons and the examination of interactive effects between combinations of experimental variables. This is particularly useful in factorially designed experiments where various variables (e.g. A,B,C) are tested at various levels (e.g. low, medium, high). Rather than testing all combinations of variables (27 experiments for A,B,C variables at three levels), select combinations are tested factorially. ANOVA can be used to look at the significance of experimental variables in the interaction between variables, and the linearity of the response surface.

Trend analyses are frequently used to evaluate if increasing or decreasing trends can be seen in time-dependent data (Gilbert, 1987). Frequently, non-parametric tests are used. This results in the testing of ranked data. Rather than testing the actual data, their rankings are tested. This is usually stipulated when data are missing or below detection limit and when no distribution of the data is assumed. The Mann-Kendall test for trend (Gilbert, 1987) is an analysis that can be used.

CHAPTER 3

RESULTS AND DISCUSSION

OVERVIEW

This study was designed to look at both the short term and longer term impacts, if any, from the use of grate ash in pavement construction. The short term evaluation was addressed through field and laboratory experiments. The longer term impacts were addressed using additional laboratory experiments and predictive models to assess long term behavior.

To examine the short term aspect, the reader is referred to Figure 3.1. The figure depicts a road schematic showing roadside soils, the road wearing course, the road binder course containing ash, the road RAP base course and a road soil subbase. A ground water table is depicted under the road. Also shown are a monitoring well, suction lysimeter, and road surface run-off. A magnification is provided of the pavement cross section consisting of the wearing, binder and base courses. A second magnification is provided of just the binder course which contains grate ash and aggregate particles. A final magnification is provided showing the interface between the grate ash particle and the bituminous polymer matrix.

As a means of addressing the immediate impact, if any, we have adopted the following hypothesis. If ash constituents are being released from the grate ash particles into the environment, then this would first manifest itself in the migration via molecular diffusion at the microscale level of ash constituents into the bituminous polymer matrix. If this were a widespread phenomenon, then it would also be manifested in extensive

Figure 3.1: General Approach Used for Presentation and Interpretation of Data for Evaluating Immediate Impacts

macroscale migration, simultaneously upwards and downwards, of ash constituents into the wearing and RAP base courses. If this were also a widespread phenomenon, then it would possibly be manifested as elevated levels of contaminants observed in the downgradient monitoring wells adjacent to the road or in the suction lysimeters under the road. A major factor to this hypothesis is the presence of preexisting contaminants in the roadside environs such as (i) lead from deposition of atmospheric lead aerosols and from the combustion of leaded gasoline from the 1940's to the late 1970's, (ii) chloride from the application of road salts since the 1930's and from other contaminant sources in the local drainage basin, and (iii) volatile organic hydrocarbons from automobile traffic since the road was built (ca. 1930's). These contaminants create a very noisy and large background signal that varies widely in concentration as a function of both time and location.

If it can be shown that microscale migration (see point 1 in Figure 3.1) and macroscale migration (see point 2) are not occurring, and if the diffusive release of ash constituents from monolithic leaching studies of road cores is virtually non-existent, then the impact of the use of ash in the pavement has to be considered non-existent. The contaminants in the roadside environment must therefore be deemed to be a result of preexisting anthropogenic activity.

To address the longer term impact, the following presentation is offered. If laboratory monoliths can be constructed and manipulated to produce specimens that conservatively approximate the field behavior of pavement materials over the long term, then diffusional leaching and leaching modeling can be used to predict what the flux

might be at the leached surface. Such flux values can be compared to fluxes associated with road salting, road contamination run-off, or the flow of contaminated ground water from upgradient sources under the road.

Table 3.1 shows how the various sections presented in this part of the report are used to evaluate the immediate impact, if any, and to predict future potential impacts for using grate ash in pavement materials. As can be shown in Table 3.1, the sections are described by general topic, and for their application to addressing either immediate or future impacts. Diffusional modeling is used to address both the immediate and future impact categories.

SITE HYDROGEOLOGY

Detailed information about site hydrogeology can be found in Appendix 1 of Volume 2 of this report. The study site is characterized by two distinct geological and hydrogeological systems. The control section is a sandy outwash deposit consisting of Windsor loamy sand (0 to 3% slope) that was deposited about 12,000 years ago by meltwater streams during glacial retreat. Figure 3.2 depicts the control section in geologic cross-section.

The test section consists of a glacial lodgement till situated over a peletic schist bedrock from the Rangely Formation. The till is a Shapleigh-Gloucester very rocky sandy loam (8 to 15% slope) deposited during the Wisconsin advance during the Pleistocene epoch. The underlying bedrock is a Silurian-age low grade metasedimentary peletic schist containing quartz (SiO_2), muscovite ($\text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2$), chlorite (group

Table 3.1: Report Sections Used for Presentation of Results and Their Discussion

General Topic	Report Sections	
	Data for Evaluating Present Road Environmental Performance	Data for Evaluating Future Environmental Performance
Background	<ul style="list-style-type: none"> - Site Hydrogeology - Asphalt Batch Plant Air Emissions - Grate Ash, Soil, & RAP Characteristics - Bottom Ash & Bottom Ash/Aggregate/Asphalt Lysimeters 	
Grate Ash Constituent Immobilization	<ul style="list-style-type: none"> - Microscale Migration - Macroscale Migration - Road Core Monolith Diffusional Leaching Behavior 	<ul style="list-style-type: none"> - Evaluation of the Effects of Pavement Void Change, Bituminous Polymer Aging, and Microcracking on Monoliths Diffusional Leaching Behavior for Pavements - Evaluation of Grain Size and the Presence of Bituminous Asphalt Cement on Granular Diffusional Leaching Behavior for RAP
Modeled Environmental Behavior	<ul style="list-style-type: none"> - Modeling Constituent Fluxes for Various Time Periods and Degrees of Wetting 	<ul style="list-style-type: none"> - Modeling Constituent Fluxes for Various Time Periods and Degrees of Wetting for Pavements and RAP
Site Environmental Evaluation	<ul style="list-style-type: none"> - Ground Water Quality - Evaluation of Preexisting Background Contamination - Comparison of Modeled Constituent Fluxes to Preexisting Background Contaminant Fluxes 	<ul style="list-style-type: none"> - Modeling Constituent Fluxes for Various Time Periods and Degrees of Wetting for Pavements and RAP

Figure 3.2: Control Section Geologic Cross Section

name for $A_6(\text{AlSi}_3)\text{O}_{10}(\text{OH})_8$ where $A = \text{Mg}, \text{Fe}^{2+}, \text{Fe}^{3+}, \text{ or } \text{Mn}$), and pyrite (FeS_2). The bedrock is highly fractured and extensive iron staining from pyrite oxidation is seen in the weathering zones in the fractures. The site does not contain geologic faults. Figure 3.3 depicts the test section in geologic cross-section.

Ground water flow in the two sections is influenced by site geology. As shown in Figure 3.2, the ground water flow in the control section is towards Paugus Bay of Lake Winnepesaukee with a west-northwest direction. The typical hydraulic gradient is shallow (0.008 ft/ft or m/m). As shown in Figure 3.3, the ground water flow in the test section is westerly with typically steep hydraulic gradients (0.14 ft/ft or m/m).

As shown in Table 3.2a, the hydraulic conductivities in the control section are relatively moderate; 12 to 28 ft/d (4.0×10^{-3} to 9.9×10^{-3} cm/s). Seepage velocities are also relatively moderate, 0.11 to 0.40 ft/d (3.9 to 20.0×10^{-5} cm/s). This translates to travel times of 8 to 19 days for a parcel of ground water to conservatively move 10 feet (3.04 m) under the control road section along flow paths. These values are typical for glacial outwash deposits under low gradients.

In the test section, dominated by highly fractured bedrock, it is assumed that the bedrock has a de-minimus primary permeability that can be examined as a porous equivalent medium. As shown in Table 3.2a, the hydraulic conductivities are low; 0.11 to 0.4 ft/d (3.90×10^{-5} to 2.0×10^{-4} cm/s). Seepage velocities are also relatively low; 0.18 to 0.37 ft/d (1.8 to 5.6×10^{-5} cm/s). This translates into travel times of 27 to 55 days for a parcel of ground water to conservatively move 10 feet (3.04 m) under the test road section along flow paths.

Figure 3.3: Test Section Geologic Cross Section. (a) Section Through Monitoring Well 3. (b) Section Through Monitoring Well 5

Table 3.2a: Site Hydrogeologic Characteristics

Well	Geology	K ft/d (cm/s)	Vs ^a ft/d (cm/s)	Travel Time to Move 10 ft (3.04 m), Days
MW 1 (Control)	Sandy Outwash Deposits	28 (9.9x10 ⁻³)	1.12 (3.9x10 ⁻⁴) ^b	8.9
MW 2 (Control)	Sandy Outwash Deposits	13 (4.6x10 ⁻³)	0.52 (1.8x10 ⁻⁴) ^b	19.2
MW 3 (Test)	Glacial Till Over Fractured Peletic Schist Bedrock (Rangely Formation)	0.2 (6.0x10 ⁻⁵)	0.18 (5.6x10 ⁻⁵) ^c	55.5
MW 4 (Test)	Glacial Till Over Fractured Peletic Schist Bedrock (Rangely Formation)	0.2 (6.0x10 ⁻⁵)	0.18 (5.6x10 ⁻⁵) ^c	55.5
MW 5 (Test)	Glacial Till Over Fractured Peletic Schist Bedrock (Rangely Formation)	0.40 (2.0x10 ⁻⁴)	0.37 (1.8x10 ⁻⁵) ^c	27.0

^a Based on $V_s = K(i)/n_e$ where V_s = seepage velocity (ft/d or m/s), i = hydraulic gradient (ft/ft or m/m), and n_e = effective porosity (unitless).

^b Assumes an effective porosity of 0.20.

^c Assumes an effective porosity of 0.15 (range 0.05 to 0.25) for fractured bedrock.

Table 3.2b: Site Water Table Elevations

WATER ELEVATIONS								
New Hampshire Ash Paving Demonstration, Laconia, NH								
		CONTROL SECTION			DEMONSTRATION SECTION			
		Dug Well	MW2	MW1	MW4	PZ1	MW3	MW5
		upgradient	upgradient	downgradient	upgradient	upgradient	downgradient	downgradient
USGS TOC ^a Elevation (ft)		519.23	514.71	512.93	538.89	522.53	517.96	516.03
Bottom of Well Elevation (ft)		500.23	494.71	492.93	515.39	506.03	498.96	499.53
ELEVATIONS (ft):								
Prepaving	Nov., 1992	508.23	505.71	504.93	527.89	-	505.96	510.53
	Jan. 29, 1993	504.45	505.06	504.35	532.78	516.66	509.33	514.78
	Feb. 25, 1993	505.15	504.71	504.35	530.19	515.82	507.73	513.32
	Apr. 1, 1993	506.15	505.63	504.77	536.89	520.28	512.13	516.03
	Apr. 23, 1993	507.02	506.51	505.96	534.29	517.99	512.50	512.99
Postpaving	Jul. 9, 1993	506.48	505.88	506.31	528.56	511.57	507.11	509.72
	Sept. 24, 1993	506.29	505.59	504.98	529.24	513.08	506.63	510.97
	Dec. 7, 1993	506.67	506.04	505.43	534.22	516.45	510.63	512.86
	Apr. 6, 1994	507.34	506.71	506.03	535.69	517.68	513.23	513.23
	May 12, 1994	508.03	507.36	506.68	534.65	516.33	512.15	513.18
	June 28, 1994	507.40	502.73	506.16	529.89	513.03	511.75	511.16
	Sept. 8, 1994	506.73	506.61	505.43	528.31	511.36	505.86	509.13
	Oct. 14, 1994	506.04	505.62	505.35	530.14	512.03	506.29	510.07
		(10/18/94)						

^aTop of Casing

Water table elevations at the various sampling locations are shown in Table 3.2b. Elevations are shown for the entire study period. The water table elevations are more dynamic in the test section because of the proximity of bedrock to ground surface and the artesian-like conditions of the bedrock water-bearing formation. In the winter, with ground freezing, evidence of artesian conditions were seen at MW3 and MW5.

During well installations, low levels of volatile organic hydrocarbons (VOCs) were detected with the photoionization detector. Values of 3-15 ppm were detected in MW 1, MW 2, MW 3 and MW 4. No VOCs were seen in MW 5. The source of these preexisting contaminants is not known.

ASPHALT BATCH PLANT AIR EMISSIONS

Detailed results of air emission testing during asphalt production can be found in Appendix 2 of Volume 2 of this report. The purpose of the asphalt batch plant stack emission testing program was to evaluate the air emissions during processing of grate ash. The plant is presently regulated by N.H. DES Air Resources Division for particulates and visible emissions. During test and control pavement manufacture, none of the emissions limitations were exceeded.

Table 3.3 shows the general plant operational characteristics during the four runs. Runs 1 and 2 involved the manufacture of control binder course. Runs 3 and 4 involved the production of test binder course with 50% grate ash and 50% natural aggregate. Normally, air emission compliance testing uses 75 minute sample collection periods. However, the small size of the pavement job used here and problems associated with

Table 3.3: Asphalt Batch Plant Air Testing Runs on May 7, 1993

Run Number (Type of Asphalt)	Time (Elapsed Time in Minutes)	Total Tons (Tonnes) Processed	Process Rate, Tons/hr (tonnes/h)
1 (Control Asphalt)	0755 - 0840 (45)	126.05 (114.45)	168.07 (152.61)
2 (Control Asphalt)	1101 - 1215 (74)	179.75 (163.21)	145.74 (132.33)
3 (Test Asphalt)	1420 - 1535 (65)	161.94 (147.04)	129.55 (117.63)
4 (Test Asphalt)	1643 - 1750 (67)	162.12 (147.20)	144.75 (131.43)

truck availability by the pavement contractor meant that test runs were shorter than 75 minutes. Run times ranged from 40 to 75 minutes.

Table 3.4 shows the results from the particulate and multimetals emission testing. For the two control runs (Runs 1&2), the average particulate emission was 6.49×10^{-3} grains per dry standard cubic foot. For the two test runs (Runs 3 & 4), the average particulate emission was 1.66×10^{-2} grains per dry standard cubic foot; a 1.65 fold increase relative to the control. Both particulate emission rates, however, are well below the 4×10^{-2} grains per dry standard cubic foot emissions level.

Table 3.4 includes the metal emission rates for each run, as well as the average emission rates for the control and test runs. The limited data makes it difficult to statistically compare the particulate metals emissions between the control particulates for the elements of Cu, Hg, and Zn when the individual test runs are compared. No discernable differences were seen for the elements Cd, As, Be, Pb and Cr.

When the averages are considered, the control particulates were enriched relative to the test particulates for the elements of Cd, Cr, Ni and Se, because the difference between the averages was at least 67%. Using the same approach, the test particulates were enriched relative to the control particulates for Cu and Zn. The averages for the remaining elements (Hg, As, Be and Pb) were similar, with differences of approximately 40% or less.

Table 3.5 shows the data relative to HCl emissions testing. The HCl emissions rates were about 50 to 60% higher during test asphalt production. HCl is not regulated by N.H. DES for asphalt batch plant operations.

Table 3.4: Asphalt Batch Plant Particulate/Multimetals Emissions on May 7, 1993

Run Number	1	2	Average	3	4	Average
Type of Asphalt	Control	Control	Control	Test	Test	Test
Total Time, Min	40	75		75	62.5	
Stack Temp, °F	216	156		194	199	
CO ₂ in stack, %	3.6	3.6		3.8	3.8	
O ₂ in stack, %	15.9	15.9		15.8	15.8	
CO in stack, %	0.0	0.0		0.0	0.0	
N ₂ in stack, %	80.5	80.5		80.4	80.5	
Particulates, gr/DSCF	8.79x10 ⁻³	4.18x10 ⁻³	6.49x10 ⁻³	1.50x10 ⁻²	1.82x10 ⁻²	1.66x10 ⁻²
Emissions, lbs/h Particulate	2.04	0.99	1.51	3.63	4.25	3.94
Mercury, Hg	1.11x10 ⁻³	6.16x10 ⁻⁴	8.62x10 ⁻⁴	1.14x10 ⁻³	1.28x10 ⁻³	1.21x10 ⁻³
Cadmium, Cd	1.03x10 ⁻³	5.90x10 ⁻⁴	8.09x10 ⁻⁴	1.70x10 ⁻⁴	7.97x10 ⁻⁴	4.84x10 ⁻⁴
Arsenic, As	7.25x10 ⁻⁴	3.04x10 ⁻⁴	5.14x10 ⁻⁴	6.71x10 ⁻⁴	7.77x10 ⁻⁴	7.24x10 ⁻⁴
Beryllium, Be	2.02x10 ⁻⁴	9.22x10 ⁻⁵	1.47x10 ⁻⁴	1.10x10 ⁻⁴	1.24x10 ⁻⁴	1.17x10 ⁻⁴
Lead, Pb	1.31x10 ⁻²	4.43x10 ⁻³	8.79x10 ⁻³	6.03x10 ⁻³	7.97x10 ⁻³	7.00x10 ⁻³
Chromium, Cr	1.26x10 ⁻²	4.06x10 ⁻³	8.35x10 ⁻³	2.72x10 ⁻³	4.71x10 ⁻³	3.72x10 ⁻³
Copper, Cu	5.06x10 ⁻³	2.30x10 ⁻³	3.68x10 ⁻³	7.31x10 ⁻³	1.25x10 ⁻²	9.92x10 ⁻³
Nickel, Ni	8.59x10 ⁻³	9.22x10 ⁻³	8.91x10 ⁻³	3.14x10 ⁻³	6.73x10 ⁻³	4.94x10 ⁻³
Selenium, Se	6.40x10 ⁻⁴	5.72x10 ⁻⁴	6.06x10 ⁻⁴	3.23x10 ⁻⁴	3.94x10 ⁻⁴	3.58x10 ⁻⁴
Zinc, Zn	4.94x10 ⁻²	2.30x10 ⁻³	2.58x10 ⁻²	1.55x10 ⁻¹	1.10x10 ⁻¹	1.32x10 ⁻¹

Table 3.5: Asphalt Batch Plant HCl Emissions on May 7, 1993

Run Number	1	2	3	4
Type of Asphalt	Control	Control	Test	Test
% Moisture	14	16	25	26
Average Stack Temp, °F	216	156	194	199
Volumetric Flow Rate DSCFM ^a	27,057	27,540	28,208	27,424
% O ₂ (Dry)	15.9	15.9	15.8	15.7
% CO ₂ (Dry)	3.6	3.6	3.8	3.8
Total HCl Collected, mg	0.08	0.11	0.19	0.15
HCl Emission Rate, lbs/h	0.09	0.09	0.15	0.13
HCl Concentration, ppm	0.585	0.555	0.930	0.803

^a Dry standard cubic feet per minute

Visible emissions, as indicated by opacity measurement, were always below the regulatory limit of 20% for asphalt batch plants. Values for runs 1 and 2 ranged from 0 to 5%. Values for runs 3 and 4 ranged from 0 to 15%.

GRATE ASH CHARACTERISTICS COMPARED TO BOTTOM ASH

Raw data on the total composition of the grate ash can be found in Appendix 3 of Volume 2 of this report. Table 3.6 contains a summary of the fresh grate ash total element concentrations and total available element concentrations. Ranges and mean values are shown. Table 3.7 contains a summary of the aged grate ash total element concentrations and total available element concentrations. Ranges and mean values are shown. One objective of this study was to compare the general grate ash chemical characteristics to the large database present from the earlier bottom ash characterization study (Eighmy et al., 1992). Table 3.8 contains a summary of the fresh bottom ash total element concentrations and total available element concentrations. Ranges and mean values are shown (Eighmy et al., 1992; Whitehead, 1992). For all of the compositional data that are presented, some of the elements show a normal distribution of the data points. The use of mean values is valid in this case. For some elements, the data are positively skewed. The use of mean values is less valid in this case. For continuity, emphasis is placed more on ranges rather than mean values. For those elements frequently present in the ash streams as metallic components (Al, Cu, Pb, Zn, etc.) which exhibit positive skewness, some comparisons are made using box plots (see below), a more valid comparative method.

Table 3.6: Fresh Grate Ash Total Element and Total Available Composition

Element	Total Composition, mg/kg		Total Available Composition, mg/kg	
	Range	Average	Range	Average
Al	44,900-52,700	47,912	200-320	257
As	13.13-28.28	20.93	BDL	BDL
Ba	460-1,270	845	60-100	82
Br	19.85-51.54	31.97	BDL	BDL
Ca	50,800-65,300	58,600	18,615-30,075	26,608
Cd	3.44-8.60	6.93	2.60-5.20	3.95
Cl	700-2,340	1,713	802-2,803	2,027
Co	18.69-79.49	39.84	No Data	No Data
Cr	701-1,129	855	BDL	BDL
Cu	1,185-2,105	1,598	170-460	282
Fe	80,700-99,700	89,562	401-760	500
Hg	BDL	BDL	BDL	BDL
K	5,400 -11,400	7,771	800-2,002	1,226
Mn	760-1,230	937	94-220	147
Mo	19.34-41.58	29.80	BDL	BDL
Na	30,800-43,000	37,825	1,002-2,403	1,652
Ni	440-585	501	No Data	No Data
Pb	903-2,885	1,400	104-1,082	312
Sb	60.48-98.28	75.62	No Data	No Data
Se	24.19-25.08	24.63	BDL	BDL
Si	215,570-259,040	240,767	1,601-2,002	1,827
Sn	141-605	276	No Data	No Data
Sr	310-530	386	40-80	72
Ti	5,000-6,800	5,937	No Data	No Data
V	31.88-43.08	38.69	No Data	No Data
Zn	2,852-4,140	3,394	920-1,481	1,446

Table 3.7: Aged Grate Ash Total Element and Total Available Composition

Element	Total Composition, mg/kg		Total Available Composition, mg/kg	
	Range	Average	Range	Average
Al	47,900-54,400	50,907	200-600	380
As	17.56-25.04	21.04	BDL	BDL
Ba	530-1,900	1,112	60.05-140.1	87.24
Br	15.27-38.95	24.40	BDL	BDL
Ca	54,200-67,400	62,236	22,018-30,033	26,027
Cd	3.85-10.19	6.86	2.00-5.60	3.25
Cl	470-2,590	1,338	800-5,208	1,830
Co	19.77-77.20	38.60	No Data	No Data
Cr	622-1,079	787	BDL	BDL
Cu	1,161-2,242	1,516	142-440	275
Fe	84,600-112,000	99,007	400-920	623
Hg	BDL	BDL	BDL	BDL
K	4,800-10,100	7,831	800-5,209	1,473
Mn	940-1,450	1,052	102-540	171
Mo	18.69-61.87	34.45	BDL	BDL
Na	34,600-46,000	38,914	1,001-1,801	1,273
Ni	347-591	464	No Data	No Data
Pb	895-1,710	1,278	96-440	213
Sb	57.30-94.59	80.94	No Data	No Data
Se	23.48-24.56	24.02	BDL	BDL
Si	215,460-257,900	236,422	1,201-1,802	1,487
Sn	147-309	229	No Data	No Data
Sr	270-670	462	60-100	72
Ti	5,100-7,100	6,100	No Data	No Data
V	33.28-58.45	45.00	No Data	No Data
Zn	2,707-4,070	3,304	740-1,922	1,149

Table 3.8: Bottom Ash Total Element and Total Available Composition

Element	Total Composition, mg/kg		Total Available Composition, mg/kg	
	Range	Average	Range	Average
Al	34,400-64,800	52,530	490-1,160	840
As	18-189	42	BDL	BDL
Ba	785-1,480	978	48-119	76
Br	17-126	46	BDL	BDL
Ca	51,200-102,900	78,275	18,500-61,000	29,000
Cd	3-70	18	2-51	12
Cl	1,105-4,190	2,289	1,400-6,000	2,500
Co	21-43	29	No Data	No Data
Cr	867-2,005	1,419	1.8-2.3	2.1
Cu	1,140-6,980	2,414	105-490	210
Fe	56,400-114,950	82,940	510-1,850	1,100
Hg	0.0-2.3	0.95	BDL	BDL
K	7,200-11,600	9,330	650-2,000	920
Mn	605-1,560	1,033	75-280	125
Mo	20-161	45	BDL	BDL
Na	20,200-48,000	37,200	1,100-3,950	1,940
Ni	249-855	610	No Data	No Data
Pb	1,200-6,600	2,855	40-2,900	850
Sb	60-283	118	No Data	No Data
Se	No Data	No Data	BDL	BDL
Si	182,500-274,000	233,000	1,700-6,300	3,100
Sn	No Data	No Data	No Data	No Data
Sr	1-1,000	581	45-215	95
Ti	3,490-9,500	7,085	No Data	No Data
V	32-123	57	No Data	No Data
Zn	2,198-7,640	3,500	750-3,400	1,250

A comparison of the total compositional variation of elements in the earlier bottom ash database (see Table 3.8) with the data presented in Tables 3.6 and 3.7 shows (i) that all three ranges for each element overlap for all elements, (ii) the range of total concentration is larger for the bottom ash than either the fresh or aged grate ash, (iii) with two exceptions (Ba, Co), the upper value of the range is always higher for the bottom ash than either type of grate ash, and (iv) the lower value of the range is equally distributed amongst the three ash types. The data for the bottom ash total composition is sometimes positively skewed with frequent high concentration outlier values. Some of the high outliers are associated with metallic metals that report to grate siftings (e.g. Pb, Zn, Al). Some of the high outliers are associated with elements that do not report to grate siftings (e.g. Ca, Cl, Ti). These data suggest that the bottom ash high concentration outliers may be attributed to grate siftings and to possible differences in sampling and processing strategies for the ashes (see below).

A comparison of the total available compositional variation for elements from the earlier bottom ash database (see Table 3.8) with the data presented in Table 3.6 and 3.7 shows (i) that, with the exception of Al in bottom ash, all three ranges for each element overlap for all elements, (ii) the range is usually larger for the bottom ash, (iii) with the exception of Ba, K and Mn in aged grate ash, the upper value of the range is always highest in bottom ash, and (iv) the lower value of the range is equally distributed amongst the three ash types. The data for the bottom ash total available composition is positively skewed with high concentration outlier values. These values usually coincide with the high total concentration outlier values. As mentioned previously, these high

concentration outlier values may reflect both the presence of grate siftings and possible sampling artifacts (see below).

It is also useful to assess if differences exist in the fractions of an element available for leaching (total available concentration/total element concentration). The question addresses relative leachability of grate sifting. The data in Table 3.9 show (i) that with the exception of Al in bottom ash, all three ranges for each element overlap for all elements, (ii) the range is usually the largest for the bottom ash, (iii) the upper value of the range is found in all three ash types with the majority in bottom ash, and (iv) the lower value of the range is found in all three ash types with the majority in bottom ash.

Figures 3.4 and 3.5 allow for visual comparisons of data distributions for the total elemental composition in the three ash types (Figure 3.4) and for the total available composition in the three ash types (Figures 3.5). The elements Al, Cu, Pb and Zn are shown as these tend to be metallic elements associated with grate siftings (IAWG, 1994).

The data in Figure 3.4 on total element composition show that the data ranges overlap for all ash types for each element. With the exception of Pb in bottom ash, the interquartile ranges overlap for all three ash types. High and low outlier values are also present. High values are seen with Cu, Pb and Zn in bottom ash.

The data in Figure 3.5 on total available composition shows that, with the exception of Al in bottom ash, the data ranges overlap for all ash types for each element. With the exception of Al in the bottom ash, the interquartile ranges overlap for all three ash types. High and low outlier values are present. High outlier values are seen with

**Table 3.9: Percent Fractions Available for Leaching for
Fresh and Aged Grate Ash and Bottom Ash**

Element	Fresh Grate Ash Without Grate Siftings		Aged Grate Ash Without Grate Siftings		Bottom Ash with Grate Siftings
	Range (%)	Average (%)	Range (%)	Average (%)	Range (%)
Al	0.4 - 0.6	0.5	0.4 - 1	0.7	1-3
As	-	-	-	-	-
Ba	5 - 22	12	4 - 22	9	4 - 12
Br	-	-	-	-	-
Ca	41 - 54	47	35-48	42	27-68
Cd	33 - 75	55	29 - 78	51	28 - 99
Cl	94 - 100	99	85 - 100	98	70 - 100
Co	-	-	-	-	-
Cr	-	-	-	-	0.1 - 0.2
Cu	12 - 33	16	10 - 26	18	6 - 20
Fe	0.4 - 0.6	0.5	0.4 - 0.8	0.6	0.7 - 2
Hg	-	-	-	-	-
K	7 - 22	17	10 - 90	21	6 - 17
Mg	-	-	-	-	9 - 66
Mn	13 - 19	16	11 - 37	16	6 - 20
Mo	-	-	-	-	-
Na	3 - 7	4	2 - 4	3	3 - 12
Ni	-	-	-	-	-
Pb	8 - 37	18	7 - 26	17	6 - 49
Sb	-	-	-	-	-
Se	-	-	-	-	-
Si	0.7 - 0.9	0.8	0.5 - 0.8	0.6	0.5 - 4
Sn	-	-	-	-	-
Sr	15 - 26	22	12 - 30	18	3 - 35
Ti	-	-	-	-	-
V	-	-	-	-	-
Zn	32 - 43	36	27 - 52	36	20 - 45

* Fraction available for leaching means total available composition (mg/kg)/total elemental compositional (mg/kg); (-) indicates either no data collected or data was BDL.

Figure 3.4: Boxplots of Total Elemental Composition of Bottom Ash (With Grate Siftings), Fresh Grate Ash (Without Grate Siftings) and Aged Grate Ash (Without Grate Siftings) for Al, Cu, Pb and Zn

Figure 3.5: Boxplots of Total Available Composition of Bottom Ash (With Grate Siftings), Fresh Grate Ash (Without Grate Siftings) and Aged Grate Ash (Without Grate Siftings) for Al, Cu, Pb and Zn

Al, Pb, and Zn in the bottom ash. These points generally correspond to high total element concentrations. High outlier values are seen with Cu for all ash types.

The data presented in Tables 3.6 through 3.9 and in Figures 3.4 and 3.5 point to the fact that bottom ash containing grate siftings is similar in elemental composition and element availability to grate ash. However, the bottom ash has high outlier values for many elements. Some of these elements are frequently associated with metallic metals that report to the grate siftings stream (e.g Pb, Al, Zn). Some of these elements are not necessarily associated with grate siftings (e.g Ca, Cl, Ti) and many reflect artifacts in sampling (bottom ash was sampled manually with shovels from ash moving along with drag chain flights, grate ash was sampled using roll-offs that collected the entire content of material from the drag chain system) or in processing (bottom ash was hand sieved, grate ash was trommeled with a large field trommel).

While these outlier elements are not more readily leachable, they do contribute to modest increases in potential driving fluxes in diffusive leaching situations with ash pavement monoliths.

THE EFFECTS OF AGING ON GRATE ASH TOTAL AVAILABLE COMPOSITION

A second objective of this study was to examine the influence of aging on element total availabilities in the grate ash. This aggressive leaching procedure, conducted at pH 4.0, would not detect subtle differences in leachability associated with carbonation reactions that might be observed at field pH values. Rather, it would detect major differences in mineralogy which would increase or decrease solubility at pH 4. Few changes in availability were seen after the six months of field aging. Student's t-test (Miller and Miller, 1988) was used to evaluate the influence of aging reactions on the

total availability of elements in the grate ash. The test was conducted on populations of unequal size (7 versus 14) so variances were sometimes pooled. As shown in Table 3.10, the elements Na and Si had increased availability in the fresh ash and the elements Fe and Al had increased availability in the aged ash (Student's t-test, 95% probability level, pooled variances, two-tailed comparison). The reasons for this are presumed to be ash weathering reactions which robustly affected mineralogy for these elements.

In Europe, aging is frequently utilized to geochemically stabilize grate ash prior to its use as granular material in road subbases, granular fill, wind barriers, sound barriers, etc. This is done to make the granular material more amenable to compaction (IAWG, 1994) and to promote $\text{CO}_2(\text{g})$ uptake and modest reductions in ash pH to values around 7 or 8. These values correspond to minimum solubilities for many metals. At many waste-to-energy facilities in Europe, grate siftings are collected at the point of generation and not combined with the grate ash. This allows for metals recovery and for the minimization of potential $\text{H}_2(\text{g})$ generation when elemental metals in the siftings (e.g. Al^0) are oxidized. A bottom ash utilization study in Germany has shown that H_2 generation in granular subbase bottom ash material below pavements (not in the pavement itself) can cause deterioration in physical performance from blistering (Kluge et al., 1981). Aging is promoted to allow elemental metal oxidation to occur prior to use in situations where this may be problematic to physical performance and where siftings are present in the ash.

The situation where ash is encapsulated in a hydrophobic pavement is different than most utilization scenarios common in Europe. Presumably, the bituminous material would impede H_2O uptake into a waste material so that H_2O -driven aging reactions would not occur in such a matrix. While there is no data on expansive aging phenomena

Table 3.10: Statistical Evaluation of Element Availability Between Fresh and Aged Grate Ash Samples^{a,b}

Element	Significant Difference ^c	Higher Value
Al	SD	Aged
Ba	NSD	-
Ca	NSD	-
Cd	NSD	-
Cl	NSD	-
Cu	NSD	-
Fe	SD	Aged
K	NSD	-
Mn	NSD	-
Na	SD	Fresh
Pb	NSD	-
Si	SD	Fresh
Sr	NSD	-
Zn	NSD	-

^an = 7 fresh, n = 14 for aged.

^bBased on Student's t-test (two tailed, 95% probability).

^cSD = significant difference, NSD = no significant difference.

of MSW bottom ash or grate ash in pavement materials, there is extensive data on steel slags (Emery, 1982). While steel slags are similar to bottom ash as a residue from a high temperature process, they are chemically different from bottom ash. Therefore, it is not clear if bottom ash or grate ash will react in a manner similar to steel slags with regard to physical performance. However, there is substantial evidence that steel slags will expand in pavements when unreacted CaO and MgO phases in the slag are hydrolyzed to $\text{Ca}(\text{OH})_2$ and $\text{Mg}(\text{OH})_2$ and that this can happen in hydrophobic pavements with low water absorptivity (Farrand and Emery, 1995; Noureldin and McDaniel, 1990; Emery, 1982). These concepts may warrant further study for the use of ashes in pavement.

REGULATORY TESTING

The aged grate ash (2 months aging) was subjected to TCLP testing. The data are shown in Table 3.11. In the earlier characterization study (Eighmy et al., 1992) the bottom ash was subjected to limited TCLP testing; none of the regulated analytes exceeded regulatory limits. As shown in Table 3.11, lead was the only element to exceed the limit value of 5 mg/L (1 out of 14 samples tested exceeded the limit). As shown in the boxplot in Figure 3.6, the lead data is log normally distributed. The data points are positively skewed with outlier values at the high end. Using the procedure established by the U.S. EPA (1984, 1987) and by N.H. DES, the upper confidence interval (UCI) for the raw data and log transformed data were calculated. As shown in Table 3.12, using the non-normalized data, the UCI is 4.49 mg/L which is below the 5.0 mg/L regulatory limit. More appropriately, with non-normally distributed data which have been transformed into normally distributed data using a log transformation, the UCI is 1.91 mg/L. This value is also below the 5.0 mg/L regulatory limit. By all measures, the grate

Table 3.11: Grate Ash Pile TCLP Leaching Data

Sample Number	pH After Heating w/Acid	Extract Used	Final Extract pH	Ag	As	Ba	Cd	Cr	Hg	Se	Pb
Aged Ash (2 months old)											
Concentration, mg/L											
1	4.16	1	5.85	<0.05	<0.5	<0.5	0.06	<0.1	<0.01	<0.5	0.8
2	5.09	2	4.43	<0.05	<0.5	<0.5	0.10	<0.1	<0.01	<0.5	4.4
3	4.19	1	5.72	<0.05	<0.5	<0.5	0.09	<0.1	<0.01	<0.5	2.0
4	3.71	1	5.56	<0.05	<0.5	<0.5	0.12	<0.1	<0.01	<0.5	0.9
5	3.48	1	5.48	<0.05	<0.5	<0.5	0.12	<0.1	<0.01	<0.5	1.8
6	4.16	1	5.62	<0.05	<0.5	<0.5	0.06	<0.1	<0.01	<0.5	20.0
7	4.22	1	5.66	<0.05	<0.5	<0.5	0.08	<0.1	<0.01	<0.5	1.0
8	4.27	1	5.73	<0.05	<0.5	<0.5	0.07	<0.1	<0.01	<0.5	0.9
9	3.89	1	5.73	<0.05	<0.5	<0.5	0.08	<0.1	<0.01	<0.5	0.9
10	4.11	1	5.79	<0.05	<0.5	<0.5	0.08	<0.1	<0.01	<0.5	0.9
11	3.85	1	5.60	<0.05	<0.5	<0.5	0.05	<0.1	<0.01	<0.5	1.4
12	3.50	1	5.87	<0.05	<0.5	<0.5	0.06	<0.1	<0.01	<0.5	0.6
13	4.46	1	5.62	<0.05	<0.5	<0.5	<0.05	<0.1	<0.01	<0.5	0.8
14	4.80	1	5.74	<0.05	<0.5	<0.5	<0.05	<0.1	<0.01	<0.5	0.9
Regulatory Limit				5.0	5.0	100	1.0	5.0	0.2	1.0	5.0

Figure 3.6: Scatter (a) and Box (b) Plots for Grate Ash TCLP Lead Data for Pile Samples (n=14)

Table 3.12: Grate Ash Pile TCLP Leaching Data Analysis

<u>Aged Ash Only (n=14), Non-normalized</u>	<u>Log Normalized</u>
$\bar{x} = 2.66$	$\bar{x} = 0.14$
$S_y = 5.08$	$S_y = 0.40$
$t = 1.350$ (one tailed @ $p=0.10$ for $n-1 = 13$)	$t = 1.350$
$\sqrt{n} = 3.74$	$\sqrt{n} = 3.74$
upper confidence interval (UC) = $\frac{t S_y}{\sqrt{n}} = \frac{(1.35)(5.08)}{3.74}$	UCI = 0.14
$\bar{x} + \text{UCI} = 2.66 + 1.83 = 4.49$ (passes)	$\bar{x} + \text{UCI} = 0.28$
	Untransformed = 1.91 mg/L (passes)

ash, as represented by random sampling of the temporary storage pile, is non-hazardous according to Federal regulations and the State of New Hampshire rules.

ROADSIDE SOILS

Raw data on the total composition of the roadside soils can be found in Appendix 3 of Volume 2 of this report. Tables 3.13 and 3.14 contain summaries of the road side surface soil total element concentration and total available element concentration in the control and test sections, respectively. Samples were collected adjacent to MW 1 and MW 2 in the control section and adjacent to MW 3 and MW 5 in the test section. Ranges and mean values are shown. Pb and Cl concentrations are relatively high. The anthropogenic input of Pb from atmospheric deposition and leaded gas combustion, and Cl from salting explains the higher values found in roadside soils. The lead values are typical for urban roadside soils (Lagerwerff and Specht, 1970). These values are preexisting to the paving project. No marked differences can be seen in the composition or leachability of surface soil elements from either section when Tables 3.13 and 3.14 are compared.

Table 3.15 contains roadside deep soil total element concentrations. These samples were collected during installation of the lysimeter trenches. The data show that these soils are similar in composition to the surface soils with the exception that the deep soils were enriched in Al, Ca, Cl, Na relative to the surface soils and depleted in Cr, Cu, Ni, Pb, Sb, and Zn relative to the surface soils. Again, the data suggest that the roadside soil environment contains preexisting anthropogenic contaminants relative to typical soils (see Table 1.10).

Table 3.13: Roadside Surface Soil (Control Section) Total Element and Total Available Composition

Element	Total Composition, mg/kg		Total Available Composition, mg/kg	
	Range	Average	Range	Average
Al	56,300-64,400	61,083	20.01-140.0	63.8
As	3.19-6.45	5.08	BDL	BDL
Ba	350-490	424	BDL	BDL
Br	11.09-13.90	12.50	BDL	BDL
Ca	6,580-8,100	7,273	140-560	266
Cd	BDL	BDL	BDL	BDL
Cl	68-124	96	600-800	700
Co	5.09-6.41	5.50	No Data	No Data
Cr	172-422	287	BDL	BDL
Cu	20.00-40.00	29.33	6.00-6.01	6.00
Fe	18,850-24,460	21,387	62-170	131
Hg	BDL	BDL	BDL	BDL
K	15,100-20,100	17,816	800-1,200	900
Mn	486-780	589	5.00-28.02	10.91
Mo	2.50-6.22	4.39	BDL	BDL
Na	14,300-16,400	14,950	BDL	BDL
Ni	97-243	164	No Data	No Data
Pb	79-269	162	BDL	BDL
Sb	0.30-0.61	0.44	No Data	No Data
Se	BDL	BDL	BDL	BDL
Si	337,140-371,800	352,930	40.03-40.05	40.04
Sn	30.28-34.73	32.50	No Data	No Data
Sr	210	210	BDL	BDL
Ti	1,850-3,050	2,353	No Data	No Data
V	33.39-46.90	40.06	No Data	No Data
Zn	78-161	104	6.00-50.0	18.3

Table 3.14: Roadside Surface Soil (Test Section) Total Element and Total Available Composition

Element	Total Composition, mg/kg		Total Available Composition, mg/kg	
	Range	Average	Range	Average
Al	55,000-63,300	59,017	20.01-80.05	50.03
As	3.38-4.75	4.05	BDL	BDL
Ba	310-430	385	BDL	BDL
Br	BDL	BDL	BDL	BDL
Ca	6,400-8,400	7,245	80-220	116
Cd	BDL	BDL	BDL	BDL
Cl	68.65-82.12	75.38	200-600	450
Co	3.77-6.29	5.03	No Data	No Data
Cr	199-492	315.70	BDL	BDL
Cu	16.00-23.00	20.33	BDL	BDL
Fe	13,500-24,760	19,825	88-220	138
Hg	BDL	BDL	BDL	BDL
K	15,300-20,800	18,333	600-600	600
Mn	487-720	619.58	3.80-5.60	4.47
Mo	2.90-6.59	4.66	BDL	BDL
Na	14,100-16,200	14,950	BDL	BDL
Ni	92-278	172.30	No Data	No Data
Pb	110-167	131.17	BDL	BDL
Sb	0.26-0.93	0.47	No Data	No Data
Se	BDL	BDL	BDL	BDL
Si	342,400-372,300	360,925	BDL	BDL
Sn	27.74	27.74	No Data	No Data
Sr	180-380	280	BDL	BDL
Ti	1,600-2,250	1,843	No Data	No Data
V	30.26-48.73	36.09	No Data	No Data
Zn	39.44-97.38	61.81	4.00-6.00	5.00

Table 3.15: Roadside Deep Soil Composite Total Element Composition

Element	Total Control Composition, mg/kg	Total Test Composition, mg/kg
Al	71,600	68,900
As	3.78	5.49
Ba	< 360	690
Br	< 23.66	< 11.02
Ca	12,200	10,500
Cd	< 2.78	< 3.54
Cl	250	136
Co	5.37	5.58
Cr	158	183
Cu	< 5.00	< 5.00
Fe	16,100	22,000
Hg	< 5.00	< 5.00
K	16,900	23,700
Mn	610	435
Mo	3.80	6.01
Na	20,200	20,500
Ni	81.24	80.09
Pb	41.00	31.00
Sb	0.13	0.14
Se	< 0.54	< 0.59
Si	345,300	358,500
Sn	No Data	No Data
Sr	< 400.00	< 260.00
Ti	2,860	2,610
V	43.42	38.30
Zn	37.56	35.61

RECYCLED ASPHALT PAVEMENT

Recycled asphalt pavements (RAP) are the by-products of pavement grinding which are either recycled for use as base course material or in formulation and batching of new pavements. The materials evaluated here were from pavement grinding of Rt. 3 during reconstruction as well as from grindings from other locations in Laconia.

Raw data on the total composition of the RAP can be found in Appendix 3 of Volume 2 of this report. The RAP material was also characterized for general background evaluation. The data are shown in Table 3.16. The RAP contains elevated levels of Al, As, Ba, Co, Fe, K, Mn, Mo, Ti, and V relative to the roadside soils. No marked differences can be seen when comparing the control and test RAP samples.

PAVEMENT MICROSCALE MIGRATION

An analysis was performed on Cu, Zn, Al, and Si grate ash particles on portions of cores removed from the test section after 1.25 years of pavement service. Figures 3.7 through 3.10 present diffusion profiles of these respective elements from the grate ash particles into the surrounding bituminous polymer matrix. The diffusion profiles depict the normalized weight percent of the element in question radially from within the metal matrix to the polymer matrix on a scale of microns. Four profiles were taken for each element. Lead particles were not observed in the 20 thin sections that were analyzed.

Similar results were found for the Cu, Zn and Al. The weight percent of the metal decreased significantly from the original detected concentration within the particle to the concentration in the surrounding bituminous binder. This value decreases to near zero normalized weight percent just beyond the interface. Consequently, the diffusion

Table 3.16: RAP Composite Total Element Composition

Element	Total Control Composition, mg/kg	Total Test Composition, mg/kg
Al	77,100	69,800
As	7.15	8.17
Ba	540	560
Br	< 26.72	< 13.99
Ca	8,900	8,400
Cd	< 2.75	< 2.84
Cl	< 200	204
Co	9.40	10.76
Cr	350	395
Cu	< 5.00	< 5.00
Fe	26,000	30,800
Hg	< 5.00	< 5.00
K	23,800	24,300
Mn	840	940
Mo	7.55	6.48
Na	15,200	14,300
Ni	174	198
Pb	32.00	36.00
Sb	0.22	0.21
Se	< 0.59	< 0.63
Si	320,300	334,700
Sn	No Data	No Data
Sr	< 400	< 310
Ti	4,400	3,700
V	93.88	94.93
Zn	55.29	70.43

Figure 3.7: Diffusion Profiles for Cu in Thin Sections A,B,C and X at $t=1.25$ Years

Figure 3.8: Diffusion Profiles for Cu and Zn in Thin Sections B,C,D and F at $t=1.25$ Years

Figure 3.9: Diffusion Profiles for Al in Thin Sections B,C,D and E at $t=1.25$ Years

Figure 3.10: Diffusion Profiles for Si in Thin Sections 2a,2c and Full A at $t=1.25$ Years

profiles are very steep. This is clearly seen for the Cu, Zn, and Al. Occasionally an unclean interface was analyzed causing the diffusion profile to jump up and down before leveling off to low values. This is the case for Section A of the Cu particle seen in Figure 3.7.

The Si particle profiles were not good examples for showing diffusion profiles. This is because a significant amount of silicon naturally exists within the natural aggregate fines ubiquitously mixed in the bitumen, thus making it very difficult to find a smooth, clear interface between the ash glass particle and bitumen.

The methods of Torstenfeld (1986) were used to linearize the diffusion profiles so as to produce an effective diffusion coefficient for molecular diffusion processes occurring at the ash particle/bitumen interface ($D_{e,m}$). Assuming one dimensional diffusion the following equation can describe molecular diffusion from an ash particle into a polymer matrix:

$$\frac{dC}{dt} = \frac{\partial}{\partial x} \left(D_{e,m} \frac{dC}{dx} \right) \quad (20)$$

where C is concentration (moles/m³), t is time (seconds), x is radial distance (m), and $D_{e,m}$ is an effective diffusion coefficient for non-aqueous diffusion (m²/s). Assuming a one dimensional planar source, the solution to Equation 20 is:

$$\frac{C}{M} = \frac{0.5}{\sqrt{\pi D_{e,m} t}} e^{\frac{-x^2}{4D_{e,m} t}} \quad (21)$$

where M is the total amount of diffusing substance per unit area (moles/m²). Equation 21 can be rewritten as:

$$C = 0.5M (\pi D_{e,m} t)^{-0.5} e^{\frac{-x^2}{4D_{e,m} t}} \quad (22)$$

Taking the log of both sides of Equation 22 yields a linear function for a line with a slope and intercept:

$$\log C = \text{constant} - [1/(4 D_{e,m} t)]X^2 \quad (23)$$

If this function is plotted on a log C versus X^2 graph, the slope of the plot is equal to $-1/(4D_{e,m} t)$. From this, a $D_{e,m}$ can be calculated. Diffusion profile data from the interface into the polymer matrix were plotted on a log C versus X^2 plot. Linear regressions were used to fit a straight line to the data. Slopes were used to calculate $D_{e,m}$ values.

Table 3.17 shows the results of the analysis. The values that are shown are in the 10^{-16} to 10^{-17} range, making them 1 to 3 orders of magnitude less diffusive than their counterparts in the monolith leach test where aqueous diffusion in a tortuous monolith is occurring. The observed $D_{e,m}$ values are similar to values reported for molecular diffusion in polymer solids and are considered to be very low diffusivities. They demonstrate a virtual absence of migration from the ash particles into the bituminous monolith.

Table 3.17: Calculated D_{em} Values for Microscale Molecular Diffusion Processes

Ash Particle	Section	Constituent	Correlation Coefficient r	Probability Level P^a	$D_{e,m}$ (m^2/s)
Copper	X	Cu	0.184	0.84	7×10^{-17}
Copper	A	Cu	0.808	0.10^b	6×10^{-16}
Copper	B	Cu	0.749	0.16	7×10^{-17}
Copper	C	Cu	0.851	0.05	7×10^{-17}
Brass	B	Cu	0.729	0.10	5×10^{-17}
Brass	C	Cu	0.510	0.38^b	3×10^{-16}
Brass	D	Cu	0.679	0.10	1×10^{-16}
Brass	F	Cu	0.907	0.10^b	6×10^{-17}
Brass	B	Zn	0.471	0.42	7×10^{-17}
Brass	C	Zn	0.527	0.36^b	7×10^{-16}
Brass	D	Zn	0.827	0.05^b	2×10^{-17}
Brass	F	Zn	0.638	0.60^b	4×10^{-16}
Aluminum	B	Al	0.650	0.20	4×10^{-16}
Aluminum	C	Al	0.878	0.05^b	3×10^{-16}
Aluminum	D	Al	INVALID INTERFACE		
Aluminum	E	Al	0.570	0.37^b	3×10^{-15}
Silicon	2A	Si	0.904	0.05	5×10^{-16}
Silicon	3A	Si	0.657	0.34	4×10^{-16}

^aProbability level that correlation is due to chance.^bOne Outlier Removed

PAVEMENT MACROSCALE MIGRATION

Figures 3.11 through 3.16 present boxplots of element concentrations in the RAP, binder and wearing courses of cores removed from the test and control section slabs after 1.25 years of service. Also included in the plots for reference purposes are the values for the roadside surface soils. The raw data are presented in Appendix 4 of Volume 2 of this report.

The purpose of the macroscale migration experiment was to assess if large scale migration of grate ash constituents from the binder course in the test section simultaneously occurred upwards into the wearing course and downwards into the RAP course. If large scale migration had occurred, then the test section binder and RAP courses would have elevated concentrations relative to their control section counterparts. Student's t-test (Miller and Miller, 1988) was used to compare populations of equal size.

As shown in Table 3.18, there are no significant differences in element concentrations between the test and control RAP courses and wearing courses. Al was the only element to show a significant difference. However, the difference was only unidirectional. If whole scale migration were occurring, it would have to be bidirectional. The microscale migration data show this is not the case. The significant difference represents a Type II error where, at the 95% confidence level, there can be differences 5% of the time. For most elements, there are obvious significant differences between the test and control binder courses because of the presence of the grate ash as a 50% substitute in the test binder course. However, Si, Al and K were higher in the control binder because of the preponderance of these elements in natural aggregates.

Figure 3.11: Boxplots of Ca, Si, Al and Fe in RAP, Binder and Wearing Course Samples at t=1.25 Years

Figure 3.12: Boxplots of Na, Cl, K and Br in RAP, Binder and Wearing Course Samples at t=1.25 Years

Figure 3.13: Boxplots of Cr, Ti, Ni and Co in RAP, Binder and Wearing Course Samples at t=1.25 Years

Figure 3.14: Boxplots of Pb, Cu, Zn and Cd in RAP, Binder and Wearing Course Samples at t=1.25 Years

Figure 3.15: Boxplots of As, Se, V and Sb in RAP, Binder and Wearing Course Samples at $t=1.25$ Years

Figure 3:16: Boxplots of Ba, Sr, and Mo in RAP, Binder and Wearing Course Samples at t=1.25 Years

**Table 3.18 Statistical Evaluation of Element Concentration Differences
In the Various Pavement Courses**

Element	RAP Course		Binder Course		Wearing Course	
	Significant Difference	Higher Value	Significant Difference	Higher Value	Significant Difference	Higher Value
Ca	NSD	-	SD	Test	NSD	-
Si	NSD	-	SD	Control	NSD	-
Al	NSD	-	SD	Control	SD	Test
Fe	NSD	-	SD	Test	NSD	-
Na	NSD	-	SD	Test	NSD	-
Cl	NSD	-	SD	Test	NSD	-
K	NSD	-	SD	Control	NSD	-
Br ^b	-	-	-	-	-	-
Cr	NSD	-	SD	Test	NSD	-
Ti	NSD	-	SD	Test	NSD	-
Ni	NSD	-	SD	Test	NSD	-
Co	NSD	-	SD	Test	NSD	-
Pb	NSD	-	SD	Test	NSD	-
Cu	NSD	-	SD	Test	NSD	-
Zn	NSD	-	SD	Test	NSD	-
Cd ^b	-	-	-	-	-	-
As	NSD	-	NSD	-	NSD	-
Se ^b	-	-	-	-	-	-
V	NSD	-	NSD	-	NSD	-
Sb	NSD	-	SD	Test	NSD	-
Ba	NSD	-	SD	Test	NSD	-
Sr ^b	-	-	-	-	-	-
Sn ^b	-	-	-	-	-	-
Mo	NSD	-	SD	Test	NSD	-

^a SD = significant difference, NSD = no significant difference using Student's t-test (two tailed, 95% probability).

^b All values below detection limits or not enough data to perform calculations.

These data show that no macroscale migration had occurred from the test binder course up into the wearing course or down into the test base course during the 1.25 year study period.

ROAD CORE MONOLITH DIFFUSIONAL LEACHING BEHAVIOR

Tables 3.19 and 3.20 summarize monolithic leaching data for road cores removed from the road at $t=0$ years from the control and test section, respectively. The raw data are presented in tabular form in Appendix 5 of Volume 2 of this report. Figures 3.17 and 3.18 depict the range of pD_e and R values for the road cores from the control and test section, respectively. As shown in the two tables, information is provided on the dominant release behavior for each element, the range of pD_e values seen for the elements exhibiting diffusion-based leaching, the range of chemical retention values, the availability of the element in the monolith, and the cumulative flux (mg/m^2) seen after 64 days of continuous exposure to leachant. In the control section cores, only Ca, Mg and Mn exhibit diffusive leaching behavior while in the test section cores; Ca, Mg, Mn, Si, Na, Zn, Cl, and SO_4^{2-} exhibit diffusive leaching behavior. The observed pD_e values are similar to previously reported values (Whitehead, 1992, de Groot et al., 1990). The most diffusive elements are Cl, Na, Ca, and SO_4^{2-} .

Tables 3.21 and 3.22 summarize monolithic leaching behavior for road cores removed from the road at $t=1.25$ years from the control and test section, respectively. The raw data is presented in tabular form in Appendix 6 of Volume 2 of this report. Figures 3.19 and 3.20 depict the range of pD_e and R values for the road cores from the

Table 3.19: Summary of Elemental Leaching Behavior for Control Road Section Road Cores at t = 0 Years

Element	Release Behavior ^a	pD_e Range (m ² /s)	Chemical Retention Range (unitless)	Availability (mg/kg)	Cumulative Flux Range at Day 64 (mg/m ²)
Al	No Release	-	-	80.1	-
As	D _s	-	-	< 2.00	0.43-2.50
Ba	No Release	-	-	< 2.00	-
B	No Release	-	-	< 100.2	-
Cd	No Release	-	-	< 1.00	-
Ca	D _f	13.8-14.1	8.41-15.9	1,262.1	561.1-728.0
Cr	No Release	-	-	< 2.00	-
Cu	LR	-	-	< 4.01	0.80-20.4
Fe	D _s , D _p	-	-	460.8	33.3-55.3
Pb	LR	-	-	< 1.00	0.68-2.91
Mg	D _f	13.8-14.0	7.90-12.1	100.2	56.1-70.7
Mn	D _f	14.3-14.5	24.9-39.9	72.1	21.6-27.2
Hg	No Release	-	-	< 0.06	-
Mo	No Release	-	-	< 1.00	-
K	No Release	-	-	1,202.0	-
Se	No Release	-	-	< 2.00	-
Si	LR	-	-	100.2	37.4-88.8
Na	No Release	-	-	< 200.3	-
Sr	No Release	-	-	< 20.0	-
Zn	LR	-	-	8.01	8.02-23.3
Cl	No Release	-	-	801.3	-
SO ₄	SW, D _p	-	-	< 200.3	208.1-443.9
Br	LR	-	-	< 200.3	40.1-88.8

^a D_s = dissolution, SW = surface wash-off, D_f = diffusion, D_p = depletion; shown in order of predominance, LR = limited release (less than three data points).

Table 3.20: Summary of Elemental Leaching Behavior for Test Road Section
Road Cores at $t = 0$ Years

Element	Release Behavior ^{a,b}	pD_e Range (m^2/s)	Chemical Retention Range (unitless)	Availability (mg/kg)	Cumulative Flux Range at Day 64 (mg/m^2)
Al	No Release	-	-	161.4	-
As	LR	-	-	< 2.02	0.44
Ba	No Release	-	-	20.2	-
B	No Release	-	-	< 100.9	-
Cd	No Release	-	-	< 1.01	-
Ca	D_f	13.8-14.3	6.83-44.6	7,264.1	2,960.8-5,340.1
Cr	No Release	-	-	< 2.02	-
Cu	LR	-	-	76.7	4.58-4.88
Fe	SW, (D_s, D_p)	-	-	726.4	1.33-154.8
Pb	LR	-	-	50.4	0.71-2.13
Mg	D_f	14.3-14.6	23.1-72.3	383.4	115.4-145.6
Mn	D_f	14.3-15.2	71.0-130.1	88.8	11.7-19.8
Hg	LR	-	-	< 0.06	0.01
Mo	D_s	-	-	< 1.01	1.38
K	No Release	-	-	1,008.9	-
Se	No Release	-	-	< 2.02	-
Si	D_f	14.0-14.2	5.95-32.5	524.6	150.9-230.8
Na	D_f	12.2-12.8	1.00	403.6	843.4-1498.1
Sr	No Release	-	-	20.2	-
Zn	(D_p, D_s) D_p	15.7-15.9	459.1-1046.6	322.8	9.57-24.0
Cl	D_f	12.1-13.4	1.14-7.48	807.1	887.8-2538.4
SO ₄	D_f	12.8-13.5	0.91-6.75	3,430.3	3,950.7-8,212.1
Br	SW	-	-	< 201.8	44.4-188.2

^a D_s = dissolution, SW = surface wash-off, D_f = diffusion, D_p = depletion; shown in order of predominance, LR = limited release (less than three data points).

^b () = no release behavior predominates within brackets.

Figure 3.17: Boxplots of pD_e and R from Control Section Road Cores at $t=0$ Years

Figure 3.18: Boxplots of pD_e and R from Test Section Road Cores at t=0 Years

Table 3.21: Summary of Elemental Leaching Behavior for Control Road Section
Road Cores at $t = 1.25$ Years

Element	Release Behavior ^{a,b}	pD_e Range (m ² /s)	Chemical Retention Range (unitless)	Availability (mg/kg)	Cumulative Flux Range at Day 64 (mg/m ²)
Al	No Release	-	-	40.0	-
As	LR	-	-	< 2.00	0.41-1.73
Ba	No Release	-	-	< 20.0	-
B	No Release	-	-	< 1.00	-
Cd	No Release	-	-	< 1.00	-
Ca	D_f	13.9-14.6	4.75-25.9	1562.0	399.2-649.7
Cr	No Release	-	-	< 2.00	-
Cu	(D_s, D_p)	-	-	< 4.00	20.3-86.1
Fe	$D_p(D_s, D_p)$	14.3-14.8	11.8-33.1	440.6	33.3-57.3
Pb	D_p	-	-	< 1.00	1.73-13.7
Mg	D_f	13.8-14.3	2.95-10.9	100.1	31.9-68.6
Mn	D_f	14.2-14.4	7.30-11.8	66.1	23.6-31.7
Hg	No Release	-	-	< 0.06	-
Mo	No Release	-	-	< 20.0	-
K	No Release	-	-	< 60.8	-
Se	No Release	-	-	< 2.00	-
Si	No Release	-	-	< 140.2	-
Na	LR	-	-	< 200.3	40.4
Sr	No Release	-	-	< 20.0	-
Zn	D_s, D_p	-	-	12.0	30.7-172.5
Cl	LR	-	-	1401.8	40.6-161.4
SO ₄	D_p, D_s, D_f	12.0	0.09	< 200.3	303.0-887.8
Br	LR	-	-	< 200.3	81.2

^a D_s = dissolution, SW = surface wash-off; D_f = diffusion, D_p = depletion; shown in order of predominance, LR = limited release (less than three data points).

^b () = no release behavior predominates within brackets.

Table 3.22: Summary of Elemental Leaching Behavior for Test Road Section
Road Cores at $t = 1.25$ Years

Element	Release Behavior ^{a,b}	pD_e Range (m ² /s)	Chemical Retention Range (unitless)	Availability (mg/kg)	Cumulative Flux Range at Day 64 (mg/m ²)
Al	No Release	-	-	100.5	-
As	No Release	-	-	< 2.01	-
Ba	No Release	-	-	< 20.1	-
B	No Release	-	-	< 100.5	-
Cd	No Release	-	-	< 1.00	-
Ca	D_f	14.0-14.9	6.08-46.4	5,827.3	1,172.2-3,385.5
Cr	No Release	-	-	< 2.01	-
Cu	(D_s, D_p)	-	-	54.2	16.4-124.8
Fe	(D_f, D_s, D_p)	14.4-14.9	13.2-44.4	422.0	12.9-39.3
Pb	D_s, D_p	-	-	28.1	2.87-25.6
Mg	D_f	14.1-14.6	6.30-18.9	221.0	63.7-111.8
Mn	D_f	14.4-14.5	12.5-17.1	46.2	12.5-16.3
Hg	No Release	-	-	< 0.06	-
Mo	No Release	-	-	< 20.1	-
K	No Release	-	-	1406.6	-
Se	No Release	-	-	< 2.01	-
Si	LR	-	-	482.3	35.1-103.8
Na	D_f	13.0	1.00	401.9	233.8-638.8
Sr	No Release	-	-	< 20.1	-
Zn	(D_s, D_p)	-	-	132.6	47.9-443.0
Cl	D_f, D_s	12.6	0.66	< 200.9	212.4-519.0
SO ₄	D_f	13.0-14.2	0.92-14.9	3,215.0	1,104.3-5,269.8
Br	No Release	-	-	< 200.9	-

^a D_s = dissolution, SW = surface wash-off, D_f = diffusion, D_p = depletion; shown in order of predominance, LR = limited release (less than three data points).

^b () = no release behavior predominates within brackets.

Figure 3.19: Boxplots of pD_e and R from Control Section Road Cores at $t=1.25$ Years

Figure 3.20: Boxplots of pD_e and R from Test Section Road Cores at t=1.25 Years

control and test section, respectively. As with the $t=0$ road cores, Ca, Fe, Mg, Mn and SO_4^{2-} are the elements that diffuse out of control cores. Ca, Fe, Mg, Mn, Na, Cl and SO_4^{2-} diffuse out of the test cores.

A significant difference was seen using Student's t-test (95% probability, pooled variances, two tailed comparison) in the pD_e values for Ca in the test cores between $t=0$ years and $t=1.25$ years. A decrease in diffusivity is seen; most likely from increased retention in the monolith. Diffusive leaching behavior was never seen for lead. For all monoliths, lead release was either limited or attributed to surface wash-off. Cumulative fluxes for lead were low ($<25 \text{ mg/m}^2$).

EVALUATION OF THE EFFECTS OF PAVEMENT VOID CHANGE, BITUMINOUS POLYMER AGING AND MICROCRACKING ON MONOLITH DIFFUSIONAL LEACHING BEHAVIOR

Table 3.23 summarizes the pertinent monolith leaching data from the factorial experiment where voids, aging, and microcracking were used as experimental variables. Data include the type of release behavior, the range of pD_e values, the range of R values, the availability of the element in the monolith, and the cumulative flux after 64 days of continuous exposure to leachant. The raw data are presented in tabular form in Appendix 7 of Volume 2 of this report.

The effective diffusion coefficients that were calculated from the experiment are shown in Figure 3.21. Diffusing species with small ionic radii usually were the most diffusive (D_e values of $10^{-12} \text{ m}^2/\text{s}$ or pD_e values of 12). Diffusing species or anions with

Table 3.23: Summary of Elemental Leaching Behavior for the Monolith Leach Test Varying Void Content, Aging, and Microcracking Levels

Element	Release Behavior ^{a,b}	pD_e Range (m ² /s)	Chemical Retention Range (unitless)	Availability (mg/kg)	Cumulative Flux Range at Day 64 (mg/m ²)
Al	D_p, D_s	-	-	221.8	4.28-103.6
As	No Release	-	-	< 2.02	-
Ba	No Release	-	-	20.2	-
B	No Release	-	-	< 100.8	-
Cd	No Release	-	-	< 1.01	-
Ca	D_f, D_s	12.4-14.5	13.1-58.5	7,863.6	2,788.8-21,895.3
Cr	LR	-	-	< 2.02	0.69-886.4
Cu	(SW, D_p) D_f	14.4	406.5	102.8	1.39-36.0
Fe	D_p, D_s, SW, D_f	13.7	74.9	137.1	3.85-196.5
Pb	(D_f, D_s, D_p)	15.6-15.9	279.0-1038.3	98.8	0.41-10.3
Mg	$D_f, (D_s, SW)$	12.8-14.5	11.7-67.9	362.9	81.82-636.6
Mn	$D_f (SW, D_p)$	13.9-15.5	135.1-4229.9	98.8	10.0-78.2
Hg	No Release	-	-	< 0.06	-
Mo	No Release	-	-	< 20.2	-
K	D_p	-	-	1008.1	171.1-1049.3
Se	No Release	-	-	< 2.02	-
Si	D_f, D_s	14.1-15.0	29.6-437.9	766.2	97.2-314.8
Na	D_f	11.0-13.0	1.00	403.3	545.5-5246.5
Sr	LR	-	-	< 40.3	4.28-28.0
Zn	D_p, D_f, D_s, SW	12.2-16.3	4.11-9936.2	221.8	2.10-72.7
Cl	$D_f, (D_s, SW, D_p)$	11.3-13.2	1.40-11.1	806.5	681.9-6925.3
SO ₄	D_f, D_s	11.1-13.5	1.19-6.07	3,629.2	3,682.0-46,448.8
Br	No Release	-	-	< 201.6	-

^a D_s = dissolution, SW = surface wash-off, D_f = diffusion, D_p = depletion; shown in order of predominance, LR = limited release (less than three data points).

^b () = no release behavior predominates within brackets.

pD_e For Various Diffusing Species

R For Various Diffusing Species

Figure 3.21: Boxplots of pD_e and R from Laboratory Monolith Study of Voids, Microcracking, and Aging

larger ionic radii were less diffusive (pD_e values of 12-16). These values are similar to ones reported by de Groot et al. (1990) for asphalt paving blocks where electrostatic precipitator ash was used as mineral filler and for earlier studies by our group using bottom ash but at various substitution levels of 25, 50 and 75% (Eighmy et al., 1992; Whitehead, 1993).

Tables 3.24a and b provide results from the use of ANOVAs to evaluate the effects of voids, microcracking, and aging on tortuosity and effective diffusivity for a mobile constituent such as Na. Also included are interaction terms between the various combinations of variables (e.g. microcracking and aging). Microcracking, aging, and an interaction term between microcracking and aging were the only variables significantly influencing tortuosity. Microcracking only affected Na pD_e values; this was the only element to leach in all the specimens. The microcracking, aging and the interaction term effects were non-linear.

Reactivity (R) values are also shown in Figure 3.21. The values shown are typical for bituminous asphalt systems governed by hydrophobic surfaces where chemical interaction between a diffusing ion and the monolith is less likely. Diffusing species with a small likelihood of sorption or coprecipitation in the matrix exhibit reactivities close to Na. However, species with high sorption or coprecipitation potential, such as Pb, Mn, Zn and Cu, show high values. There were no strong relationships between R and the experimental variables that were tested.

The reported effective diffusion coefficients are 4 to 5 log units smaller than diffusion coefficients of these ions in water. The dramatic reduction is due to the

Table 3.24a: ANOVA Table to Determine the Influence of Microcracking, Aging, and Void Content on Tortuosity

	Effect	Sum of Sq.	d.f.	Ms	F _{calc}	F _{tab}	NSD/SD ^c
Total	-	401,837,744	14	28,702,696	-	-	-
CF	-	158,718,204	1	158,718,204	-	-	-
A(Voids)	-2427.9	11,789,154	1	11,789,154	5.99	6.61	NSD
B(Aging)	-3706.6	27,477,396	1	27,477,396	13.96	6.61	SD
C(Microcr.)	-8286.8	137,3412,80	1	13,7341,280	69.77	6.61	SD
AB ^a	64.3	8,275	1	8,275	0.0042	6.61	NSD
AC ^a	2234.3	9,984,416	1	9,984,416	5.07	6.61	NSD
BC ^a	3582.7	25,671,837	1	25,671,837	13.04	6.61	SD
ABC ^a	-44.8	4,010	1	4,010	0.0020	6.61	NSD
Error		9,843,004	5	1,968,601	1.0	-	-
LOF ^b	2124.4	21,000,168	1	21,000,168	10.67	6.61	SD

Table 3.24b: ANOVA Table to Determine the Influence of Microcracking, Aging, and Void Content on Na pD_e Values

	Effect	Sum of Sq.	d.f.	Ms	F _{calc}	F _{tab}	NSD/SD ^c
Total	-	2,030.8	14	145.6	-	-	-
CF	-	2,025.6	1	2,025.6	-	-	-
A(Voids)	-0.275	0.151	1	0.151	1.03	6.61	NSD
B(Aging)	-0.325	0.211	1	0.211	1.43	6.61	NSD
C(Microc.)	-1.425	4.061	1	4.061	27.63	6.61	SD
AB ^a	-0.125	0.031	1	0.031	0.211	6.61	NSD
AC ^a	-0.025	0.00125	1	0.00125	0.0085	6.61	NSD
BC ^a	0.125	0.031	1	0.031	0.211	6.61	NSD
ABC ^a	0.025	0.00125	1	0.0125	0.0085	6.61	NSD
Error		0.735	5	0.147	1.0	-	-
LOF ^b	-0.0063	0.000187	1	0.000187	6.61	NSD	SD

^aInteraction terms for the variables A,B,C.

^bLOF = lack of fit.

^cNSD = no significant difference, SD = significant difference at 95% confidence level.

difficulties associated with ion diffusion in a bituminous polymer matrix where pathways are highly tortuous and reaction sites on ash particles can interrupt the diffusion process.

As shown in Figures 3.22 and 3.23, monolith void content and bitumen aging had little influence on monolith tortuosity or diffusion pathlength. However, in agreement with the results from ANOVA analysis, the presence of microcracking dramatically reduced tortuosity (τ) values by reducing diffusion pathlength (Figure 3.24).

The pD_e values are dependent on both τ and R . Given the large τ values and the relatively low R values, it is apparent that the high degree of tortuosity provided by asphalt accounts for the very low fluxes occurring from such specimens. The maintenance of monolithic integrity is therefore one consideration for keeping fluxes of grate ash constituents at very low levels.

EVALUATION OF GRAIN SIZE AND THE PRESENCE OF BITUMINOUS ASPHALT CEMENT ON GRANULAR DIFFUSIONAL LEACHING BEHAVIOR

Table 3.25 summarizes the granular leaching behavior of ash constituents.

Appendix 8 in Volume 2 of this report provides the complete data tables. The type of release behavior, the range of pD_e values, the range of chemical retention values, the range of availability and the cumulative flux ranges at day 64 are shown in the table.

Figure 3.25 depicts the pD_e and R values in scatter plot form.

The data show that for granular materials, chemical retention becomes a much more dominant factor than tortuosity in controlling release. Tortuosity (τ) is reduced when monoliths are converted to granular forms (Figure 3.26). This occurs because crushing removes the hydrophobic tortuous monolithic control (thus reducing tortuosity)

Figure 3.22: Influence of Voids on Tortuosity in Monolith Diffusional Leaching

Figure 3.23: Influence of Aging on Tortuosity in Monolith Diffusional Leaching

Figure 3.24: Influence of Microcracking on Tortuosity in Monolith Diffusional Leaching

Table 3.25: Summary of Elemental Leaching Behavior for the Granular Diffusion Leaching Test

Element	Release Behavior ^{a,b}	pD_e Range (m ² /s)	Chemical Retention Range (unitless)	Availability Range (mg/kg)	Cumulative Flux Range at Day 64 (mg/m ²)
Al	LR	-	-	221.7-405.4	106.0
As	No Release	-	-	<2.02-<2.03	-
Ba	No Release	-	-	20.1-60.8	-
B	No Release	-	-	<100.8-<101.3	-
Cd	LR	-	-	<1.01-1.82	4.24
Ca	D _f	12.1-12.9	58.5-230.8	7,860.4-14,999.1	11,031.2-48,859.1
Cr	No Release	-	-	<2.02-<2.03	-
Cu	D _p	-	-	102.8-283.08	31.0-387.0
Fe	LR	-	-	608.1-1370.5	21.2-31.8
Pb	D _s ,D _f	13.3	3,857.7	98.8-101.3	3.10-45.6
Mg	D _p ,D _s	11.0-12.9	9.55-109.2	362.8-547.3	420.2-6785.1
Mn	D _p ,D _s ,D _p	13.6-14.1	3,755.5-5,966.6	98.8-119.6	3.00-70.5
Hg	No Release	-	-	< 0.06	-
Mo	No Release	-	-	<20.1-<20.3	-
K	LR	-	-	1,007.7-1,621.5	3,180.5-5,404.8
Se	No Release	-	-	<2.02-<2.03	-
Si	No Release	-	-	765.9-1216.1	-
Na	D _f	9.63-10.8	1.00	403.1-810.8	4,801.9-25,974.6
Sr	No Release	-	-	<40.3-40.5	-
Zn	(D _p ,D _s ,D _p)	13.2-13.8	610.6-8,725.4	221.7-668.9	68.2-805.7
Cl	(D _p ,D _p),D _s	10.5-11.1	3.08-4.33	806.2-1,418.8	5,577.6-38,696.1
SO ₄	D _f	10.5-11.4	2.59-7.12	362.9-5,472.7	30,056.9-112,908.0
Br	LR	-	-	<201.5-<202.7	619.7-3,180.5

^a D_s = dissolution, SW = surface wash-off, D_f = diffusion, D_p = depletion; shown in order of predominance, LR = limited release (less than three data points).

^b () = no release behavior predominates within brackets.

Figure 3.25: Boxplots of (a) Effective Diffusion Coefficients and (b) Chemical Retention of Samples From the Granular Diffusion Test

Figure 3.26: Influence of Particle Size and the Presence of Asphalt Cement on Tortuosity in Granular Diffusional Leaching

while increasing ash particle surface area (the increasing reactive site availability). A comparison of pD_e values between all grate ash monolith leaching data and granular leaching data shows that the elements Ca and Mn had similar pD_e values. These elements are reactive and tend to sorb easily. The elements Na, SO_4^{2-} , and Cl had modest reductions of pD_e values (1 to 3 log units) during granular leaching. These elements are conservative and do not sorb. The elements Zn, Mg, and Pb also had modest reductions in pD_e values (1 to 3 log units). These elements are also reactive, but less than Ca and Mn. The presence of asphalt cement appears to still control leaching behavior, but to a lesser degree than when in monolith form. Ash grain size, in the absence of bituminous asphalt, has a limited effect on diffusional leaching behavior in the granular diffusion test.

BROKEN PAVEMENT AND BOTTOM ASH LYSIMETER LEACHING

In the earlier characterization study (Eighmy et al., 1992), outdoor field lysimeters were built to evaluate field leaching behavior of bottom ash in pile form under a percolation (advection) scenario and pavements made with bottom ash in a field disposal scenario where diffusion is still the dominant leaching process. These data are included in this report because of their applicability regarding diffusional leaching and leaching behavior.

The field lysimeter compositional data for leachates (bottom ash and bottom ash/aggregate/asphalt) collected from November, 1990 through November, 1994 are provided in Appendix 9 of Volume 2 of this report. Table 3.26 summarizes the leaching behavior

Table 3.26: Summary of Leachate Characteristics of Bottom Ash and Bottom Ash/Aggregate/Asphalt from Outdoor Lysimeters

Parameter	Range of Values	
	Bottom Ash	Bottom Ash/Asphalt
L/S	0.082-1.846	0.262-5.872
pH	6.21-8.12	6.94-7.96
Alkalinity (mg/L as CaCO ₃)	29.0-159.60	21.3-100.7
Conductivity (μmhos/cm)	2,205-8,855	71-517
COD (mg/L)	8.0-400.0	15-55
Total Phenols (μg/L)	<10-<50	<10-<50
NH ₄ ⁺ -N (mg/L)	0.07-16.0	0.06-0.65
NO ₃ ⁻ -N (mg/L)	<0.05-3.70	<0.05-0.08
NO ₂ ⁻ -N (mg/L)	<0.05-<0.50	<0.05-0.06
Cl ⁻ (mg/L)	30-1,800	4-42
SO ₄ ²⁻ (mg/L)	780-3,000	16-720
Br ⁻ (mg/L)	<1-30	<1-4.7
PO ₄ ³⁻ (mg/L)	<0.01-0.67	<0.01-0.38
Al (mg/L)	0.02-0.16	<0.10
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.50-4.4	<0.50
Ba (mg/L)	<0.10-0.15	<0.10
Ca (mg/L)	500-1,100	14-120
Cd (mg/L)	<0.0005-0.011	<0.005-0.0014
Cr (mg/L)	<0.01	<0.01-0.18
Cu (mg/L)	<0.02-0.59	<0.02-0.25
Fe (mg/L)	<0.03-15.0	<0.03-3.90
Hg (mg/L)	<0.0003-0.0006	<0.0003
K (mg/L)	36-220	<3-9
Mg (mg/L)	6.5-170	1.2-13

Table 3.26: Summary of Leachate Characteristics of Bottom Ash and Bottom Ash/Aggregate/Asphalt from Outdoor Lysimeters (Continued)

Parameter	Range of Values	
	Bottom Ash	Bottom Ash/Asphalt
Mn (mg/L)	0.16-2.70	0.020-1.10
Mo (mg/L)	<0.10-0.34	<0.10
Na (mg/L)	100-800	5.6-32
Pb (mg/L)	<0.005-0.028	<0.005-0.05
Se (mg/L)	<0.01-<0.02	<0.01
Si (mg/L)	1.4-5.0	1.2-6.0
Sr (mg/L)	1.7-4.4	<0.10-<0.50
Zn (mg/L)	<0.02-0.085	<0.02-0.08

that occurred over the four year period by showing the range of values obtained for each analyte.

Calcium, SO_4^{2-} , Cl, Na, K, alkalinity, and COD leached in the greatest concentrations from both lysimeter systems. NH_4^+-N , Br^- , $\text{PO}_4^{3-}-\text{P}$, B, Fe, Mg, Mn, Sr, and Si leached, but at much lower levels. The beneficial encapsulating effect of the asphalt cement is documented by the low levels of salts and other elements which leached from the bottom ash/aggregate/asphalt lysimeter. Figures 3.27 through 3.32 illustrate the concentrations leached over time for both lysimeters for the parameters Ca, Cl, K, SO_4^{2-} , Na, and Pb. These analytes were selected because of their discussion and use later in the report. Concentrations for Ca and SO_4^{2-} tend to peak in the summer months of May, June, July, and August and decrease during the fall months. This could be related to temperature effects on dissolution of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). In addition, initial concentrations of the soluble salts Na, K, and Cl from bottom ash leachate decreased significantly over time. This is due to surface wash-off of these soluble phases from the bottom ash with the first contact with percolation. This initial wash-off does not occur with the bottom ash/aggregate/asphalt because of the encapsulating effect of the bituminous polymer.

Figures 3.33 through 3.38 illustrate unified leaching plots for Ca, Cl, K, SO_4^{2-} , Pb, and Na. The cumulative amount of the constituent released (in mg/kg dry bottom ash) is shown in relation to the cumulative L/S ratio over the four years. The plots normalize release to the amount of bottom ash present; removing the diluting effect of asphalt cement and aggregate from the pavement materials. The plots also use the detection

Figure 3.27: Ca Concentrations in Bottom Ash and Bottom Ash/Aggregate/Asphalt Leachates Over Time from the Outdoor Lysimeters

Figure 3.28: Cl Concentrations in Bottom Ash and Bottom Ash/Aggregate/Asphalt Leachates Over Time from the Outdoor Lysimeters

Figure 3.29: K Concentrations in Bottom Ash and Bottom Ash/Aggregate/Asphalt Leachates Over Time from the Outdoor Lysimeters

Figure 3.30: SO_4^{2-} Concentrations in Bottom Ash and Bottom Ash/Aggregate/Asphalt Leachates Over Time from the Outdoor Lysimeter

Figure 3.31: Na Concentrations in Bottom Ash and Bottom Ash/Aggregate/Asphalt Leachates Over Time from the Outdoor Lysimeters

Figure 3.32: Pb Concentrations in Bottom Ash and Bottom Ash/Aggregate/Asphalt Leachates Over Time from the Outdoor Lysimeters

Figure 3.33: Ca Cumulative Release Plots from Bottom Ash and Bottom Ash/
Aggregate/Asphalt as a Function of Cumulative L/S from the Outdoor
Lysimeter

Figure 3.34: CI Cumulative Release Plots from Bottom Ash and Bottom Ash/
Aggregate/Asphalt as a Function of Cumulative L/S from the Outdoor
Lysimeters

Figure 3.35: K Cumulative Release Plots from Bottom Ash and Bottom Ash/
Aggregate/Asphalt as a Function of Cumulative L/S from the Outdoor
Lysimeters

Figure 3.36: SO_4^{2-} Cumulative Release Plots from Bottom Ash and Bottom Ash/Aggregate/Asphalt as a Function of Cumulative L/S from the Outdoor Lysimeters

Figure 3.37: Na Cumulative Release Plots from Bottom Ash and Bottom Ash/Aggregate/Asphalt as a Function of Cumulative L/S from the Outdoor Lysimeters

Figure 3.38: Pb Cumulative Release Plots from Bottom Ash and Bottom Ash/Aggregate/Asphalt as a Function of Cumulative L/S from the Outdoor Lysimeters

limit value when actual measurements were below detection. The total elemental and total available concentrations (mg/kg dry bottom ash) are shown as benchmark asymptotes for each plot. A total elemental concentration asymptote is not shown for sulfate because this measure was never determined. Bottom ash leachate release is greater by factors of 10 to 100 than release from the pavement for all elements except lead. No constituent release reaches the total available asymptote over the range of cumulative L/S values that were observed. The lead data are confounded by the fact that most of the data points are below detection limit (<0.005 mg/L) for the pavement lysimeter. Because of the normalization to the bottom ash present in the lysimeter, the pavement value increases more dramatically. In fact, only 35 mg of Pb has been released from the 7,239 kg of pavement material from the pavement lysimeter and 28 mg has been released from the 4,591 kg of bottom ash material from the bottom ash lysimeter over the four year period.

MODELING CONSTITUENT FLUXES FOR VARIOUS TIME PERIODS AND DEGREES OF WETTING

One of the inherent benefits towards using the monolith diffusion or granular diffusion leaching tests to evaluate the environmental behavior of waste materials in products is the ability to predict potential fluxes from the monolith surface for constituents in the monolith exhibiting diffusive leaching behavior.

The monolithic leaching scenarios depicted in Figures 1.6 and 1.7 are based on complete, continuous immersion in the leachant solution for 64 days. The fluxes that are measured for diffusing species result because the diffusing constituents, upon reaching

the monolith/water interface, can quickly diffuse away into the "infinite" volume represented by the leachant. While this behavior does allow for modeling of constituent fluxes from the monolith, it does not completely predict the real behavior of the monolith in the field.

Consider the schematic shown in Figure 3.39. A number of pavement scenarios are depicted; a new pavement, a moderately aged pavement, an aged pavement, and a pavement that has been granularized and converted back into a compacted base course pavement made with RAP. In all cases, grate ash is present in the materials. In all cases, precipitation cannot readily infiltrate through the various intact pavement courses above the layers containing grate ash.

The modeling of cumulative release from the asphalt monoliths or asphalt granular material can be used to predict what flux would occur at the interface between the grate ash-containing binder course and the grate ash-containing RAP/soil base course, or the RAP/soil interface. The wetting that would occur at the interface would be ephemeral. Vadose zone moisture would condense at the interface whenever the binder course or RAP temperature was cool enough to allow condensation to form. This could occur during part of a diurnal cycle (early morning), or during part of the seasonal cycles (Spring, Fall). Once water condensed at the interface, migration of water, via diffusion, into the binder course or RAP would commence. Diffusion of constituents to the interface would then follow. The migration of diffusing constituents into the ephemeral water layer would occur whenever condensate was present at the interface.

Figure 3.39: Schematic Depicting the Potential for Constituent Fluxes from the Lower Pavement Surface and Subsequent Attenuation of Those Constituents

Increased microcracking would provide for voids allowing for capillarity to increase the wetting time at the interface.

While these phenomena at the interface can be modeled using Equation 16 in Chapter 1, the modeling neglects a number of important phenomena that will occur in the RAP/soil base course, the soil subbase, and the native soils in the vadose zone above the water table which profoundly influence whether the contaminants will ever reach the water table. Consider the nature of the ephemeral soil water in these layers. It will be present as a function of soil porosity (capillarity), water vapor pressure, and soil particle temperature. It is quite likely that this ephemeral layer is also present on a diurnal or semi-seasonal basis. These condensed layers may not be contiguous. For migration to occur from the interface along a diffusion gradient downwards to the water table, a diffusion path must be present. However, this path is tortuous, and non-contiguous. Background contamination in the RAP and subbase soils may diminish or reverse any diffusional gradient that is present.

For conservative constituents such as chloride, the opportunity for attenuation is minimal. However, the fluxes coming from the interface would be so small as to make their measurements difficult to quantify in the field. For reactive constituents such as lead and zinc, the opportunity for attenuation is great. Soil oxyhydroxide surfaces (FeOOH , $\alpha\text{-Al}_2\text{O}_3$, hydrous MnO_2), clays, and soil organic carbon provide a virtually infinite supply of sorption sites for lead and zinc to react at between the interface and the ground water table (EPRI, 1984; Sposito, 1989; McBride, 1994). Additionally, lead and zinc can precipitate out on the soil particle surface.

Recent work by the Netherlands Energy Research Foundation has shown that the soil interface is highly reactive for metals diffusing out of a granular pile of grate ash. The pile has been in place for 15 years. While chloride can migrate downwards via percolation, lead is accumulated in the top few centimeters of native soil below the pile (Kosson et al., 1995; van der Sloot and Hoede, 1994a,b). One would expect similar behavior, but on a much smaller scale, for the situation depicted in Figure 3.39.

With the above mentioned caveats, diffusional leaching parameters and equation 16 in Chapter 1 were used to model leaching behavior for five scenarios: (i) a new road at the beginning of its service life based on road core monolith leaching data, (ii) a new road at the beginning of its service life based on laboratory monolith leaching data, (iii) a moderately aged road at the middle to end of its service life using laboratory monolith leaching data, (iv) an aged road past the end of its service life using laboratory monolith leaching data and (v) a road comprised of a compacted RAP base course (derived from the reuse of a grate ash binder course) using granular diffusion leaching data.

For each scenario, three timeframes were used to model cumulative release during that timeframe: 1.50 years (the duration of the present study), 20 years (the expected service life of the road, corresponding to the year 2013), and 100 years (a reference point).

For each timeframe for each scenario, three wetting conditions at the interface were used: 5, 10 and 20%. These are a range of reasonable estimates for a road binder course covered by an impermeable wearing course and a RAP base course covered by traditional pavement courses subjected to periodic condensation. These percent wetting

values are estimates and would require field verification. In all cases, the output of the modeling effort is cumulative flux (g/m^2) at the interface for the indicated timeframe.

The modeling effort is summarized in Table 3.27. The summary includes only the 10% wetting scenario for the various timeframes. The remaining wetting scenarios (5%, 20%) are presented in tables in Appendix 10 of Volume 2 of this report.

The data shown in Table 3.27 indicate that the fluxes that could be expected to occur at the interface are quite low for the constituents that could be modeled because of their diffusive behavior (Ca, Cl, Fe, Mg, Mn, Na, Pb, Si, SO_4^{2-} , Zn). The data presented for Pb are used for comparison only; very little diffusive leaching behavior was seen for Pb.

For the new road scenario, using cores from both the test and control sections, modeled cumulative fluxes at the interface ranged from none (Pb) to $4.34 \text{ g}/\text{m}^2$ (SO_4^{2-}) over the 1.5 year period. In some instances, fluxes at the interface from the control road interface were higher than the test road (Fe, Mn). In others (Ca, Cl, Mg, Na, Si, SO_4^{2-} , Zn), the opposite was true.

For the new road scenario, using laboratory monoliths from the voids, microcracking and aging study, modeled cumulative fluxes at the interface ranged from none (Cl, Na, Si, Zn) to $1.18 \text{ g}/\text{m}^2$ (SO_4^{2-}) over the 1.5 year timeframe.

For the moderately aged road scenario, using laboratory monoliths from the voids, microcracking, and aging study, modeled cumulative fluxes at the interface ranged from none (Fe, Pb, Zn) to $14.99 \text{ g}/\text{m}^2$ (Cl) for the 20 year timeframe.

Table 3.27: Modeled Cumulative Release at the Binder/Soil Interface and RAP/Soil Interface for Various Road Scenarios and Times

Scenario (Modeling Timeframe)	Monolith and Granular Leach Test Samples Used for Modeling	Cumulative Release at Interface for 10% Wetting										
		Constituent	Ca	Cl	Fe	Mg	Mn	Na	Pb ^a	Si	SO ₄ ²⁻	Zn
		Units	g/m ²	g/m ²	g/m ²	g/m ²	g/m ²	g/m ²	g/m ²	g/m ²	g/m ²	g/m ²
New Road (t=1.5 years)	Road Cores from Test Section Road Cores from Control Section (t=0 & 1.25 years)		2.93	2.00	0.12	0.11	0.02	1.13	-	0.24	4.34	0.02
			0.77	^b	0.15	0.06	0.03	-	-	-	1.18	-
New Road (t=1.5 years)	Laboratory Monoliths (Voids=10%, Microcracking=L, Aging=L)		2.70	1.74	0	0.11	0.01	0.78	0.03	0.15	3.94	-
Moderately Aged Road (t=20 years)	Laboratory Monoliths (Voids=7.5%, Microcracking=M, Aging=M)		41.69	14.99	-	1.18	0.10	10.04	-	0.93	63.9	-
Aged Road (t=20 years)	Laboratory Monoliths (Voids=5%, Microcracking=H, Aging=H)		60.18	24.57	-	1.39	0.19	13.79	-	1.04	98.5	-
RAP Road (t=100 years)	Granular Diffusion (<3/4" with 7% Asphalt Cement)		96.90	73.80	-	4.21	-	59.64	-	-	269	-

^aBased on very limited diffusional leaching data.^bNo diffusion observed.

For the aged road scenario, using laboratory monoliths from the voids, microcracking, and aging study, modeled cumulative fluxes at the interface ranged from none (Fe, Pb, Zn) to 98.5 g/m² (SO₄²⁻) for the 20 year timeframe.

For the RAP base course road scenario, using granular diffusion test samples comprised of <3/4" (1.9 cm) grate ash pavement materials, modeled cumulative fluxes at the interface ranged from none (Fe, Mn, Pb, Si, Zn) to 269 g/m² (SO₄²⁻) over the 100 year timeframe.

While these data are illustrative of the range of fluxes that could occur at the interface for timeframes of interest, they do not model any subsequent attenuation in the RAP/soil, subbase soil, or native soil below the road. Given the extremely low driving gradients and the high background signals of preexisting Pb, Cl, SO₄²⁻, and other contaminants, it is highly likely that conservative constituents such as Na, Cl and SO₄²⁻ will not readily migrate to the groundwater table. It is even more likely that reactive constituents such as Ca, Fe, Mg, Mn, Pb, Si, and Zn will remain very close to the interface and not migrate at all.

WATER QUALITY DATA

The complete set of ground water, surface water, suction lysimeter, and road runoff water quality is presented in Appendix 11 of Volume 2 of this report. For presentation purposes, the data from each of the sampling locations (including monitoring wells [MW] and surface water [SW] stations) has been summarized in Tables 3.28 through 3.39 for the dug well, MW 1, MW 2, MW 3, MW 4, MW 5, the test section

Table 3.28: Water Quality Data for the Dug Well

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	5.9-15.0
pH	-	6.82-7.11
Alkalinity (mg/L as CaCO ₃)	-	35-50
Conductivity (μmhos/cm)	-	140-158
NO ₃ ⁻ -N (mg/L)	0.43-2.10	0.17-1.40
NO ₂ ⁻ -N (mg/L)	<0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.10	<0.05-1.40
SO ₄ ²⁻ (mg/L)	8	7-8
PO ₄ ³⁻ -P (mg/L)	0.02-0.13	<0.01-0.08
Br ⁻ (mg/L)	<1	<1-6
Cl ⁻ (mg/L)	14-19	12-24
TOC (mg/L)	<1-1.0	<1-3
COD (mg/L)	7	-
Total Phenols (μg/L)	<10	<10-12
VOCs (μg/L)	None	None
BN/As (μg/L)	None	None
Ag (mg/L)	<0.02	-
Al (mg/L)	0.40	0.3-3.9
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.50	<0.05
Ba (mg/L)	<0.10	<0.1-0.20
Ca (mg/L)	18-27	15-24
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	0.02	<0.01
Cu (mg/L)	<0.01-0.02	<0.02
Fe (mg/L)	0.52-0.99	0.88-14
Hg (mg/L)	<0.0003	<0.0003

Table 3.28: Water Quality Data for the Dug Well (Continued)

Parameter	Prepaving Range	Postpaving Range
K (mg/L)	<3	<3-3
Mg (mg/L)	1.4-1.5	1.3-2.8
Mn (mg/L)	0.033-0.051	0.009-0.16
Mo (mg/L)	<0.10	<0.10
Na (mg/L)	14-19	12-22
Pb (mg/L)	<0.005	<0.005-0.038
Se (mg/L)	<0.01	<0.01
Si (mg/L)	6.00	4.7-7
Sr (mg/L)	<0.10	<0.10-0.10
Zn (mg/L)	0.28-0.37	0.43-2.40

Table 3.29: Water Quality Data for Monitoring Well 1

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	5.3-15
pH	-	6.70-6.83
Alkalinity (mg/L as CaCO ₃)	-	29-32
Conductivity (μmhos/cm)	-	125-199
NO ₃ ⁻ -N (mg/L)	1.8-1.9	2.1-4.2
NO ₂ ⁻ -N (mg/L)	<0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.07	<0.05-0.14
SO ₄ ²⁻ (mg/L)	10-11	8-10
PO ₄ ³⁻ -P (mg/L)	<0.02-1.5	<0.01-0.30
Br ⁻ (mg/L)	<1	<1
Cl ⁻ (mg/L)	17-21	20-26
TOC (mg/L)	3	1-3
COD (mg/L)	46	-
Total Phenols (μg/L)	<10	<10
VOCs (μg/L)	Trace chloroform	None
BN/As (μg/L)	None	None
Ag (mg/L)	<0.02	-
Al (mg/L)	19	7.4-16
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.05	<0.5
Ba (mg/L)	<0.10-0.10	<0.10-0.10
Ca (mg/L)	12-22	14-24
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	<0.01	<0.01
Cu (mg/L)	<0.02-0.03	<0.02
Fe (mg/L)	2.7-11	2.7-4.9
Hg (mg/L)	<0.0003	<0.003

Table 3.29: Water Quality Data for Monitoring Well 1 (Continued)

Parameter	Prepaving Range	Postpaving Range
K (mg/L)	4	4-5
Mg (mg/L)	2-3.8	2-2.7
Mn (mg/L)	0.15-0.40	0.14-0.33
Mo (mg/L)	<0.1	<0.1
Na (mg/L)	20	17-21
Pb (mg/L)	<0.005-0.020	0.007-0.020
Se (mg/L)	<0.01	<0.01
Si (mg/L)	14	8-56
Sr (mg/L)	<0.10	<0.10
Zn (mg/L)	0.03-0.11	<0.02-0.03

Table 3.30: Water Quality Data for Monitoring Well 2

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	5.4-16
pH	-	6.53-6.68
Alkalinity (mg/L as CaCO ₃)	-	25-29
Conductivity (μmhos/cm)	-	134-150
NO ₃ ⁻ -N (mg/L)	2.3-2.5	1.8-2.4
NO ₂ ⁻ -N (mg/L)	<0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.09	<0.05-0.13
SO ₄ ²⁻ (mg/L)	8	6-9
PO ₄ ³⁻ -P (mg/L)	<0.02-1.5	<0.01-0.11
Br ⁻ (mg/L)	<1	<1-14
Cl ⁻ (mg/L)	15-24	13-33
TOC (mg/L)	2-3	1-3
COD (mg/L)	<5	-
Total Phenols (μg/L)	<10	<10
VOCs (μg/L)	trace, trimethylsilanol	None
BN/As (μg/L)	None	None
Ag (mg/L)	<0.02	-
Al (mg/L)	11	4.9-17
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.50	<0.50
Ba (mg/L)	<0.10	<0.1-0.10
Ca (mg/L)	12-15	13-24
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	<0.01	<0.01
Cu (mg/L)	<0.02	<0.02-0.03
Fe (mg/L)	1.3-3.9	2.9-6.4
Hg (mg/L)	<0.0003	<0.0003

Table 3.30: Water Quality Data for Monitoring Well 2 (Continued)

Parameter	Prepaving Range	Postpaving Range
K (mg/L)	<3-4	4-6
Mg (mg/L)	1.8-2.6	2.3-3.2
Mn (mg/L)	0.033-0.36	0.12-0.68
Mo (mg/L)	<0.10	<0.10
Na (mg/L)	12-18	10-21
Pb (mg/L)	<0.005-0.011	<0.005-0.020
Se (mg/L)	<0.01	<0.01
Si (mg/L)	6	8.2-50
Sr (mg/L)	<0.10	<0.1-0.10
Zn (mg/L)	<0.02-0.05	<0.02-0.03

Table 3.31: Water Quality Data for Monitoring Well 3

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	5.6-15.5
pH	-	5.26-5.75
Alkalinity (mg/L as CaCO ₃)	-	7-10
Conductivity (μmhos/cm)	-	785-1,520
NO ₃ ⁻ -N (mg/L)	0.93-1.30	0.38-0.87
NO ₂ ⁻ -N (mg/L)	0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.06	<0.05-0.13
SO ₄ ²⁻ (mg/L)	68-76	61-88
PO ₄ ³⁻ -P (mg/L)	<0.02-0.44	<0.01-0.03
Br ⁻ (mg/L)	<1	<1-7
Cl ⁻ (mg/L)	170-260	210-390
TOC (mg/L)	<1	<1-5
COD (mg/L)	7	-
Total Phenols (μg/L)	<10	<10-22
VOCs (μg/L)	Trace, trimethylsilanol	None
BN/As (μg/L)	None	Trace, Diethylphthalate
Ag (mg/L)	<0.02	-
Al (mg/L)	3.2	1.2-22
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.50	<0.50
Ba (mg/L)	<0.10-0.10	<0.1-0.9
Ca (mg/L)	22-24	22-86
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	<0.01-0.03	<0.01-0.37
Cu (mg/L)	<0.02	<0.02-0.26
Fe (mg/L)	0.53-1.60	0.65-30
Hg (mg/L)	<0.0003	<0.0003

Table 3.31: Water Quality Data for Monitoring Well 3 (Continued)

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Parameter	Prepaving Range	Postpaving Range
K (mg/L)	4	4-7
Mg (mg/L)	8-9.8	8.8-22
Mn (mg/L)	0.81-1.5	0.95-3.20
Mo (mg/L)	<0.10	<0.10
Na (mg/L)	150-230	130-220
Pb (mg/L)	<0.005	<0.005-0.05
Se (mg/L)	<0.01	<0.01
Si (mg/L)	13	15-35
Sr (mg/L)	<0.10	0.2-0.4
Zn (mg/L)	0.20-0.21	0.16-0.63

Table 3.32: Water Quality Data for Monitoring Well 4

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	5.9-16
pH	-	6.61-6.78
Alkalinity (mg/L as CaCO ₃)	-	55-68
Conductivity (μmhos/cm)	-	750-900
NO ₃ ⁻ -N (mg/L)	<0.05	<0.05
NO ₂ ⁻ -N (mg/L)	<0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.08	<0.05-0.17
SO ₄ ²⁻ (mg/L)	53-56	42-61
PO ₄ ³⁻ -P (mg/L)	<0.02-0.12	<0.01-0.04
Br ⁻ (mg/L)	<1	<1-5
Cl ⁻ (mg/L)	120-190	150-220
TOC (mg/L)	<1	<1-3
COD (mg/L)	14	-
Total Phenols (μg/L)	<10-45	<10
VOCs (μg/L)	Trace, trimethylsilanol	None
BN/As (μg/L)	None	None
Ag (mg/L)	<0.02	-
Al (mg/L)	0.10	<0.10-1.2
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.05	<0.05
Ba (mg/L)	0.10	0.10-0.20
Ca (mg/L)	45	44-62
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	<0.01-0.01	<0.01
Cu (mg/L)	<0.02	<0.02-0.03
Fe (mg/L)	10-12	15-26
Hg (mg/L)	<0.0003	<0.0003

Table 3.32: Water Quality Data for Monitoring Well 4 (Continued)

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Parameter	Prepaving Range	Postpaving Range
K (mg/L)	<3	<3-3
Mg (mg/L)	13-14	11-16
Mn (mg/L)	0.65-0.74	0.71-1.0
Mo (mg/L)	<0.10	<0.10
Na (mg/L)	66-89	77-110
Pb (mg/L)	<0.005	<0.005-0.018
Se (mg/L)	<0.01	<0.01
Si (mg/L)	14	10-14
Sr (mg/L)	<0.10	0.3-0.4
Zn (mg/L)	<0.02-0.04	0.03-0.08

Table 3.33: Water Quality Data for Monitoring Well 5

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	6.1-15.5
pH	-	6.52-6.73
Alkalinity (mg/L as CaCO ₃)	-	48-64
Conductivity (μmhos/cm)	-	800-900
NO ₃ ⁻ -N (mg/L)	<0.05	<0.05-0.06
NO ₂ ⁻ -N (mg/L)	<0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.12	<0.05-0.13
SO ₄ ²⁻ (mg/L)	58-60	58-84
PO ₄ ³⁻ -P (mg/L)	<0.02-0.43	<0.01-0.03
Br ⁻ (mg/L)	<1	<1-12
Cl ⁻ (mg/L)	140-200	180-250
TOC (mg/L)	<1	<1-3
COD (mg/L)	<5	-
Total Phenols (μg/L)	<10-20	<10-22
VOCs (μg/L)	None	None
BN/As (μg/L)	None	None
Ag (mg/L)	-	-
Al (mg/L)	1.80	0.9-7.2
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.50	<0.50
Ba (mg/L)	0.10	0.1-0.2
Ca (mg/L)	44-48	50-62
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	<0.01-0.02	<0.01
Cu (mg/L)	<0.02-0.03	<0.02-0.09
Fe (mg/L)	7.7-12	11-44
Hg (mg/L)	<0.0003	<0.0003

Table 3.33: Water Quality Data for Monitoring Well 5 (Continued)

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Parameter	Prepaving Range	Postpaving Range
K (mg/L)	3-4	4-5
Mg (mg/L)	8.90	9.3-12
Mn (mg/L)	0.68-0.95	0.82-1.40
Mo (mg/L)	<0.10	<0.10
Na (mg/L)	89-96	93-130
Pb (mg/L)	<0.005-0.014	0.007-0.050
Se (mg/L)	<0.01	<0.01
Si (mg/L)	13	13-26
Sr (mg/L)	<0.10	0.3-0.4
Zn (mg/L)	<0.02-0.04	0.03-0.17

Table 3.34: Water Quality Data for Test Section Suction Lysimeter

Parameter	Prepaving Range ^a	Postpaving Range
Temperature (°C)	-	-
pH	-	-
Alkalinity (mg/L as CaCO ₃)	-	-
Conductivity (μmhos/cm)	-	-
NO ₃ ⁻ -N (mg/L)	-	<0.05-0.06
NO ₂ ⁻ -N (mg/L)	-	<0.05
NH ₄ ⁺ -N (mg/L)	-	<0.05-0.25
SO ₄ ²⁻ (mg/L)	-	130-950
PO ₄ ³⁻ -P (mg/L)	-	0.01-0.03
Br ⁻ (mg/L)	-	<1
Cl ⁻ (mg/L)	-	96-640
TOC (mg/L)	-	9-21
COD (mg/L)	-	-
Total Phenols (μg/L)	-	19-39
VOCs (μg/L)	-	None
BN/As (μg/L)	-	None
Ag (mg/L)	-	-
Al (mg/L)	-	<0.10-0.40
As (mg/L)	-	<0.01
B (mg/L)	-	<0.50
Ba (mg/L)	-	<0.10
Ca (mg/L)	-	180-383
Cd (mg/L)	-	<0.005
Cr (mg/L)	-	<0.01
Cu (mg/L)	-	<0.02-0.10
Fe (mg/L)	-	0.16-4.20
Hg (mg/L)	-	<0.0003

Table 3.34: Water Quality Data for Test Section Suction Lysimeter (Continued)

Parameter	Prepaving Range ^a	Postpaving Range
K (mg/L)	-	5-12
Mg (mg/L)	-	8.8-28
Mn (mg/L)	-	6.6-15
Mo (mg/L)	-	<0.10
Na (mg/L)	-	170-383
Pb (mg/L)	-	<0.005-0.044
Se (mg/L)	-	<0.01
Si (mg/L)	-	7.6-16.3
Sr (mg/L)	-	0.20-0.47
Zn (mg/L)	-	0.08-0.32

^aSuction lysimeters installed during paving.

Table 3.35: Water Quality Data for Control Section Suction Lysimeter

Parameter	Prepaving Range ^a	Postpaving Range ^b
Temperature (°C)	-	-
pH	-	-
Alkalinity (mg/L as CaCO ₃)	-	-
Conductivity (μmhos/cm)	-	-
NO ₃ ⁻ -N (mg/L)	-	2.5-25
NO ₂ ⁻ -N (mg/L)	-	<0.05-0.12
NH ₄ ⁺ -N (mg/L)	-	-
SO ₄ ²⁻ (mg/L)	-	370-490
PO ₄ ³⁻ -P (mg/L)	-	<0.05
Br ⁻ (mg/L)	-	<10
Cl ⁻ (mg/L)	-	6,500-7,700
TOC (mg/L)	-	-
COD (mg/L)	-	-
Total Phenols (μg/L)	-	-
VOCs (μg/L)	-	-
BN/As (μg/L)	-	-
Ag (mg/L)	-	-
Al (mg/L)	-	-
As (mg/L)	-	-
B (mg/L)	-	-
Ba (mg/L)	-	-
Ca (mg/L)	-	-
Cd (mg/L)	-	-
Cr (mg/L)	-	-
Cu (mg/L)	-	-
Fe (mg/L)	-	-
Hg (mg/L)	-	-

Table 3.35: Water Quality Data for Control Section Suction Lysimeter (Continued)

Parameter	Prepaving Range ^a	Postpaving Range ^b
K (mg/L)	-	-
Mg (mg/L)	-	-
Mn (mg/L)	-	-
Mo (mg/L)	-	-
Na (mg/L)	-	-
Pb (mg/L)	-	-
Se (mg/L)	-	-
Si (mg/L)	-	-
Sr (mg/L)	-	-
Zn (mg/L)	-	-

^aSuction lysimeters installed during paving.

^bLimited data because of difficulties in collecting sufficient volumes of samples.

Table 3.36: Water Quality Data for the Test Section Road Run-Off

Parameter	Prepaving Range ^a	Postpaving Range
Temperature (°C)	-	6.8-22
pH	-	5.75-6.71
Alkalinity (mg/L as CaCO ₃)	-	3.8-68
Conductivity (μmhos/cm)	-	33-1,500
NO ₃ ⁻ -N (mg/L)	-	<0.05-0.93
NO ₂ ⁻ -N (mg/L)	-	<0.05-0.11
NH ₄ ⁺ -N (mg/L)	-	<0.05-1.80
SO ₄ ²⁻ (mg/L)	-	6-45
PO ₄ ³⁻ -P (mg/L)	-	<0.01-0.06
Br ⁻ (mg/L)	-	<1
Cl ⁻ (mg/L)	-	2-430
TOC (mg/L)	-	4-30
COD (mg/L)	-	-
Total Phenols (μg/L)	-	<10-72
VOCs (μg/L)	-	Trace, methylene chloride
BN/As (μg/L)	-	Trace, Bis(2-ethylhexyl) phthalate
Ag (mg/L)	-	-
Al (mg/L)	-	0.10-1.40
As (mg/L)	-	<0.01
B (mg/L)	-	<0.50
Ba (mg/L)	-	<0.10
Ca (mg/L)	-	3.1-16
Cd (mg/L)	-	<0.005
Cr (mg/L)	-	<0.01-0.02
Cu (mg/L)	-	<0.02-0.03
Fe (mg/L)	-	0.22-17

Table 3.36: Water Quality Data for the Test Section Road Run-off (Continued)

Parameter	Prepaving Range ^a	Postpaving Range
Hg (mg/L)	-	<0.0003
K (mg/L)	-	<3
Mg (mg/L)	-	0.30-1.20
Mn (mg/L)	-	0.048-0.64
Mo (mg/L)	-	<0.10
Na (mg/L)	-	2-320
Pb (mg/L)	-	<0.005-0.098
Se (mg/L)	-	<0.01
Si (mg/L)	-	0.3-3.9
Sr (mg/L)	-	<0.10-0.10
Zn (mg/L)	-	0.03-0.32

^aRun-off collection systems installed during paving.

Table 3.37: Water Quality Data for the Control Section Road Run-Off

Parameter	Prepaving Range ^a	Postpaving Range
Temperature (°C)	-	0.3-23.5
pH	-	5.50-7.42
Alkalinity (mg/L as CaCO ₃)	-	4-42
Conductivity (μmhos/cm)	-	39-2,600
NO ₃ ⁻ -N (mg/L)	-	<0.05-1.10
NO ₂ ⁻ -N (mg/L)	-	<0.05-0.07
NH ₄ ⁺ -N (mg/L)	-	0.16-1.50
SO ₄ ²⁻ (mg/L)	-	3-66
PO ₄ ³⁻ -P (mg/L)	-	<0.01-0.51
Br ⁻ (mg/L)	-	<1-5
Cl ⁻ (mg/L)	-	2-580
TOC (mg/L)	-	4-50
COD (mg/L)	-	-
Total Phenols (μg/L)	-	<10-25
VOCs (μg/L)	-	Trace, Acetone
BN/As (μg/L)	-	Trace, Bis(2-ethylhexyl) phthalate
Ag (mg/L)	-	-
Al (mg/L)	-	0.10-3.40
As (mg/L)	-	<0.01
B (mg/L)	-	<0.50
Ba (mg/L)	-	<0.10
Ca (mg/L)	-	3.4-15
Cd (mg/L)	-	<0.005
Cr (mg/L)	-	<0.01-0.015
Cu (mg/L)	-	<0.02-0.05
Fe (mg/L)	-	0.36-3.80

Table 3.37: Water Quality Data for the Control Section Road Run-Off (Continued)

Parameter	Prepaving Range ^a	Postpaving Range
Hg (mg/L)	-	<0.0003
K (mg/L)	-	<3-10
Mg (mg/L)	-	0.20-1.20
Mn (mg/L)	-	0.024-0.39
Mo (mg/L)	-	<0.10
Na (mg/L)	-	1-410
Pb (mg/L)	-	<0.005-0.17
Se (mg/L)	-	<0.011
Si (mg/L)	-	0.4-4.5
Sr (mg/L)	-	<0.10
Zn (mg/L)	-	0.03-0.43

^aRun-off collection systems installed during paving.

Table 3.38: Water Quality Data for Surface Water Station 2

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	2.2-23
pH	-	6.04-6.47
Alkalinity (mg/L as CaCO ₃)	-	9-27
Conductivity (μmhos/cm)	-	125-353
NO ₃ ⁻ -N (mg/L)	<0.05-0.60	0.15-1.0
NO ₂ ⁻ -N (mg/L)	<0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.31	<0.05-0.68
SO ₄ ²⁻ (mg/L)	14-15	<1-21
PO ₄ ³⁻ -P (mg/L)	<0.02	<0.01-0.02
Br ⁻ (mg/L)	<1	<1-9
Cl ⁻ (mg/L)	35-560	20-130
TOC (mg/L)	4-5	2-5
COD (mg/L)	11	-
Total Phenols (μg/L)	<10-15	<10
VOCs (μg/L)	None	None
BN/As (μg/L)	None	None
Ag (mg/L)	<0.02	-
Al (mg/L)	0.40	<0.10-0.90
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.50	<0.50
Ba (mg/L)	<0.10	<0.10
Ca (mg/L)	8-17	7.8-20
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	<0.01	<0.01
Cu (mg/L)	<0.02	<0.02-0.02
Fe (mg/L)	0.42-4.70	0.45-7.6
Hg (mg/L)	<0.0003	<0.0003

Table 3.38: Water Quality Data for Surface Water Station 2 (Continued) 231

Parameter	Prepaving Range	Postpaving Range
K (mg/L)	<3-4	<3-4
Mg (mg/L)	1.9-2.3	1.8-3.3
Mn (mg/L)	0.084-0.47	0.12-2
Mo (mg/L)	<0.10	<0.10
Na (mg/L)	22-76	13-84
Pb (mg/L)	<0.005	<0.005-0.023
Se (mg/L)	<0.01	<0.01
Si (mg/L)	5	3.8-6.0
Sr (mg/L)	<0.10	<0.10
Zn (mg/L)	0.03-0.11	0.02-0.08

Table 3.39: Water Quality Data for Surface Water Station 3

Parameter	Prepaving Range	Postpaving Range
Temperature (°C)	-	1.6-22.5
pH	-	6.22-7.08
Alkalinity (mg/L as CaCO ₃)	-	4-10
Conductivity (μmhos/cm)	-	15-740
NO ₃ ⁻ -N (mg/L)	<0.05	<0.05-0.07
NO ₂ ⁻ -N (mg/L)	<0.05	<0.05
NH ₄ ⁺ -N (mg/L)	0.06	<0.05-0.13
SO ₄ ²⁻ (mg/L)	6	2-35
PO ₄ ³⁻ -P (mg/L)	<0.01	<0.02
Br ⁻ (mg/L)	<1	<1-4
Cl ⁻ (mg/L)	11-30	4-17
TOC <1-3(mg/L)	2-3	<1-3
COD (mg/-L)	14	-
Total Phenols (μg/L)	<10	<10
VOCs (μg/L)	Trace, Trimethyl Silanol	None
BN/As (μg/L)	None	None
Ag (mg/L)	<0.02	-
Al (mg/L)	<0.10	<0.10
As (mg/L)	<0.01	<0.01
B (mg/L)	<0.50	<0.50
Ba (mg/L)	<0.10	<0.10
Ca (mg/L)	4.1-4.3	1.4-5.3
Cd (mg/L)	<0.005	<0.005
Cr (mg/L)	<0.0-0.02	<0.01
Cu (mg/L)	<0.02	<0.02-0.02
Fe (mg/L)	0.08-0.41	<0.03-0.12
Hg (mg/L)	<0.003	<0.0003

Table 3.39: Water Quality Data for Surface Water Station 3 (Continued) 233

Parameter	Prepaving Range	Postpaving Range
K (mg/L)	<3	<3
Mg (mg/L)	0.70-0.80	0.70-0.90
Mn (mg/L)	0.021-0.13	0.009-0.058
Mo (mg/L)	<0.10	<0.10
Na (mg/L)	8-10	3-11
Pb (mg/L)	<0.005	<0.005
Se (mg/L)	<0.01	<0.01
Si (mg/L)	0.80	0.3-0.7
Sr (mg/L)	<0.10	<0.10
Zn (mg/L)	<0.02	<0.02

suction lysimeter station, the control section suction lysimeter, the test section road run-off station, the control section road run-off station, SW 2, and SW 3; respectively. The tables present minimum and maximum values for data collected prior to paving, where appropriate, and for data collected after paving.

In examining the data, it is apparent that four different types of water quality are present: relatively pristine ground water in the control section (comprised of the dug well, MW 1, MW 2, and the suction lysimeters under the control section); mildly contaminated ground water in the test section (comprised of MW 3, MW 4, MW 5, and the suction lysimeters in the test section); contaminated road run-off (from both the control and test sections); and surface water of varying water quality (comprised of SW 2 and SW 3).

These general classifications are based on both water quality data comparisons and hydrogeologic considerations. Some clarification is required. The suction lysimeter in the test section was placed below the seasonally-high ground water table because of requirements to have it below the frost line. The suction lysimeter in the control section was placed below an excavated portion of the old macadam road. The macadam, as a regional confining layer, may have interfered with localized vapor movement and kept the subgrade soils relatively dry. Consequently, neither set of devices collected vadose zone moisture.

The ground water in the control section is characterized by relatively good water quality both prior to and after paving with low salt levels and relatively low levels of Fe, Mn and Al. The ground water in the test section is characterized by poor water quality

both prior to and after paving with much higher salt levels and high concentrations of Fe, Mn and Al. The Fe is visually apparent in the wells and comes from pyrite oxidation present in the pelitic schist in the Rangeley Formation. The road run-off is characterized by high salts and metals content in both the test and control section. The surface water varies from pristine in Paugus Bay of Lake Winnepesaukee to road run-off impacted in the stream running under the control section.

Table 3.40 lists the New Hampshire drinking water standards (Env-Ws 310-319), the New Hampshire ground water standards (Env-Ws 410), and the Federal drinking water standards promulgated under the Safe Drinking Water Act. Standards are shown for primary standards (maximum contaminant levels or MCLs as well as action levels) and secondary standards (secondary maximum contaminant levels or SMCLs). The data presented in Tables 3.28 through 3.39 and in Appendix 11 can be compared to the standards shown in Table 3.40.

For primary drinking water standards, the only analyte that exceeds an MCL or action level is lead (action level of 0.015 mg/L). For the control section, exceedences that occurred prior to paving occurred at MW 1 (0.020 mg/L on 4/23/94). Exceedences that occurred postpaving occurred at the upgradient dug well (0.038 mg/L on 7/9/93), at MW 2 (0.020 mg/L on 6/28/94), and at the control road run-off station (0.14 mg/L on 4/8/84, 0.17 mg/L on 5/12/94). The presence of lead both prior to paving and in the road section where the ash is absent demonstrates the preexisting and continuing widespread lead contamination of the site by anthropogenic activity. For the test section, there are no exceedences prior to paving. Exceedences that occurred postpaving

Table 3.40: Water Quality Standards

Parameter, mg/l	NHDES Drinking Water Standard (Env-WS 310-319)	NHDES Groundwater Standard (Env-WS 410)	Federal Drinking Water Standard (SDWA)
Nitrate (as N)	10.0 (MCL)	10 (MCL)	10 (MCL)
Nitrite (as N)	1.0 (MCL)	1 (MCL)	1 (MCL)
Chloride	250 (SMCL)		250 (SMCL)
Sulfate	250 (SMCL)	400	250 (SMCL)
Bromide			
Orthophosphate			
Total Organic Carbon			
Chemical Oxygen Demand			
Ammonia-N			
Aluminum	0.05 (SMCL)		0.05-0.2 (SMCL)
Arsenic	0.05 (MCL)	0.05 (MCL)	0.05 (proposed)
Barium	2.0 (MCL)	2 (MCL)	2 (MCL)
Boron		0.62	
Cadmium	0.005 (MCL)	0.005 (MCL)	0.005 (MCL)
Calcium			
Chromium, total	0.1 (MCL)	0.1 (MCL)	0.1 (MCL)
Copper	1.3 (Action Level)	1.3 (MCL)	1.3 (Action Level)
Iron	0.3 (SMCL)		0.3 (SMCL)
Lead	0.015 (Action Level)	0.015 (MCL)	0.015 (Action Level)
Magnesium			
Manganese	0.05 (SMCL)		0.05 (SMCL)
Mercury	0.002 (MCL)	0.002 (MCL)	0.002 (MCL)
Molybdenum			
Potassium		35	
Selenium	0.05 (MCL)	0.05 (MCL)	0.05 (MCL)

Table 3.40: Water Quality Standards (Continued)

Parameter, mg/l	NHDES Drinking Water Standard (Env-WS 310-319)	NHDES Groundwater Standard (Env-WS 410)	Federal Drinking Water Standard (SDWA)
Silicon			
Silver	0.10 (SMCL)		0.10 (SMCL)
Sodium	100-250 (SMCL)		
Strontium			
Zinc	5 (SMCL)		5 (SMCL)
Total phenols			
VOCs	Varies	Varies	Varies
BN/As	Varies	Varies	Varies

occurred at MW 3 (0.050 mg/L on 12/7/93, 0.032 mg/L on 4/6/94, 0.040 mg/L on 6/28/94), at MW 4 (0.016 mg/L on 7/9/93, 0.018 mg/L on 9/8/94), at MW 5 (0.019 mg/L on 7/9/93, 0.020 mg/L on 12/7/93, 0.026 mg/L on 4/6/94, 0.020 mg/L on 5/12/94, 0.050 mg/L on 6/28/94, 0.026 mg/L on 9/8/94), in the test section suction lysimeter (0.039 mg/L on 12/7/93, 0.044 mg/L on 4/6/94, and 0.020 mg/L on 5/12/94) and in the test road run-off station (0.098 mg/L on 4/6/94, 0.089 mg/L on 5/12/94). It should be noted that lead is found in the ground water in the test section upgradient from the test road. The highest observed lead concentration was seen in the road run-off in the control section.

Because primary drinking water standards (i) are exceeded prior to paving with grate ash, (ii) exceeded in the control section, and (iii) exceeded upgradient in the test section, then the presence of lead must be deemed to be preexisting and ubiquitous. Subsequent sections of the report point to an absence of trend in water quality degradation in the test section and to the determination that lead (as well as other contaminants) are preexisting anthropogenic contaminants that are not from the ash binder course in the test section.

Further review of the water quality data in Appendix 11 and in Tables 3.28 through 3.39 reveals that a number of secondary standards are exceeded. It is useful to clarify that the contaminants that exceed the SMCL (Cl, Fe, Mn, Al, SO_4^{2-} , Na) are also representative of preexisting anthropogenic activity (Cl, Na from road salting) or from aquifer geochemistry (Fe, SO_4^{2-} , Mn, Al from rock weathering and pyrite oxidation). Exceedences occur prior to paving in both the control and test sections. They continue

in both sections as well as in the upgradient well in the test section, and in both surface water stations after paving.

EVALUATION OF PREEXISTING ANTHROPOGENIC CHLORIDE AND LEAD

Lead and chloride are both anthropogenic elements that have been present at the site since leaded gasolines were used (1940's) and road salting was first practiced (1930's). While leaded gasoline use was curtailed in the late 1970's and early 1980's, road salting is still extensively practiced.

The efforts to monitor water quality were two fold: (i) identify the presence of preexisting contamination at the site prior to paving and (ii) develop a sufficiently large database that allows the use of statistical trend analyses to determine if ground water or surface water qualities were being adversely impacted by the activities associated with the use of asphalt binder course containing grate ash.

Figures 3.40 through 3.51 present lead and chloride data for the dug well, MW 1, MW 2, MW 3, MW 4, MW 5, the test suction lysimeter, the control suction lysimeter, the test road run-off, the control road run-off, SW 2 and SW 3, respectively. As can be seen in the data, lead is present at many of the locations prior to the paving. Chloride is present at all locations prior to paving. The highest reported lead concentration was seen in the road run-off from the control section on May 12, 1994 (0.17 mg/L). The highest reported chloride concentrations were seen in the control suction lysimeter on May 12, 1994 (7,700 mg/L), and the control road run-off on April 6, 1994 (580 mg/L).

Figure 3.40: Chloride and Lead Concentrations Over Time for the Dug Well

Figure 3.41: Chloride and Lead Concentrations Over Time for Monitoring Well 1

Figure 3.42: Chloride and Lead Concentrations Over Time for Monitoring Well 2

Figure 3.43: Chloride and Lead Concentrations Over Time for Monitoring Well 3

Figure 3.44: Chloride and Lead Concentrations Over Time for Monitoring Well 4

Figure 3.45: Chloride and Lead Concentrations Over Time for Monitoring Well 5

Figure 3.46: Chloride and Lead Concentrations Over Time for the Test Section Suction Lysimeter

Figure 3.47: Chloride and Lead Concentrations Over Time for the Control Section Suction Lysimeter

Figure 3.48: Chloride and Lead Concentrations Over Time for the Test Section Road Runoff

Figure 3.49: Chloride and Lead Concentrations Over Time for the Control Section Road Run-off

Figure 3.50: Chloride and Lead Concentrations Over Time for Surface Water Station 2

Figure 3.51: Chloride and Lead Concentrations Over Time for Surface Water Station 3

The Mann-Kendall test for trend (Gilbert, 1988) was used to evaluate increasing or decreasing trends in the lead and chloride data as a function of time. It is a non-parametric test that does not require testing for variance homogeneity or normal distributions. It can also be used with missing data or detection limit values. Table 3.41 summarizes the results; no significant trends were seen for either element for the dug well, MW 2, MW 3, MW 4, MW 5, the road run-off in either section or SW 3. In MW 1 and SW 2 in the control section, increasing trends for Cl were seen. The reasons for this increase are not known but may relate to road salting practices.

Ion ratios were used to ascertain the identity of the salts present in high concentration in the ground water in the test section and to see if they originated from the grate ash. The premise here is that if leachable grate ash constituents were dissolving into the ground water at MW 3, MW 4 or MW 5, then the characteristic relative concentrations of conservative ions such as K, Ca, Cl, and SO_4^{2-} in the grate ash must be identical to the signatures seen in the ground water. If the ash signatures differ from the ground water signatures, then the source of these mobile constituents at the test site must be from some other source.

Figures 3.52 through 3.54 show the K/Cl, Ca/Cl and Na/ SO_4^{2-} ratios (fingerprints) for all samples collected at the demonstration site over time. Data from the bottom ash lysimeter (BAL), bottom ash/asphalt lysimeter (BA/AL), aged grate ash total availability tests, and test section road core binder course monolith leaching data are also shown. In all cases, ratios derived from samples containing ash differ from those at MW 3, MW 4 and MW 5.

Table 3.41: Summary of Statistical Trend Analyses for Lead and Chloride Data at the Various Sampling Locations^a

Location	Lead Data			Chloride Data		
	n	p	trend?	n	p	trend?
Dug Well	10	0.443	No	13	0.168	No
MW 1	10	0.443	No	13	0.003	Yes
MW 2	10	0.364	No	13	0.524	No
MW 3	10	0.431	No	13	0.153	No
MW 4	10	0.271	No	13	0.102	No
MW 5	10	0.054	No	13	0.218	No
Test Suction Lysimeter	4	0.375	No	6	0.068	No
Control Suction Lysimeter	0	-	-	2	-	-
Test Road Run-Off	6	0.577	No	6	0.50	No
Control Road Run-Off	7	0.186	No	7	0.186	No
SW 2	10	0.364	No	13	0.034	Yes
SW 3	10	0.535	No	13	0.168	No

^a Based on non-parametric Mann-Kendall test for trend where $n < 40$.

K/Cl Fingerprints

Figure 3.52: K/Cl Fingerprint

Ca/Cl Fingerprints

Figure 3.53: Ca/Cl Fingerprint

Na/SO₄ Fingerprints

Figure 3.54: Na/SO₄²⁻ Fingerprint

To further demonstrate the use of this ratio method, plots of K/Cl versus Ca/Cl, Na/SO₄²⁻ versus Ca/Cl, and Na/SO₄²⁻ versus K/Cl are shown for (i) all data (see Figures 3.55, 3.57, 3.59, respectively) and for (ii) just the MW 3, MW 4 and MW 5 data along with all the data for ash containing samples (see Figures 3.56, 3.58, 3.60, respectively). In all cases comparing MW 3, MW 4 and MW 5 to grate ash specimens, the two populations of data are markedly different from one another.

Lead stable isotope analyses were used to identify the source of Pb in the ground water in MW 3, MW 4 and MW 5. There are four naturally occurring stable isotopes of lead; ²⁰⁴Pb, ²⁰⁶Pb, ²⁰⁷Pb, and ²⁰⁸Pb. ²⁰⁴Pb is the only isotope that is not formed by radiogenic processes, whereas ²⁰⁶Pb is derived from the radioactive decay of ²³⁸U, ²⁰⁷Pb is derived from the radioactive decay of ²³⁵U, and ²⁰⁸Pb is derived from the radioactive decay of ²³²Th (Ault et al., 1970). These radiogenic decay processes occurred in the earth's crust over long geologic times.

At the time that lead ore deposits are formed in crustal materials, the radiogenic lead isotopes are spatially separated from their parents so that the ratios of all the four isotopes are fixed in that ore body (Gaudette, 1995). When lead is mined from specific ore deposits world wide, the ratios of ²⁰⁶Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁴Pb, ²⁰⁸Pb/²⁰⁴Pb, ²⁰⁷Pb/²⁰⁶Pb, etc. are characteristic of their respective ore bodies; the ratios provide a fingerprint of the ore body. Thus the fingerprints for lead mined in Australia, Canada (eastern and western), Peru, South Africa, and the United States (Idaho, Missouri, Montana, New Jersey, New York) are unique to each deposit (Ault et al., 1970). This means that when lead is used in manufacturing processes (e.g. lead additives in gasoline, paints, batteries,

K/Cl vs Ca/Cl

Figure 3.55: K/Cl Versus Ca/Cl (All Data)

Figure 3.56: K/Cl Versus Ca/Cl (Select Data)

Figure 3.57: Na/SO₄²⁻ Versus Ca/Cl (All Data)

Figure 3.58: Na/SO₄²⁻ Versus Ca/Cl (Select Data)

Figure 3.59: Na/SO₄²⁻ Versus K/Cl (All Data)

Figure 3.60: Na/SO₄²⁻ Versus K/Cl (Select Data)

electronics, etc.), the manufactured product will have lead possessing the same isotopic fingerprints as the ore deposit which was the source of the lead. More often than not, the manufacturing process has relied on the use of the same lead source over time so that the isotopic fingerprint does not vary (Gaudette, 1995).

The presence of attributable isotopic fingerprints for lead means that mass spectrometry can be used to identify the source of lead in environmental samples. Examples include its use in characterizing atmospheric pollution on a regional or hemispherical basis (Grousset, et al., 1994; Mukai et al., 1993), in characterizing regional soil contaminant sources (Gulson et al., 1981), in characterizing marine (Fegal et al., 1987) and estuarine (Gobeil et al., 1994) sediment contaminant sources, and in characterizing hydrocarbon contaminant sources (Gaudette, 1995). The use of the technique is widespread, and is applicable to other sample types besides environmental samples.

The data from the lead isotope of the solid and aqueous samples is presented in Table 3.42. A careful examination of the data suggests that the $^{207}\text{Pb}/^{204}\text{Pb}$ ratio was the most suitable for showing that the lead in the grate ash is different than the lead in the ground water in the test section (e.g. MW 3, MW 4, MW 5).

Table 3.43 depicts some typical $^{207}\text{Pb}/^{204}\text{Pb}$ ratios for ore bodies, atmospheric dusts, soils, sediments, petroleum products, and WTE ashes. The values range from 14.60 to 16.30. Certain ore bodies have low ratios, others have very high ratios. Environmental samples most likely having multiple lead sources (dusts, soils) have wide ranges in ratios. Samples having more site specific sources (sediments, lichens) have

Table 3.42: Lead Isotope Ratios

Sample #	Sample Type	Pb Conc. (ppm)	$^{206}\text{Pb}/^{204}\text{Pb}$	Error (206/204)	$^{207}\text{Pb}/^{204}\text{Pb}$	Error (207/204)	$^{208}\text{Pb}/^{204}\text{Pb}$	Error (208/204)	$^{206}\text{Pb}/^{207}\text{Pb}$	Error (207/206)	$^{208}\text{Pb}/^{207}\text{Pb}$	Error (208/207)	Sample Type
1	Ash #11	2796.6	18.9877	0.004	15.6168	0.004	38.3872	0.01	0.82247	0.0002	1.21585	0.0003	Ash #11
2	Ash #13	2470.8	18.8536	0.01	15.6514	0.008	38.3364	0.038	0.83016	0.0004	1.20459	0.0006	Ash #13
3	Ash #6	1583.2	18.5686	0.02	15.5222	0.002	37.8031	0.037	0.83504	0.0001	1.19755	0.0001	Ash #6
4	Ash #4	2388.4	18.6359	0.01	15.5858	0.0009	38.0576	0.019	0.83633	0.0005	1.1957	0.0001	Ash #4
5	Soil Control	644	19.0429	0.018	15.6223	0.0019	38.4533	0.019	0.82038	0.0007	1.21895	0.0002	Soil Control
6	Soil Control	10.3	18.994	0.0724	15.6071	0.0095	38.3933	0.015	0.82169	0.0005	1.21701	0.0007	Soil Control
7	Soil Test	244.7	19.2379	0.0185	15.7263	0.0038	38.6047	0.038	0.81746	0.0002	1.2233	0.0003	Soil Test
8	Soil Test	43.7	18.7772	0.0282	15.6363	0.0263	38.2804	0.0507	0.83273	0.0014	1.20068	0.002	Soil Test
9	Binder Control	31.2	20.8252	0.13	15.7673	0.042	38.6587	0.083	0.75713	0.002	1.32078	0.003	Binder Control
10	Base Control	43.9	18.8634	0.011	15.6586	0.0027	38.4968	0.007	0.82573	0.0002	1.21105	0.0002	Base Control
11	Binder Test	5374.8	18.9147	0.014	15.6794	0.0095	38.4858	0.019	0.82895	0.0005	1.20635	0.0007	Binder Test
12	Base Test	94.9	19.5518	0.008	15.7703	0.0059	39.0185	0.059	0.80659	0.0003	1.23978	0.0005	Base Test
		Conc. (ppb)											
14	Water (MW1)	49.8	19.3816	0.004	15.6292	0.0378	38.6374	0.0111	0.80640	0.00156	1.24006	0.00240	Water (MW1)
15	Water (MW2)	144.6	19.0406	0.0451	15.4726	0.0372	38.4194	0.0282	0.81385	0.00062	1.22872	0.00093	Water (MW2)
16	Water (MW2QC)	49.05	18.9383	0.0423	15.4637	0.0346	38.1622	0.0185	0.81653	0.00048	1.22470	0.00072	Water (MW2QC)
17	Water (MW3)	19.6	18.7847	0.0448	15.4708	0.0369	37.7052	0.0286	0.82358	0.00097	1.21420	0.00143	Water (MW3)
18	Water (MW4)	139.5	18.5635	0.0652	15.4684	0.0543	37.8980	0.0217	0.83316	0.00089	1.20024	0.00128	Water (MW4)
19	Water (MW5)	23.6	17.7626	0.0776	14.7920	0.0183	35.6798	0.0312	0.83276	0.00103	1.20083	0.00148	Water (MW5)
20	Water (SW2)	2.4	18.5279	0.0453	15.4975	0.0378	37.5835	0.0232	0.83644	0.00061	1.19554	0.00067	Water (SW2)
21	Water (SW3)	2.5	17.7118	0.0813	15.8822	0.0233	37.0994	0.0281	0.89670	0.00131	1.11520	0.00183	Water (SW#)
22	HNO ₃ (Blank)	0.51	18.7042	0.0666	15.4895	0.0551	38.0005	0.0555	0.82813	0.00110	1.20754	0.00180	Water (Blank)

Table 3.43: Reported $^{207}\text{Pb}/^{204}\text{Pb}$ Ratios

Sample	$^{207}\text{Pb}/^{204}\text{Pb}$	Source
<u>Ore Bodies</u>		
South Africa (Rosetta Mine)	14.09	Ault et al., 1970
Manitowadge, Ontario	14.35	Gaudette, 1995
NWT, Canada (Conaco Mine)	15.10	Ault et al., 1970
Broken Hill, NSW, Australia	15.48-15.73	Ault et al., 1970; Gaudette, 1995
Cerro de Pasco, Peru	15.67	Ault et al., 1970
Coeur d'Alene, Idaho	15.37-15.57	Ault et al., 1970; Gaudette, 1995
South East Missouri	16.00-16.02	Ault et al., 1970; Gaudette, 1995
Joplin, Missouri	16.09	Ault et al., 1970
Franklin, New Jersey	15.68	Ault et al., 1970
Balmat, New York	15.59-15.65	Ault et al., 1970
<u>Atmospheric Dusts</u>		
Alp, Southeast France	15.48-15.67	Grousset et al., 1994
<u>Lichens</u>		
Quebec	15.20-15.45	Gaudette, 1995
<u>Soils</u>		
Aldelaide, Australia	14.60-16.30	Gulson et al., 1981
<u>Sediments</u>		
St. Lawrence Estuary	15.58-15.62	Gobeil et al., 1995
Monteray Bay, California	15.52-15.61	
<u>Petroleum Products</u>		
Crude Oil	15.13-15.78	Gaudette, 1995
Gasoline (1985)	15.59-15.78	Gaudette, 1995
Unleaded Gasoline (1992-1994)	15.55-15.65	Gaudette, 1995
Asphalt	15.74	Gaudette, 1995
<u>Incinerator Ash</u>		
Helsinki Bottom Ash	15.92	Jaakkola et al., 1983
Vancouver, B.C. Grate Siftings	15.8061	Gaudette, 1995
Vancouver, B.C. Bottom Ash	15.6685	Gaudette, 1995
Quebec ESP Ash	15.7449	Gaudette, 1995

narrower ranges. Petroleum products have ratios dependent upon the source of the lead used in the product (usually either Missouri or Broken Hill, NSW, Australia ores). The small data base for MSW ash samples shows a fairly narrow region.

The data from Table 3.42 have been plotted in Figure 3.61 for the $^{207}\text{Pb}/^{204}\text{Pb}$ ratios for the four ash samples and the ground water samples from MW 3, MW 4 and MW 5. One would expect the WTE grate ash samples to reflect a mixture of isotopic fingerprints from all of the various sources of lead that were used in products which were disposed as MSW in the watershed for the WTE facility. This would be weighted towards more recently manufactured materials. One would also expect that test site ground water lead to be at least a mixture of isotopic signatures from (i) leaded gasoline combustion, (ii) deposition of atmospheric dusts and aerosols, and (iii) abrasion of bituminous asphalt particles from road wearing course surfaces.

As shown in Table 3.44, the three monitoring well ratios in the test section differ from the ash ratios. The lower confidence interval for the grate ash $^{207}\text{Pb}/^{204}\text{Pb}$ ratios using a one-tailed t-test ($p = 0.10$) is 15.5491. All three of the monitoring well samples fall below the lower confidence interval. This demonstrates that the grate ash lead signature is different from the ground water signature and is not the source of lead in the ground water.

COMPARISON OF MODELED CONSTITUENT FLUXES TO PREEXISTING BACKGROUND CONTAMINANT FLUXES

In an attempt to put grate ash constituent fluxes occurring at the binder/soil and RAP interface into perspective, modelled fluxes from the control and test section binder

Figure 3.61: $^{207}\text{Pb}/^{204}\text{Pb}$ Ratios for Selected Samples

Table 3.44: $^{207}\text{Pb}/^{204}\text{Pb}$ Data Analysis

Aged Bottom Ash (n=4), non-normalized

$$\bar{x} = 15.5941$$

$$s_y = 0.05488$$

$$t = 1.638 \text{ (one tailed @ } p = 0.10 \text{ for } n-1 = 3)$$

$$\sqrt{n} = 2$$

$$\text{lower confidence interval (LCI)} = \frac{t s_y}{\sqrt{n}} = \frac{(1.638)(0.05488)}{2} = 0.0449$$

$$\bar{x} - \text{LCI} = 15.5941 - 0.0449$$

$$= 15.5492$$

course monolith leaching data at $t=0$ were compared to fluxes of contaminants entering the system by upgradient ground water flow or by road run-off infiltration adjacent to the road edge. Figure 3.62 schematically depicts the fluxes that are compared. It should be noted that these comparisons are very conservative because the modeled fluxes at the lower binder course/soil and RAP interface are only occurring at that interface. No subsequent downward migration is expected because of extensive attenuation or very low fluxes.

The results are presented in Table 3.45 for Al, Ca, Cl, Fe, K, Mg, Mn, Na, Si, Pb, SO_4 and Zn, respectively. Modeled fluxes occurring over the 1.5 year period were compared to fluxes associated with ground water movement and road run-off infiltration. In all cases, the fluxes that could have occurred at a 10% wetting level at the interface are smaller by factors of 10 to 10,000 than the fluxes associated with background contamination in the ground water flow from regions upgradient from the road under the road. The interface fluxes are smaller by factors of 10 to 100 than fluxes associated with road run-off contaminant infiltration. For sodium and chloride specifically, the interface fluxes are smaller by a factor of 100 than fluxes associated with road salting. These are considered to be conservative comparisons given the unlikely event of subsequent migration from the interface. The modeled fluxes at the interface are negligible compared to anthropogenic background signals.

1- Upgradient Groundwater Flux

Seepage Velocity (L/T) x Upgradient Concentration (M/L³)
x 1.5 Year Conversion Factor (T/T) = Flux (M/L²T)

2- Road Runoff Flux

Concentration (M/L³) x Annual Precipitation (L) x 1.5 Year
Conversion Factor (T/T) = Flux (M/L²T)

3- Road Salting Flux

Application Rate (M/LT) x Road Width (L) x 1.5 Year
Conversion Factor (T/T) = Flux (M/L²T)

4- Modeled Flux At Interface Only

Monolith Density (M/L³) x Availability (M/M) x
[Diffusion Coefficient (L²/T) x 1.5 Years (T)]^{0.5} = Flux (M/L²T)

Figure 3.62: Comparative Flux Depiction

Table 3.45: Comparative Fluxes for Elements of Interest

		Flux, g/m ² •1.5 years												
Location		Constituent	Al	Ca	Cl	Fe	K	Mg	Mn	Na	Si	Pb	SO ₄ ²⁻	Zn
1.	Estimated Contaminant Flux from Upgradient Aquifer													
	◦ Control Section		118	2,090	1,810	310	330	170	5	1,700	580	2.2	830	78
	◦ Test Section		30	2,800	9,600	925	165	780	46	4,800	650	0.8	2,800	3
2.	Estimated Road Run-Off Flux													
	◦ Control Section		1.5	11	136	3.3	10	1.0	0.34	96	2.6	0.11	23	0.34
	◦ Test Section		1.0	10	123	7.8	-	1.0	0.31	90	2.8	0.09	20	0.22
3.	Estimated Road Salting Flux for Na, Cl													
	◦ Control Section		NA ^a	NA	747	NA	NA	NA	NA	485	NA	NA	NA	NA
	◦ Test Section		NA	NA	747	NA	NA	NA	NA	485	NA	NA	NA	NA
4.	Modeled Flux at Binder/RAP & Soil Interface													
	◦ Control Section		- ^b	0.8	-	0.15	-	0.06	0.03	-	-	-	1.2	-
	◦ Test Section		-	2.9	2.0	0.12	-	0.11	0.02	1.1	0.24	-	4.3	0.02

^aNA = not applicable.^bDashes denote that element did not leach via diffusion from road cores.

ENVIRONMENTAL BEHAVIOR OF BOTTOM ASH VERSUS GRATE ASH FROM THE CONCORD WTE FACILITY

This study provides an opportunity to compare the environmental performance of bottom ash relative to grate ash from the Concord WTE facility when these materials are used in asphaltic binder course. Results collected during the earlier two year bottom ash characterization study (Eighmy et al., 1992; Whitehead, 1992; Zhang, 1993) can be used to compare to results from the present grate ash utilization study. To facilitate comparisons, upper and lower range limits are qualitatively compared. Given the frequent non-normal distributions with bottom ash and differences in sample population size, only range comparisons are attempted. The results of these comparisons show that there are no apparent major differences between the two residue streams from an environmental perspective and that each behave similarly with respect to leaching behavior in asphalt monoliths.

To facilitate this comparison, the behavior of four elements was evaluated. The four elements: calcium, silicon, chloride, and lead, were selected because of their different environmental behaviors and their potential to indicate behaviors of other elements in their respective classifications.

Calcium was chosen because it is a major element in both ashes, it exhibits diffusive leaching, and is responsive to pH-based chemical retention leaching phenomena. Silicon was selected because it is a major element in both ashes, it is an aluminosilicate matrix element, it exhibits diffusive leaching, and is relatively less reactive during leaching. Chloride was chosen because it is a minor element, it is relatively the most diffusive ash element leaching from asphaltic monoliths, and is non-

reactive during leaching. Lead was chosen because it is a minor element in both ashes, it is also one of the few elements (including Al, Cu, and Zn) that is present in higher total concentrations in bottom ash relative to grate ash (because of its potentially higher concentration in grate siftings), and because of its sporadic leaching behavior as indicated by its limited release at very low fluxes via surface wash-off, dissolution, and occasionally diffusion from asphalt monoliths. These elements cover the range of elements exhibiting leaching behavior in bituminous monoliths made with grate or bottom ash.

Table 3.46 depicts the data that were used to examine the behaviors of bottom ash relative to grate ash from the Concord WTE plant. The data for each element are presented in vertical columns. The parameters that are compared are presented in numerous groupings of rows in the table.

The upper group of rows in Table 3.46 examines the data on the ash materials themselves (total element compositional range, total available compositional range). Upper and lower range values are shown because the data tend to be non-normally distributed. Under each element, qualitative comparisons are made between fresh bottom ash (aged < 1 week), fresh grate ash (aged < 2 months), and aged grate ash (aged ~ 6 months). The fresh bottom ash was collected as numerous composite daily samples over a 1½ year period between 1990 and 1992. The fresh grate ash was collected as numerous grab samples from a large pile. The pile was generated over a two month period in November and December, 1992. The aged grate ash was collected as numerous grab samples from the same large pile.

Table 3.46: Comparison of Environmental Behavior of Four Elements in Bottom Ash and Grate Ash and in Asphalt Monoliths

Element	Calcium			Silicon			Chloride			Lead		
Ash Parameter	Fresh Bottom Ash	Fresh Grate Ash	Aged Grate Ash	Fresh Bottom Ash	Fresh Grate Ash	Aged Grate Ash	Fresh Bottom Ash	Fresh Grate Ash	Aged Grate Ash	Fresh Bottom Ash	Fresh Grate Ash	Aged Grate Ash
Total Element Composition Range (mg/kg)	51,200-102,900 (n=18)*	50,800-65,300 (n=7)	54,200-67,400 (n=14)	182,500-274,000 (n=18)	215,600-259,000 (n=7)	215,500-257,900 (n=14)	1,100-4,190 (n=18)	700-2,340 (n=7)	470-2,590 (n=14)	1,200-6,600 (n=18)	900-2,890 (n=7)	900-1,700 (n=14)
Total Available Composition Range (mg/kg)	18,500-61,000 (n=18)	18,600-30,100 (n=7)	22,000-30,000 (n=14)	1,700-6,300 (n=18)	1,600-2,000 (n=7)	1,200-1,800 (n=14)	1,400-6,000 (n=18)	800-2,800 (n=7)	800-5,200 (n=14)	40-2,900 (n=18)	100-1,000 (n=7)	100-440 (n=14)
Monolith Leaching	Bottom Ash Lab Study	Grate Ash Lab VCA Study	Grate Ash Field Road Cores	Bottom Ash Lab Study	Grate Ash Lab VCA Study	Grate Ash Field Road Cores	Bottom Ash Lab Study	Grate Ash Lab VCA Study	Grate Ash Field Road Cores	Bottom Ash Lab Study	Grate Ash Lab VCA Study	Grate Ash Field Road Cores
% Ash	25-75	50	50	25-75	50	50	25-75	50	50	25-75	50	50
% Voids	7.1-7.8	5-10	6	7.1-7.8	5-10	6	7.1-7.8	5-10	6	7.1-7.8	5-10	6
% Asphalt Cement	5.5-11.1	7	7	5.5-11.1	7	7	5.5-11.1	7	7	5.5-11.1	7	7
Availability Range in Monolith (mg/kg)	7,300-18,900 (n=4)	7,860 (n=1)	5,830-7,260 (n=8)	800-1,500 (n=4)	770 (n=1)	480-530 (n=8)	850-1,900 (n=4)	806 (n=1)	200-800 (n=8)	50-100 (n=4)	100 (n=1)	30-50 (n=8)
Cumulative Flux Range @ Day 64 (mg/m ²)	6,700-7,800 (n=4)	2,790-21,900 (n=14)	1,170-5,340 (n=8)	200-240 (n=4)	100-320 (n=14)	35-230 (n=8)	6,400-7,300 (n=4)	680-6,920 (n=14)	210-2,500 (n=8)	Sporadic Release (n=4)	0.4-14.0 (n=14)	1-27 (n=8)
pD _s Range -log m ² /sec	13.6-15.3 (n=4)	12.4-14.5 (n=14)	13.8-14.9 (n=8)	14.5-15.3 (n=4)	14.1-15.0 (n=14)	14.0-14.2 (n=8)	11.7-12.2 (n=4)	11.3-13.2 (n=14)	12.1-13.4 (n=8)	No Diffusion (n=4)	15.6-15.9 (n=14)	No Diffusion (n=8)
Tortuosity Range (τ)	450-2,310 (n=4)	133-14,600 (n=14)	2,190-13,800 (n=8)	450-2,310 (n=4)	130-14,600 (n=14)	2,190-13,800 (n=8)	450-2,310 (n=4)	133-14,600 (n=14)	2,190-13,800 (n=8)	450-2,310 (n=4)	133-14,600 (n=14)	2,190-13,800 (n=8)
Chemical Retention Range (R)	52-66 (n=4)	13-59 (n=14)	6.0-46 (n=8)	262-362 (n=4)	30-440 (n=14)	6.0-33 (n=8)	1.4-2.1 (n=4)	1.0-11 (n=14)	1.0-7.0 (n=8)	No Diffusion (n=4)	280-1,000 (n=14)	No Diffusion (n=4)
Monolith Leaching Behavior	Diffusion	Diffusion, Dissolution	Diffusion	Diffusion	Diffusion, Dissolution	Diffusion, Limited Release	Diffusion	Diffusion, Dissolution, Surface Wash Off, Depletion	Diffusion, Dissolution	Limited Release	Diffusion, Dissolution, Depletion, Only 2 of 14 Specimens Exhibited Diffusive Behavior	Limited Release, Dissolution, Depletion

n denotes the number of samples or monoliths that were analyzed.

The lower group of rows in Table 3.46 examine monothic leaching behavior (monolith mix formulation, element total availability ranges in the monolith material, cumulative flux ranges after 64 days of leaching in the monolith leach test, pD_e ranges, tortuosity (τ) ranges, chemical retention (R) ranges, and leaching behavior). Upper and lower range values are shown because the data tend to be non-normally distributed. Under each element, qualitative comparisons are made between results of the earlier two year study (Eighmy et al., 1992; Whitehead, 1992) involving the effects of bottom ash substitution on monolithic leaching, to results from this present study using monoliths containing aged grate ash from the laboratory evaluation of voids, cracking and aging and to results from this present study using monolith road cores from the paving demonstration (aged grate ash, both $t = 0$ year and $t = 1.25$ year cores). The earlier bottom ash laboratory study evaluated three ash loadings (25, 50, 75%) and used Marshall design procedures so that voids ranged from 7.1 to 7.8% and asphalt cement percentages varied from 5.5 to 11.1%. The present laboratory voids, cracking and aging study used a 50% ash substitution and gyratory test methods at preset void levels (5, 7.5, 10%) at the design asphalt cement percentage (7%). The change in pavement design procedure (Marshall to gyratory) reflects an evolution in our view of pavement design with a lightweight, porous aggregate substitute to better simulate field compaction. Despite this change, general monolith physical properties (strength, flow) were similar. The present field road core study used field compacted road cores with 50% ash substitution compacted in the field to void levels of 6% at the design asphalt cement level of 7%. It is important to note that some of the data presented from the laboratory voids, cracking and aging study used monoliths that were purposefully aged and cracked to examine potential future worst case environmental behavior. These data should be viewed conservatively (artificially more diffusive).

Calcium is the first element to be compared in Table 3.46. The total composition range in all three comparative categories are generally overlapping and similar, though high outliers are seen in the bottom ash. The total available composition range are also generally overlapping and similar, though high outliers are seen in the bottom ash. The monolithic leaching behavior in all three comparative categories is similar, although some differences can be attributed to ash loading and monolith cracking. The availabilities of calcium in the monolith are generally overlapping. The cumulative fluxes are also similar. The pD_e values, tortuosity values, and chemical retention values are also relatively similar. Despite the variable bottom ash loading in the laboratory bottom ash study, the use of cracked monoliths in the laboratory voids cracking, and aging study, and the use of cored monoliths with cut surfaces from the field study, the data regarding calcium leaching behavior is similar for all three scenarios. Diffusion is the dominant controlling mechanism for the pH sensitive and geochemically reactive calcium for both ash types. Similar behaviors were seen for Fe, Mg, and Mn; the only other reactive cations to leach from monoliths constructed with ash and bituminous asphalt.

Silicon is the next element to be compared in Table 3.46. There are no real apparent differences in the ranges of values for total element composition. The bottom ash has a larger total available composition limit than the grate ashes. The monolith leaching in all three comparative categories is similar, although some differences can be attributed to ash loading and monolith cracking. The ranges reported for availabilities in the monolith, the cumulative flux values that are reported, the pD_e ranges, tortuosity ranges, and chemical retention ranges are all similar. Diffusion is the dominant controlling mechanism for the geochemically non-reactive silicon for both ash types.

The next element to be compared is chloride. As shown in Table 3.46, chloride total element composition is generally similar among the three ash types, though high outliers are seen in the bottom ash. The total available composition data also show

similar concentration ranges between the three ash types, though high outliers are seen in the bottom ash. The monolith leaching in all three comparative categories is similar. Some increased availabilities and cumulative fluxes can be seen in the bottom ash at the 75% ash loading value. Some increased cumulative fluxes can be seen in the bottom ash at the 75% ash loading and in the cracked grate ash monoliths. The observed ranges for pD_e , tortuosity, and chemical retention are generally similar. For the relatively mobile and non-reactive chloride, diffusion is the controlling mechanism for both ash types. Similar behavior was seen for sulfate and sodium; the only other non-reactive cations or anions to leach from the monoliths.

The last element to be compared in Table 3.46 is lead. The total element composition ranges and total available composition ranges tend to overlap between the three ash types. Some high outliers are observed in the bottom ash. Lead generally exhibits similar monolithic leaching behaviors between the three comparative categories. In general, lead leaches sporadically from all of the monolithic specimens. The ranges shown for availability in the monolith and tortuosity are similar. The leaching mechanisms between the three scenarios showed some modest variation. The bottom ash monoliths exhibited very sporadic leaching. The road core grate ash specimens also exhibited very sporadic leaching. Release was limited in both cases. The laboratory voids, cracking, and aging specimens also exhibited sporadic behavior; 2 of the 14 specimens showed some diffusive leaching behavior. The reported diffusivities are low. These data still suggest no apparent differences for lead leaching between the ash types. For the reactive lead; limited release, surface wash-off, and occasionally diffusion are the controlling mechanisms for both ash types. These data are also supported by the field leaching of bottom ash pavement materials in the outdoor lysimeter where lead leaching has been limited and sporadic. The only other element that exhibiting leaching behavior

and which also falls in the lead classification was zinc. It exhibited similar behaviors between both ash types.

It is also possible to compare the relative environmental performance of both the bottom ash and grate ash from the Concord WTE facility in RAP applications. In the earlier two year bottom ash study (Eighmy et al., 1992; Whitehead, 1992), monolith specimens containing various loadings of fresh bottom ash (50 to 100%) and at various asphalt cement loadings (8, 9, 10, 11 and 12%) were manufactured using Marshall methods. The monoliths were crushed to pass 1.9 cm and leached at pH 4 for 4 hours under agitated conditions. Release, as measured by cumulative release per dry weight of bottom ash, was quantified and compared to bottom ash controls. As shown in Table 3.47, the factors by which element releases were reduced ranged from 2.5 to 6.6 for calcium, 2.0 to 6.0 for silicon, 1.3 to 2.5 for chloride, and 1.5 to 7.5 for lead. The results show the partial control of release of elements through the uptake of asphalt cement into the pores of the bottom ash particles.

While absolute comparisons to grate ash RAP leaching cannot be made because a different type of leaching test was used, the data on granular diffusional leaching can be used to compare behavior as quantified by cumulative fluxes at day 64 between grate ash specimens and granularized grate ash asphalt monoliths. Diffusional leaching tests were conducted on materials at two sizes (< 1.9 cm, < 300 μ m). The materials were either fresh grate ash or fresh grate ash used in laboratory monoliths made at a 50% ash substitution and at 7% asphalt cement. As shown in Table 3.47, the factors by which element fluxes were reduced ranged from 1.7 to 4.4 for calcium, 2.8 to 4.2 for chloride, and 2.3 to 12.3 for lead. The results show the partial control of flux of elements through the uptake of asphalt cement into the grate ash pore structure. The relative reductions are similar to those seen for bottom ash and are indicative of similar behaviors between

Table 3.47: Comparison of Environmental Behavior of Four Elements in Bottom Ash and Grate Ash Asphalt RAP Materials

Element	Calcium	Silicon	Chloride	Lead
Bottom Ash Regranularized Leaching (mg/kg bottom ash)				
Release for Bottom Ash	20	1,200	2,000	150
Release for Granularized Monoliths	3-8	300-600	800-1,500	20-100
Reduction Factor	2.5-6.6	2.0-6.0	1.3-2.5	1.5-7.5
Grate Ash Granular Diffusion Leaching (mg/m² @ day 64)				
Cumulative Release for < 1.9 cm Grate Ash	47,000-48,900	Not Tested	23,200-23,900	38.2
Cumulative Release for < 1.9 cm Granularized Monoliths	11,000-12,500	Not Tested	5,580-6,000	3.1-6.0
Reduction Factor	3.7-4.4	-	3.8-4.2	6.3-12.3
Cumulative Release for < 300 μ m Grate Ash	44,600-48,700	Not Tested	35,500-38,700	29.1-45.6
Cumulative Release for < 300 μ m Granularized Monoliths	23,700-26,800	Not Tested	12,000-12,900	6.6-12.9
Reduction Factor	1.7-2.0	-	2.8-3.2	2.3-6.9

the two ashes with respect to asphalt cement reducing element fluxes through imposition of diffusional barriers.

In summary, there are no apparent differences in the environmental behavior of both ash types when incorporated into asphaltic monoliths. In the companion volume on physical testing (Volume 3, Gress et al., 1996), the bottom ash and grate ash laboratory monoliths had similar Marshall design characteristics (flow, stability, unit weight, voids). These data suggest that the grate ash and bottom ash behave in similar fashions with respect to environmental and physical performance.

AGING REQUIREMENTS

The data presented in the previous section and elsewhere in this report suggests that the leaching behaviors of grate ash and bottom ash are similar, particularly from asphaltic monoliths. Monolith leaching data are similar between Concord bottom ash (Eighmy et al., 1992; Whitehead, 1992) and Concord grate ash laboratory monoliths and field pavement monoliths. Total availability leaching data between Concord bottom ash (Eighmy et al., 1992; Whitehead, 1992) and Concord grate ash are similar. Lysimeter leaching of Concord bottom ash over extended periods of time also shows bottom ash to be non-problematic particularly with respect to leaching of heavy metals.

The data presented here also suggests that aging has no marked impact on reducing availabilities of elements in grate ash. Of the 28 analytes that were quantified with the Dutch Total Availability Leaching Test, only four were found to significantly vary between fresh and aged grate ash using student's t-test (95% probability, pooled variance, two tailed comparison). The elements Na and Si had significantly higher availabilities in the aged grate ash. Fe and Al had significantly higher availabilities in the fresh grate ash. The Dutch Total Availability Leaching Test is an aggressive leaching test. The observed differences between the fresh and aged grate ashes for Na, Si, Fe and

Al are likely to be the most robust examples of aging reactions. Many more subtle and beneficial transformations (carbonation, solid phase diagenesis) would only be seen with leaching tests employing distilled water where the natural buffer capacity of the ash would dominate at or around slightly basic pH values. Tests along these lines were not conducted because these transformations are probably not significant for materials used in hydrophobic monolithic matrices.

From a materials performance perspective, the in place performance of the road in Laconia appears to be fully satisfactory for the first 2½ years of service life. It is not clear if the pavement performance has benefitted from the aging of the grate ash. Data from one other ash paving project (Rt. 129 in Lynn, Massachusetts) suggests that pavements should perform well over longer times (over 10 years). It is not known if that bottom ash was aged prior to its use. We do not have data on materials performance of pavements made with fresh grate ash. Therefore, there is uncertainty associated with the need to age the grate ash or bottom ash from a physical performance perspective.

If bottom ash (with grate siftings) from the Concord WTE facility is to be used in asphaltic pavements without aging, then it is likely that its environmental behavior will be similar to that of grate ash and would not be problematic. From a materials performance perspective, a conservative approach would be to age the bottom ash prior to use or to otherwise treat the ash to increase the geochemical stability of the material. Aging experiences in Europe suggest one to three months is appropriate provided that adequate moisture content is maintained in the material (IAWG, 1994). A minimum value of one to three months would provide a conservative approach to aging. Further studies may show (i) aging is not required or that this time period could be reduced if aging were shown to be less important for bottom ash use in pavements, (ii) aging reactions could be accelerated, or (iii) treatment methods could be used to enhance geochemical stability.

If grate ash (without grate siftings) from the Concord WTE facility is to be used in asphaltic pavements without aging, then, based on the research completed to date, it is likely that its environmental behavior would not be problematic. From a materials performance perspective, aging should be less important because grate siftings have been removed. Since we do not have data on the use of fresh grate ash from a materials performance perspective, a conservative approach would be to have grate ash generators or users evaluate the need for grate ash aging as needed.

APPLICATION OF THESE RESULTS TO ANALOGOUS USES

One aspect of this five year research project, including the earlier two year bottom ash characterization study (Eighmy et al., 1992; Whitehead, 1992; Zhang, 1993), was to conduct a study of sufficient scope that would allow for the considered use of bottom ash or grate ash from other facilities in bituminous asphalt binder course applications.

It was felt that if (i) the time dependent physical and chemical properties of the ash stream at the Concord WTE facility were carefully documented, (ii) proper hot mix binder course formulation and design was achieved, (iii) full-scale paving was successful from both a physical and environmental perspective, (iv) fundamental environmental behavior of the materials was studied and modeled, and (v) behavior of the product in subsequent applications after the end of its intended life (e.g. as RAP in base course) was evaluated, then this would be a study of sufficient scope to allow for the considered use of bottom ash or grate ash from other WTE facilities in binder course applications. Consequently, the scopes of both the earlier two year study and the present study were prepared with these considerations in mind. Ideally, the very extensive effort conducted for the Laconia, N.H. paving project would demonstrate the feasibility of the concept of using bottom ash or grate ash in binder course. Analogous uses elsewhere could make

use of this effort by conducting substantially less extensive evaluations on ashes from other facilities.

If bottom ash or grate ash from another WTE facility were to be considered for use as a partial aggregate substitute in hot mix bituminous asphalt binder course applications, then certain design and performance considerations would need to be addressed. If the analogous use were very similar to the scenario studied for the Laconia project, then the considerations would be simple. If the analogous use differed from the one studied here, then the considerations might be more expansive. For simplicity's sake, an analogous use of a grate or bottom ash stream from a similar WTE facility in a bituminous hot mix asphalt binder course application will be discussed.

Table 3.48 presents suggested design and performance criteria that could be considered for an analogous use. The basic premise underlying the listing of criteria in Table 3.48 is that if an analogous combustor produces an analogous ash that is used in an analogous binder course application, then the short and long term environmental and physical performance of the product should be similar to the materials studied here.

The first grouping in Table 3.48 is a listing of criteria for combustor and ash type. To be similar, the combustor should be a mass burn facility using a modern grate system (reciprocating, rocking, rolling, or traveling grates) and good combustion practices. These types of grate systems are usually associated with high temperature combustion that produce well combusted ashes with low loss on ignition values and slag particles that are melted and crystallized. The ashes can be either bottom or grate ashes. As discussed in the previous section, the requirements for aging for use of these ashes in hydrophobic hot mix binder courses would need to be verified by the user for physical performance considerations. Aging has no apparent beneficial effects on altering monolithic leaching behavior from an environmental perspective. Moisture control would involve considerations for fugitive dust control at storage and processing sites.

Table 3.48: Suggested Criteria for Analogous Applications

Category	Criteria
Combustor/Ash Types	
Combustor Type	Modern Mass Burn with Good Combustion Practices
Grate Type	Reciprocating, Rocking, Rolling, Traveling
Ash Type	Bottom, Grate
Ash Treatment	Physical
Ash Aging	To be Determined By User
Moisture Control	Yes
Ash Characteristics	
Total Metals	
-Si	Distribution and Central Tendency Similar to Concord Grate or Bottom Ashes
-Cl	
-Pb	
LOI	$\bar{x} < 10$
Mix Design	
Binder Course Type	State or User Specified
Ash Substitution	< 50%
Mix Design	State or User Specified
Mix Design Performance	State or User Specified
Environmental Performance	
Monolith Leaching Test or Other Suitable Test	
Monolith Total Availability (If Monolith Leach Test is Used)	
-Cl	< 2,000 mg/kg
-Pb	< 150 mg/kg

Values of 16% moisture content (weight of water/dry weight of ash) are good for fugitive dust control and aging (if promoted). Values higher than that can be detrimental to the manufacture of hot mix pavements because reduced throughputs in the drum drier may be required to allow time to remove moisture. Moisture can be managed via the addition of water or the use of covers to promote drying.

The second grouping in Table 3.48 is a listing of criteria for ash characteristics from an environmental perspective. It should be noted that ash physical properties are addressed in mix design criteria (see below). To be analagous, the ash that is generated should have certain characteristics that are similar to those exhibited by the Concord WTE bottom ash. With regards to total metals composition, three elements have been selected as indicator parameters.

To be analagous, the distribution and central tendency of the silicon total concentration data should be similar to those seen in this study for the grate or bottom ashes. Silicon is found in modern mass burn bottom ashes at concentrations between 100,000 and 350,000 mg/kg (IAWG, 1994). This element is indicative of slag chemistry (Eusden et al., 1994; Eusden and Eighmy, 1995) and the type of crystalline phases that precipitate out of slags. Similar values will ensure slag particles with good viability and porosity.

To be analagous, the distribution and central tendency of the chloride total concentration data should be similar to those seen in this study for the grate or bottom ashes. Chloride is found in modern mass burn bottom ashes at concentrations between 500 and 5,000 mg/kg (IAWG, 1994). It is, relatively, the most diffusive ash element in asphaltic monoliths. Similar values will mean that the diffusional driving gradient will be similar to or less than the ones observed in this work.

To be analagous, the distribution and central tendency of the lead total concentration data should be similar to those seen in this study for the grate or bottom

ashes. Lead is found in modern mass burn bottom ashes at concentrations between 100 and 6,500 mg/kg (IAWG, 1994). This element is usually present in grate ash at lower concentrations. Lead is a minor element in ash and rarely mobilizes from ash/asphalt monoliths. Release mechanisms involve limited release, surface wash-off, and occasionally diffusion.

Loss on ignition (LOI) is added as a surrogate parameter for combustion efficiency, slag melting, and asphalt cement demand. Values less than 10% relate to high temperature combustion, high bed temperature slag production, and low demands for non-slag asphalt cement absorption. Ormsby (1989) has shown that as long as ash LOI values are less than 10%, acceptable pavements at high ash substitutions (up to 100%) can be made. LOI values less than 6% are generally attainable and are preferred in ash asphalt.

The next grouping in Table 3.48 is a listing of criteria regarding the hot mix bituminous asphalt mix design. Implicitly, the design of a mix suitable for use in hot mix binder course translates into monolithic materials with good control of monolithic leaching behavior, as environmental performance is directly related to physical performance (Eighmy et al., 1995). Binder course design varies by state for state-owned road systems. Municipal roads may also use binder course in road construction. Invariably, three types of pavement design procedures are used (Marshall, Hveem, and gyratory in the SUPERPAVE process). The former two are empirical and very similar. The latter is mechanistic. We have used both the Marshall and gyratory methods in this work. Binder course specifications involve many design and performance criteria (e.g. grain size, air voids, absorbed and effective asphalt, degradation, water adsorption, flow, stability, gyratory shear). If bottom ash or grate ash are used at substitutions less than 50%, then performance design criteria can be met (Zhang, 1993; Gress et al., 1991, 1992, 1996).

The only relatively important design and performance variable that relates to monolith leaching behavior is the absorbed asphalt percentage. This is the asphalt cement that is absorbed internally in the porous structure of the ash which helps promote diffusive control. As ash substitution percentages decrease, then the products become less light weight and require less asphalt cement. However, absorbed asphalt levels remain proportional to the ash loading (Gress et al., 1991), indicating that no matter what the substitution level, porous slag particles will beneficially absorb asphalt cement.

The final grouping in Table 3.48 is a listing of criteria regarding the environmental performance of the monolithic binder material. If good mix design procedures are used, then the resulting product should have sufficient strength, durability, asphalt cohesiveness and asphalt loadings to coat the internal pore structure and external surfaces of slag particles, thus ensuring diffusional control. To ensure this, some additional testing of ash from an analogous facility may be appropriate to confirm that the monolithic leaching behavior is similar to that observed in the Laconia project. The monolith leach test, or other suitable methodology, could be conducted to verify that ash constituents exhibit monolithic leaching behavior. Fluxes from monoliths are based on diffusivities (D_e) and driving gradients (availability in the monolith). Diffusivities are inherently a function of ion size, asphalt polymer structure, and temperature and do not markedly vary in ash-asphalt monolith leaching studies. Availabilities in the monolith are a function of ash loading and asphalt cement content. If the monolith leaching test is used, then criteria for the availability of chloride and lead are given that will produce fluxes similar to those observed in this work. This assumption is based on the fact that diffusivities will be generally similar for ash constituents diffusing out of asphalt products (Eighmy et al., 1992; Whitewood, 1992; de Groot et al., 1990).

The use of these suggested criteria should ensure, for analogous applications, that the short and long term environmental performance is similar to those observed in Laconia studies. Any deviations from these applications (combustor type, grate type, ash treatment, paving application) would require additional evaluations to ensure proper mix design and environmental performance.

CHAPTER 4

SUMMARY

INTRODUCTION

This project was conducted to document the feasibility of using municipal solid waste (MSW) grate ash as an aggregate substitute in the construction of a pavement binder course for a portion of Rt. 3 in Laconia, New Hampshire. The research, sponsored by the CRSW/RRC, WES, the U.S. EPA, and the U.S. DOE, was conducted over a two year period during 1993 and 1994. This study is the culmination of an earlier two year characterization study between 1990 and 1992 that documented the physical and environmental characteristics of the bottom ash as it is produced at the Penacook, NH WTE facility and used in asphaltic binder course.

This study was comprised of two principal parts; an environmental evaluation and a physical performance evaluation. The environmental evaluation centered on the implications of use of grate ash in the short term during the project period as well as on future possible life cycle scenarios for the pavement.

BACKGROUND

Bottom ash is comprised of grate ash and grate siftings. The use of both types of ash in civil engineering construction is widely practiced in Western Europe. Applications include its use as granular structural fill in wind and sound barriers, road embankments, road subbases, parking lots and bike paths. The uses that are anticipated for the U.S. include the use as aggregate substitutes in bituminous asphalt and recycled asphalt

pavements, Portland cement concrete, road subbase, granular fill, or as granular cover material at lined MSW landfills.

The requirements to establish the use of a waste material as a product in the State of New Hampshire involves defining (i) the physical and chemical variability of the ash process stream, (ii) a suitable market for the product, and (iii) an evaluation of the performance of the product. The earlier two year characterization study addressed the first two requirements by showing the relative invariability of the chemical and physical properties of the bottom ash as it is produced at the Concord plant, the successful replacement of ash for aggregate in the establishment of a pavement job mix formula, the successful manufacture of pavement at a batch hot mix asphalt plant, and the critical role that bituminous polymeric asphalt plays in controlling diffusional leaching behavior.

The project was designed to address both the potential short term and long term environmental issues associated with the use of grate ash as an aggregate substitute in an asphalt binder course. The short term issues have been addressed by using a combination of field and laboratory experiments. Additional laboratory experiments and predictive models have been used to address the potential long term environmental issues.

WHAT ARE THE SITE HYDROGEOLOGICAL CHARACTERISTICS?

The hydrogeology in the control section is dominated by glacial outwash loamy sands. Hydraulic conductivities ($12\text{-}28\text{ ft/d}$ or $4.0 \times 10^{-3} - 9.9 \times 10^{-3}\text{ cm/sec}$), shallow gradients (0.008 ft/ft or m/m), and seepage velocities ($0.5\text{ to }1.1\text{ ft/d}$ or $0.15\text{-}0.33\text{ m/d}$)

are typical for permeable soils in close proximity to surface waters (Paugus Bay on Lake Winnepesaukee). The hydrogeology in the test section is dominated by thin overlays of glacial till on top of highly fractured metasedimentary pelitic schists of the Rangely Formation. Hydraulic conductivities ($0.11\text{--}0.4$ ft/d or 3.9×10^{-5} - 20×10^{-5} cm/sec), steep gradients (0.14 ft/ft or m/m), and seepage velocities (0.18 to 0.37 ft/d) are typical for relatively permeable bedrocks. The seasonal ground water table is high in the test section. To facilitate site characterization, five monitoring wells and a preexisting dug well were used to characterize ground water. Two suction lysimeters were used to characterize vadose zone moisture below the road, two road run-off storm drains were used to characterize road run-off, and two stations were used to characterize surface waters.

WHAT ARE THE ENVIRONMENTAL IMPACTS OF MAKING PAVEMENT WITH GRATE ASH?

The asphalt batch plant was evaluated for HCl emissions, particulate emissions, metals emissions and visible emissions during the production of control and test asphalts. The plant is regulated for particulate and visible emissions. Stack testing showed that the asphalt batch plant met all applicable air emissions limits during the production of both the control and test asphalts. The average HCl emissions were higher during test asphalt production (0.09 vs 0.13 lb/h). The average particle emission was moderately higher during the test asphalt production (1.66×10^{-2} versus 6.48×10^{-3} grains/dry standard cubic foot) but less than the limit of 4×10^{-2} grains/dry standard cubic foot. The average particulate metals content was higher during the control run for Cd, Cr, Ni, and Se. The

average particulate metals content was higher during the test run for Cu and Zn.

Opacity was higher during the test asphalt run (0 to 15% compared to 0 to 10%) but less than the 20% limit.

WHAT ARE THE CHEMICAL CHARACTERISTICS OF THE GRATE ASH AND MATERIALS EXISTING AT THE SITE PRIOR TO PAVING?

The grate ash was obtained from the Wheelabrator-Concord L.P. WTE facility. This is the same facility that provided the bottom ash for the earlier study. The facility is a 500 ton per day (454 metric tonnes per day) modern mass-burn system with von Roll reciprocating grates. Only grate ash was collected. The residues were trommeled to remove oversize material prior to aging for about six months at the Franklin, N.H. secure ash monofill.

Grate ash was evaluated in both its fresh form and its aged form for total element composition and total available composition. These data were then compared to the bottom ash total element composition and total available composition data obtained in the earlier two year study (Eighmy et al., 1992; Whitehead, 1992).

For the total composition data, data ranges overlap for all elements for each ash type. However, the bottom ash usually has high concentration outlier values. For the total available composition data, data ranges overlap for all elements for each ash type. However, the bottom ash usually has high concentration outlier values that coincide with the high total composition data. Some of the high outlier elements are those traditionally associated with grate siftings (Al, Pb, Zn). Some of the high outlier elements are not associated with grate siftings (Ca, Cl, Ti). The high outliers in bottom

ash may be associated with the presence of grate siftings in the bottom ash, artifacts associated with the way the two ash types were collected or artifacts associated with minor differences in the sampling and processing (i.e., sieving and trommeling) of the ash samples.

The influence of aging on grate ash element total availability was statistically evaluated. There were slight differences in availability between the fresh and the aged grate ash as determined by Student's t-test (95% probability, pooled variances, two tailed comparison). Na and Si availabilities were significantly higher in the fresh grate ash. Al and Fe availabilities were significantly higher in the aged grate ash. These differences are attributed to robust changes in ash mineralogy during aging. More subtle changes (e.g carbonation) would not be detected because of the aggressive nature of the Dutch Total Availability test that was used.

The aged grate ash was evaluated for its TCLP characteristics and was determined to be not hazardous according to federal and state regulations.

The characteristics of the road side soils and RAP show that significant anthropogenic Pb and Cl was present at the site prior to the paving demonstration. Soil lead values ranged from 31 to 269 mg/kg. Soil chloride values ranged from 68 to 250 mg/kg. RAP lead values ranged from 32 to 36 mg/kg. RAP chloride values ranged from 200 to 204 mg/kg. The lead comes from long term deposition of lead aerosols and the use of tetraethyl lead in leaded gasoline. The chloride comes from road salting and other sources of contamination in the local watershed.

DID GRATE ASH CONSTITUENTS MIGRATE INTO THE BITUMINOUS POLYMER AT THE MICROSCALE LEVEL?

Pavement samples removed after 1.25 years of service life were subjected to SEM/XRM studies to determine if ash constituents were migrating, via molecular diffusion, from ash particles into the surrounding bituminous polymer matrix. Studies were conducted at the microscale level (on the order of tens of microns). If significant migration from the ash particle to the polymer had occurred, then high concentrations of the element would be detected in the polymer. Profiles were established for Al, Cu, and Zn because of their larger particle size and the relative ease wherein they could be identified and located with SEM/XRM x-ray spatial mapping. No evidence was seen of significant microscale migration from particles containing Al, Cu, and Zn after 1.25 years of service life. Calculated effective diffusion coefficients for molecular diffusion were in the 10^{-16} to 10^{-17} cm²/sec range; these values are extremely low and are typical for molecular diffusion in polymers. They are also in general agreement with data derived from monolith leach tests.

DID GRATE ASH CONSTITUENTS MIGRATE VERTICALLY INTO THE WEARING COURSE OR RAP BASE COURSE AT THE MACROSCALE LEVEL?

Pavement samples removed after 1.25 years of service life were subjected to elemental composition analysis using NAA and XRF analyses. Road cores from the test and control sections were disassembled into their wearing course, binder course and RAP base course components. If large scale migration had occurred up into the wearing course or down into the RAP base course from the test binder course, then the

concentrations of elements in these courses would be higher in the test section when compared to controls. With the exception of Mn and Al, statistical evaluations using Student's t-test (95% probability, pooled variances, two tailed comparisons) showed that no significant differences existed in the elemental composition of test and control sample populations for the wearing course and RAP base course. Thus no evidence of macroscale migration was seen after 1.25 years of service life.

WHAT IS THE MONOLITH LEACHING BEHAVIOR OF ROAD CORES?

Road cores taken from the road right after pavement construction ($t=0$ years) and after a 1.25 year service life ($t=1.25$ years) were subjected to the Dutch NEN 7345 Tank Leaching Test. Effective diffusion coefficients (D_e) for leaching from monoliths were determined for Ca, Fe, Mg, Mn, Si, Na, Zn, Cl, and SO_4^{2-} ; these were the only constituents exhibiting diffusive behavior. Generally, Ca, Fe, Mg, and Mn diffused from control section cores. Generally, Ca, Cl, Mg, Mn, Na, SO_4^{2-} , Si and Zn diffused from test section cores. Values ranged from $10^{-12} \text{ m}^2/\text{sec}$ (Cl) to $10^{-16} \text{ m}^2/\text{sec}$ (Zn). Such values are typical for ion diffusion under aqueous situations in tight, hydrophobic polymeric monoliths like intact pavements. Values of chemical retention (R) were less important than tortuosity (τ) in reducing diffusivity. With the exception of Ca, no significant differences using Student's t-test (95% probability, pooled variances, two tailed comparisons) were seen between test section cores after pavement construction and after 1.25 years of service life.

HOW DOES VOID CHANGE, BITUMINOUS POLYMER AGING AND MICROCRACKING INFLUENCE MONOLITH DIFFUSIONAL LEACHING BEHAVIOR SO AS TO PREDICT LONG TERM PAVEMENT BEHAVIOR?

In an effort to predict how the test road might behave 20 or more years into its service life, a factorially designed experiment using analysis of variance (ANOVA) was utilized to evaluate voids, bitumen aging, and monolith microcracking on leaching behavior. Three levels of pavement voids (5%, 7.5% and 10%), three levels of bituminous polymer aging (none, medium and high) and three levels of monolith microcracking (none, medium, and high) were used. These were selected to predict how traffic-induced densification (voids decreases), atmospheric oxygen and UV light aging (polymer oxidation), and monolithic integrity (microcracks) might influence diffusional leaching process. The results show that microcracking, and to a lesser extent aging and the interaction term between cracking and aging, are the only statistically significant process; high levels of microcracking reduce tortuosities (τ) from 8,000 to 10,000 down to 200 to 400. The results show that monolithic microcracking can influence leaching behavior.

HOW DOES GRATE ASH GRAIN SIZE AND THE PRESENCE OF BITUMINOUS ASPHALT CEMENT INFLUENCE GRANULAR DIFFUSIONAL LEACHING BEHAVIOR SO AS TO PREDICT FUTURE BEHAVIOR AS A RAP MATERIAL?

The granular diffusion leaching test was used in an attempt to predict how the test road materials might behave in a compacted form either as a RAP base course pavement (ground to $<3/4$ " or 1.9 cm) situated beneath a pavement, or as a compacted material disposed in a landfill ($<3/4$ " or 1.9 cm granular material), or as a compacted

product of road grinding (fine granular material). This test produces effective diffusion coefficients (pD_e), chemical retentions (R) and tortuosities (τ) for compacted granular material. The results showed a 1 to 3 log decrease in effective diffusion coefficients when granular behavior was compared to monolithic behavior. Tortuosities (τ) were significantly reduced (10,000 down to 50) while chemical retention (R) increased (by factors of 10). Of the three granular materials, 3/4" (1.9 cm) minus pavement with asphalt cement was the least diffusive, followed by 3/4" (1.9 cm) minus grate ash and <300 μm (0.12") grate ash. The results also showed that asphalt cement still significantly reduced leachability even in granular materials. This occurred because asphalt cement was incorporated in the internal pores of the grate ash particles, dramatically reducing the effective surface area for leaching. The use of binder course containing grate ash as a RAP material in subsequent pavement reconstructions is also a viable use.

WHAT ARE DATA ON THE LONG TERM LEACHING OF BOTTOM ASH OR PAVEMENTS CONTAINING BOTTOM ASH?

In the earlier two year characterization study (Eighmy et al., 1992), two large outdoor lysimeters were constructed to evaluate the long term, percolation-based, leaching behavior of the bottom ash from the Penacook WTE facility and the monolithic diffusional leaching of large, broken pavement materials made with bottom ash (25% substitution). The lysimeters have been in operation for four years. The constituents Ca, SO_4^{2-} , Cl, Na, and K leached in the greatest concentration from both lysimeters. NH_4^+ -N, Br, PO_4^{3-} -P, B, Fe, Mg, Mn, Sr and Si leached, but at much lower levels. The asphalt monolith reduced leachability by 1 to 2 orders of magnitude. Cumulative release

plots show the leaching history of these materials. The data are useful for evaluating leaching behavior for utilization scenarios (granular fill) or disposal scenarios that are not presently under consideration in this project.

CAN MODELING OF CONSTITUENT FLUXES FROM PAVEMENT SAMPLES FOR VARIOUS TIME PERIODS AND DEGREES OF WETTING BE USED TO PREDICT LONG TERM PAVEMENT BEHAVIOR?

A one dimensional diffusion model was used to estimate constituent release for the test pavements using a number of life cycle scenarios (new pavement, 10 year old pavement, 20 year old pavement, RAP base course pavement), a number of conservative estimates of wetting (5, 10, 20% of the time) and three reference leaching periods (1.5 years, 20 years, 100 years). The approach estimates what would be released at the lower binder course/soil interface for binder course pavements containing grate ash or at the RAP/soil interface for RAP base course containing grate ash. It assumes that an intact pavement would exist above either ash-containing course. It does not take into account any subsequent attenuation that would occur in soils below the interface. The wetting percentages are estimates of the time where the interface would be wetted by ephemeral condensation from soil water vapor. Appropriate pD_e , R , and availability values from the road cores were used for all elements exhibiting diffusional leaching behavior (Ca, Cl, Fe, Mg, Mn, Na, Si, SO_4^{2-} , Zn). As an example, chloride (a mobile constituent), is discussed. Modeled fluxes at the interface for chloride ranged from 1.41 g/m²/1.5 years to 104.4 g/m²/100 years. These fluxes are considered extremely low and do not reflect

any subsequent extensive attenuation that would occur if subsequent migration were to take place downwards towards the water table.

WHAT IS GROUND WATER QUALITY AT THE STUDY SITE?

An extensive program was undertaken to characterize the ground water, surface water, vadose zone moisture, and road run-off at the site prior to and after placement of the pavement. The ground water quality was compared to existing State and Federal drinking water quality standards. No project related impact was seen.

Lead was the only analyte to exceed primary drinking water standards MCLs. The standard was exceeded in both the control and test sections prior to the placement of pavement as well as after pavement reconstruction. No other primary drinking water standards were exceeded. The source of the lead detected in the ground water in the test section was from historical anthropogenic inputs (atmospheric deposition of lead aerosols, combustion of leaded gasoline) and not from the grate ash. Comparisons were also made for secondary drinking water standards; exceedences occurred for Cl, Fe, Mn and Na. However, like lead, they occurred in both the test and control sections prior to placement of pavement as well as after pavement reconstruction. Trend analyses were conducted for lead and chloride data for all sampling locations; no statistically significant increasing trends were seen in either the control or test section for lead; increasing trends for chloride were seen at two locations in the control section. Evaluation of lead isotope ratios ($^{207}\text{Pb}/^{204}\text{Pb}$), and of conservative ion ratios (K/Cl versus Ca/Cl , $\text{Na}/\text{SO}_4^{2-}$ versus Ca/Cl , $\text{Na}/\text{SO}_4^{2-}$ versus K/Cl) unequivocally show that the lead and chloride in

the ground water are not originating from the grate ash. They are preexisting anthropogenic contaminants.

HOW DOES COMPARISON OF MODELLED CONSTITUENT FLUXES FROM PAVEMENTS COMPARE TO PREEXISTING BACKGROUND CONTAMINATION FLUXES?

Comparisons were made for possible ash constituent fluxes that might occur at the interface between the binder course and soil to fluxes of contaminants coming from road run-off or from the migration of preexisting, mildly contaminated ground water under the road. The presence of upgradient background ground water contamination or anthropogenic activity produced fluxes that were usually orders of magnitude larger (10^2 to 10^5 times) than possible signals at the binder course/soil interface from the test road over the 1.5 year evaluation period.

ARE THE ENVIRONMENTAL BEHAVIORS OF BOTTOM ASH AND GRATE ASH FROM THE CONCORD WTE FACILITY SIMILAR?

The total elemental composition, total available composition, monolithic leaching behavior, and behavior of granular RAP material was compared for fresh bottom ash and fresh and aged grate ash. The elements Ca, Si, Cl and Pb were compared. Bottom ash was found to have high outlier concentrations for total elemental composition and total available composition. However, ranges overlapped for all three ash types. Monolith leaching behavior was similar for all ash types. Similar availabilities, fluxes, diffusivities, tortuosities, and leaching mechanisms were observed for each ash type in each element category. The leaching behavior of granularized monoliths made with

either fresh bottom ash or fresh grate ash was similar with respect to the influence of asphalt cement on the reduction of leaching (release or flux). The data shows that there are no apparent differences between the environmental behavior of bottom ash and grate ash in asphaltic products.

IS AGING REQUIRED?

If bottom ash (with grate siftings) from the Concord WTE facility is to be used in asphaltic pavements without aging, then its environmental behavior will be similar to grate ash and would not be problematic. From a conservative materials performance perspective, aging should be considered to stabilize the material. A minimum time period of one to three months would provide a conservative approach. Further studies may show that aging may not be needed or that these times can be reduced.

If grate ash (without grate siftings) is used in asphaltic pavement without aging, its environmental behavior will be acceptable. From a materials performance perspective, aging should be less important because grate siftings are absent. A conservative approach would be to have grate ash generators or users evaluate the need for grate ash aging as needed.

APPLICATION OF THESE RESULTS TO ANALOGOUS USES

The transferability of these results to analogous uses in hot mix asphalt pavement binder courses has been discussed for a scenario involving a similar combustor using a modern grate system and good combustion practices. A number of criteria have been

suggested. The grate ash or bottom ash must be processed for grain size considerations. It may be necessary to control the moisture content of the ash during storage. Aging requirements related to physical performance must be determined by the user. The ash total Si, Cl and Pb concentrations should have similar distributions and measures of central tendency to the Concord grate or bottom ash. These elements are indicative of slag chemistry and leaching behavior. Additionally, the ash loss on ignition should be controlled as values less than 10% are deemed to be acceptable for use in asphaltic pavements. The mix design for the binder course should involve state- or user-specified mix designs with ash loading less than 50%. The environmental performance of the product should involve the use of tests to verify monolithic leaching behavior or the encapsulating effect of the asphalt cement.

GRATE OR BOTTOM ASH USE AS AN AGGREGATE SUBSTITUTE IN PAVEMENTS

The use of grate ash from the Concord WTE facility as an aggregate substitute has a non-existent to negligible impact on the environmental quality at the study site. Grate ash has defined chemical and physical characteristics. Its fundamental leaching behavior and its diffusive leaching behavior in monolithic and granular forms are well understood. Models can be used to predict long term leaching behavior for all of the pavement life cycle scenarios. Its behavior is virtually indistinguishable from standard pavements. Grate or bottom ash from a modern mass burn WTE facility such as the Concord WTE facility when used in pavement binder course is an acceptable use for this light weight aggregate substitute.

REFERENCES

- APHA (1989) *Standard Methods for the Examination of Waters and Wastewaters*, 16th edition. APHA, Washington, D.C.
- ASTM (1991) *Annual Book of ASTM Standards*, ASTM, Philadelphia, PA.
- Ault, W.U., R.G. Senechal, and W.E. Erlebach (1970) Isotopic Composition as a Natural Tracer of Lead in the Environment. *Environ. Sci. Technol.* 4:305-313.
- Bastanza, G. (1982) *Summary Update of Research Projects with Incinerator Bottom Ash Residue*. Department of Environmental Management Document.
- Chesner, W.H. (1991) Environmental Issues Associated with the Use of MSW Combustor Ash in Asphalt Paving Mixes, p. 608. In: *Municipal Waste Combustion, Proceedings of the Second Annual International Conference*, AWMA Press, Pittsburgh, Penn.
- Chesner, W.H., R.J. Collins, and T. Fund (1988) *Assessment of the Potential Suitability of Southwest Brooklyn Incinerator Residue in Asphaltic Concrete Mixes*. NYSERDA Report 90-15.
- Collins, R.J., R.H. Miller, S.K. Ciesielski, E.M. Wallo, M.J. Boyle, D. Pindzola, and J. Tropea (1977) *Technology for Use of Incinerator Residue as Highway Material*. FHWA/RD-77/51.
- Crank, J. (1975) *The Mathematics of Diffusion*. Clarendon Press, Oxford.
- de Groot, G.J., and H. van der Sloot (1992) Determination of Leaching Characteristics of Waste Materials Leading to Environmental Product Certification. In: *Proc. 2nd International Symposium on Solidification/Stabilization of Hazardous, Radioactive, and Mixed Wastes*, ASTM D-34 Committee, May 29-June 1, 1990, Williamsburg, Virginia.
- de Groot, G.J., H. A. van der Sloot, P. Bonouvrie, and J. Wijkstra (1990) *Karakterisering van het Uitlooggedrag van Intacte Produkten*. MAMMOET deelrapport 09, ECN-C-90-007, Petten, the Netherlands.
- DHV Milieu en Infrastructure BV (1992a) *Rijkswaterstaat, Dienst Weg-en Waterbouwkunde. Milieutechnisch onderzoek AVI-slakken Toepassing Rijksweg 15*. Interim Deelrapport 1.

- DHV Milieu en Infrastructure BV (1992b) *Rijkswaterstaat, Dienst Weg-en Waterbouwkunde. Milieu technisch onderzoek AVI-slakken Toepassing Rijksweg 15. Interim Deelrapport 2.*
- DHV Milieu en Infrastructure BV (1992c) *Rijkswaterstaat, Dienst Weg-en Waterbouwkunde. Milieutechnisch onderzoek AVI-slakken Toepassing Rijksweg 15. Interim Deelrapport 3.*
- Ederly, J., and W.B. Ledbetter (1991) *Field Performance of Littercrete (Incinerator Residue) in a Bituminous Base.* FHWA/RD-88/022.
- Eighmy, T.T., M.R. Collins, J.V. DiPietro, and M.A. Guay (1989) Factors Affecting Inorganic Leaching Phenomena from Incineration Residues, p. 7-9 to 7-23. In (J.M. Greenblott, C. Springer, eds.) *Municipal Solid Waste Technology Conference Proceedings*, U.S. EPA, Washington, D.C.
- Eighmy, T.T., S.F. Bobowski, T.P. Ballester, and M.R. Collins (1990) Theoretical and Applied Methods of Lead and Cadmium Stabilization in Combined Ash and scrubber Residues, p. 275-314. In: (W.H. Chesner and T.T. Eighmy, eds.) *Proc. Second International Conference on Municipal Solid Waste Combustor Ash Utilization*, UNH Press, Durham, NH.
- Eighmy, T., D. Gress, X. Zhang, S. Tarr, and I. Whitehead (1992). *Interim Report: Bottom Ash Utilization Evaluation for the Concord, New Hampshire Waste-to-Energy Facility.* ERG Publication, University of New Hampshire.
- Eighmy, T.T., J.D. Eusden, Jr., K. Marsella, J. Hogan, D. Domingo, J.E. Krzanowski, and D. Stämpfli (1994) Particle Petrogenesis and Speciation of Elements in MSW Incineration Bottom Ashes, pp. 111-136. In (J.J.J.M. Goumons, H.A. van der Sloot, Th.G. Aalbers, eds.) *Waste Materials in Construction*, Elsevier Science Publ., B.V., Amsterdam.
- Eighmy, T.T., D. Crimi, S. Hasan, X. Zhang, and D.L. Gress (1995) The Influence of Void Change, Cracking and Bitumen Aging on Diffusional Leaching Behavior of Pavement Monoliths Constructed with MSE Combustor Bottom Ash. *Trans. Res. Record* 1486: 42-48.
- Emery, J.J. (1982) *Slag Utilization in Pavement Construction*, ASTM Special Publication, ASTM, Philadelphia, Penn.
- EPRI (1984) *Chemical Attenuation Rates, Coefficients, and Constants in Leachate Migration.* EPRI EA-3356, Palo Alto, California.

- Eusden, J.D. Jr., E.A. Holland, and T.T. Eighmy (1994) Petrology, Bulk Mineralogy and Melt Structure of MSW Bottom Ash from the WASTE Program, pp: 87-105. In: *Proc. 16th Canadian Waste Management Conference, Calgary, Alberta*, Environment Canada, Ottawa.
- Eusden, J.D. Jr. and T.T. Eighmy (1995) Petrology of Bottom Ashes. In: *Proc. International Conf. on Solid Waste Management: Thermal Treatment and Waste-to-Energy Technologies* (in press).
- Farrand, B. and J. Emery (1995) Recent Improvements in the Quality of Steel Slag Aggregate. *Trans. Res. Record* 1486: 137-141.
- Flegal, A.R., K.J.R. Rosman, and M.D. Stephenson (1987) Isotope Systematics of Contaminant Leads in Monterey Bay. *Environ. Sci. Technol.* 21:1075-1079.
- Freeze, R.A. and J.A. Cherry (1979) *Groundwater*. Prentice-Hall Inc., Englewood Cliffs, New Jersey.
- Gaudette, H. (1995) Personal Communication.
- Gilbert, R.O. (1987) *Statistical Methods for Environmental Pollution Monitoring*, Van Nostrand Reinhold Co., New York.
- Gobeil, C., W.K. Johnson, R.W. MacDonald, and C.S. Wong (1995) Sources and Burden of Lead in St. Lawrence Estuary Sediments: Isotopic Evidence. *Environ. Sci. Technol.* 29:193-201.
- Gress, D.L., X. Zhang, S. Tarr, I. Pazienza, and T.T. Eighmy (1991) Municipal Solid Waste Combustion Ash as an Aggregate Substitute in Asphaltic Concrete, p. 161-175. In: (J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers, eds.) *Waste Materials in Construction*, Elsevier, Amsterdam.
- Gress, D.L., X. Zhang, S. Tarr, I. Pazienza, and T. Eighmy (1992) The Physical and Environmental Properties of Asphalt Amended Bottom Ash. *Transportation Research Record*. 1345:10-18.
- Gress, D.L., T.T. Eighmy, S.J. Karpinski, V. Janoo, D. Crimi, and S.L. Hasan (1996) *The Laconia, N.H. Bottom Ash Paving Project. Physical Performance Testing Report* (Volume 1). ERG Publication, University of New Hampshire.
- Grousset, F.E., C.R. Outel, B. Thomas, P. Buat-Mnard, O.F.X. Donard, and A. Bucher (1994) Transient Pb Isotopic Signatures in the Western European Atmosphere. *Environ. Sci. Technol.* 28:1605-1608.

- Gulson, B.L., K.G. Tiller, K.J. Mizon, and R.H. Merry (1981) Use of Lead Isotopes in Soils to Identify the Source of Lead Contamination Near Adelaide, South Australia. *Environ. Sci. Technol.* 15:691-696.
- Hartlén, J. and A.-M. Fallman (1991) Sorted Bottom Ash from MSW Incineration in Road Embankments, p. 271-280. In (W.H. Chesner and T.T. Eighmy, eds.) *Proc. Third International Conference on Municipal Solid Waste Combustor Ash Utilization*, UNH Press, Durham, N.H.
- Haynes, J., and W.B. Ledbetter (1976) *Incinerator Residues in Bituminous Base Construction*. FHWA/RD-76/12.
- Hjelmar, O. (1991) Regulatory and Environmental Aspects of MSWI Ash Utilization in Denmark, p. 59-70. In (W.H. Chesner and T.T. Eighmy, eds.) *Proc. Third International Conference on Municipal Solid Waste Combustor Ash Utilization*, UNH Press, Durham, N.H.
- Hvorslev, M.J. (1951) *Time Lag and Soil Permeability in Groundwater Observations*. U.S. Army Corps of Engineers Waterways Exp. Stat. Bull. 36, Vicksburg, Miss.
- IAWG (1994) *An International Perspective on Characterization and Management of Residues from Municipal Solid Waste Incineration*, ECN, Petten, the Netherlands.
- Jakkola, T., O.J. Heinonen, M. Keinonen, A. Salmi, and J.K. Miettinen (1983) Use of $^{206}\text{Pb}/^{204}\text{Pb}$ Isotope Ratio in Lichen, Air Filter, Incinerator Ash and Gasoline Samples as Pollution Source Indicator. *Int. J. Mass Spec. Ion Phys.* 48:347-350.
- Johannessen, K.M. (1993) Fueling the Ash as Hazardous Waste Debate: A Legal Update, p. 1041-1055. In: *Proc. 1993 International Conf. on Municipal Waste Combustion*, Williamsburg, Virginia, AWMA, Pittsburgh, Penn.
- Kirkner, D.J., A.A. Jennings, and T.L. Theis (1987) *Multi-Solute Subsurface Transport Modeling for Energy Solid Wastes*. DOE/EV/10253-5.
- Kosson, D.S., T.T. Kosson, and H.A. van der Sloot (1993) Evaluation of Solidification/Stabilization Treatment Processes for Municipal Waste Combustion Residues. NTIS PB93-229 870/AS.
- Lagerwerff, J.V. and A.W. Specht (1970) Contamination of Roadside Soil and Vegetation with Cadmium, Nickel, Lead, and Zinc. *Environ. Sci. Technol.* 4:583-586.
- Lindsay, W.J. (1979) *Chemical Equilibria in Soils*. J. Wiley & Sons, N.Y.

- LIRPB (1994) *The Potential for Use of Waste-to-Energy Facility Ash - Executive Summary*, NYSERDA Report 94-9, Albany, N.Y.
- Mason, R.L., R.F. Gunst, and J.L. Hess (1989) *Statistical Design & Analysis of Experiments With Applications to Engineering and Science*. J. Wiley & Sons, N.Y.
- McBride, M.B. (1994) *Environmental Chemistry of Soils*. Oxford University Press, N.Y.
- Mehan, D.G., and W.F. Hooper (1991) Processed Ash Demonstration Project, p. 627-641. In: *Municipal Waste Combustion. Proc. Second Annual International Specialty Conference*, AWWA, Pittsburgh, Penn.
- Miller, J.C. and J.N. Miller (1988) *Statistics for Analytical Chemistry*. Ellis Horwood Ltd., Chichester, England.
- Mukai, H., N. Furuta, T. Fujii, Y. Ambe, K. Sakamoto, and Y. Hasimoto (1993) Characterization of Sources of Lead in the Urban Air of Asia Using Ratios of Stable Lead Isotopes. *Environ. Sci. Technol.* 27:1347-1356.
- Mulder, E. and R. Gerritsen (1990) *Semi-praktijkonderzoek Naar Het Uitlooggedrag Van Primaire en Secundaire Grondstoffen Als Wegfundering*. Mammoet-Deelrapport 11, TNO Ref. Nr. 90/006721, Apeldoorn, the Netherlands.
- Mulder, E. (1991) The Leaching Behavior of Some Primary and Secondary Raw Materials Used in Pilot-Scale Road Bases, p. 255-264. In: (J.J.J.M. Goumons, H.A. van der Sloot, Th.G. Aalbers) *Waste Materials in Construction*, Elsevier, Amsterdam.
- Musselman, C.N., M.P. Killeen, D. Crimi, S. Hasan, X. Zhang, and T.T. Eighmy (1994a) The Laconia, N.H. Bottom Ash Paving Project, pp. 315-328. In: (J.J.J.M. Goumons, H.A. van der Sloot, Th.G. Aalbers, eds) *Waste Materials in Construction*, Elsevier Science Publ. B.V., Amsterdam.
- Musselman, C.N., T.T. Eighmy, D.L. Gress, M.P. Killeen, J.R. Presher, and M.H. Sills (1994b) The New Hampshire Bottom Ash Paving Demonstration, US Route 3, Laconia, New Hampshire, pp. 83-90. In: *18th Biennial National Waste Processing Conference Proc.*, ASME, N.Y.
- Noureldin, A.S. and R.S. McDaniel (1990) Evaluation of Steel Slag Asphalt Surface Mixtures. *Proc. 69th TRB Annual Meeting*, Washington, D.C.
- Ormsby, W.C. (1989) Paving with Municipal Incinerator Residue, p. 49-62. In (T.T. Eighmy & W.H. Chesner, eds.) *Proc. 1st International Conference on Municipal Solid Waste Combustor Ash Utilization*, UNH Press, Durham, N.H.

- Pavlovich, R.D., H.J. Lentz, and W.C. Ormsby (1979) Incinerator Residue as Aggregate for Hot-Mix Asphalt Base Course, p. 38-44. *Transportation Research Record* 734.
- Sakai, S.I. and M. Hiraoka (1994) Ash Management in Japan: The Properties of Ash from Municipal Waste Incineration and Its Future Management Strategies. *Report to LAWG*, Kyoto University, Japan.
- Snyder, R.R. (1980) *Evaluation of Fused Incinerator Residue as a Paving Material*. FHWA-TS-88-229.
- Sposito, G. (1989) *The Chemistry of Soils*. Oxford University Press, N.Y.
- Stämpfli, D. (1991) Personal Communication.
- Stämpfli, D., H. Belevi, R. Fontanive, and P. Baccini (1990) *Reactions of Bottom Ashes from Municipal Solid Waste Incinerators and Construction Waste Samples with Water*. EAWAG Final Report, Project 3335.
- Stegemann, J.A., and J. Schneider (1991) Leaching Potential of Municipal Solid Waste Incinerator Bottom Ash as a Function of Particle Size, p. 135-143. In: (J.J.J.M. Goumans, H.A. van der Sloot, Th.G. Aalbers, eds.) *Waste Materials in Construction*, Elsevier, Amsterdam.
- Tarr, S.M. (1993) The Characterization of Municipal Solid Waste Combustor Bottom Ash Physical Properties and Its Use in Emulsified Asphalt Mixtures. Master's Thesis, University of New Hampshire, Durham, N.H.
- Tarr, S., D. Gress, and T. Eighmy (1994) The Use of Municipal Solid Waste Combustor Bottom Ash in Emulsified Asphalt Mixtures, pp. 53-77. In: (C.W. Lovell, ed.) *Proc. 2nd Annual Great Lakes Geotechnical/Geoenvironmental Conference*, Purdue University, West Lafayette, Indiana.
- Torstenfelt, B. (1986) Migration of Fission Products Strontium, Technetium, Iodine and Cesium in Clay. *Radiochimica Acta* 39:97-104.
- U.S. EPA (1979) *Methods for Chemical Analysis of Water and Wastes*. US EPA-600/4-79-020.
- U.S. EPA (1984) *Test Methods for Evaluating Solid Waste-Physical/Chemical Methods*. US EPA SW846.
- U.S. EPA (1987) *Sampling and Analysis of Municipal Refuse Incineration Ash* (Draft). Office of Solid Waste, U.S. EPA, Washington, D.C.

- van der Sloot, H.A. (1991) Personal Communication.
- van der Sloot, H.A., D. Hoede, and P. Bonouvrie (1991) *Comparison of Different Regulatory Leaching Test Procedures for Waste Materials and Construction Materials*. ECN-C-91-082, Petten, the Netherlands.
- van der Sloot, H.A. and D. Hoede (1994a) *Schattingen van de Emissie Vanvit Wegenbouw Toepassingen met Secundaire Materialen na ca. 10 Jaar Blootstelling aan Uitloging in de Praktijk*. ECN-C-93-073, Petten, the Netherlands.
- van der Sloot, H.A. and D. Hoede (1994b) *Veldmetingen van Emissies Uit Wegenbouw Toepassingen met Secundaire Materialen na ca. 10 Jaar Blootstelling aan Uitloging in de Praktijk*. ECN-C-94-026, Petten, the Netherlands.
- VEABRIN (1988) *Veabrin Kwaliteitskontrolle van AVI-Slakken '87-'88*, RAP-305/JJS/avd.
- Vehlow, J. (1991) Management of Residues from MSWI in the FRG, p. 71-84. In (W.H. Chesner, T.T. Eighmy, eds.) *Proc. Third International Conference on Municipal Solid Waste Combustor Ash Utilization*, UNH Press, Durham, NH.
- von Quintus, H.L., J.A. Scherocman, C.S. Hughes, and T.W. Kennedy (1991) *Asphalt-Aggregate Mixture Analysis System*. NCHRP 338, Transportation Research Board, National Research Council, Washington, D.C.
- Whitehead, I.E. (1992) *An Environmental Evaluation of Bottom Ash Substitution in Pavement Materials*. Master's Thesis, University of New Hampshire, Durham, N.H.
- Whitehead, I.E., T.T. Eighmy, D.L. Gress, and X. Zhang (1993) An Environmental Evaluation of Bottom Ash Substitution in Pavement Materials, pp. 356-370. In: *Municipal Waste Combustion*, AWMA, Pittsburgh, Penn.
- Zhang, X. (1993) *The Utilization of Municipal Solid Waste Incineration Bottom Ash as Paving Materials*. Ph.D. Dissertation, University of New Hampshire, Durham, N.H.
- Zhang, X., D. Gress, and T. Eighmy (1994) Bottom Ash Utilization as an Aggregate Substitute in Hot Mix Asphalt, pp. 33-52. In: (C.W. Lovell, ed.) *Proc. 2nd Annual Great Lakes Geotechnical/Geoenvironmental Conference*, Purdue University, West Lafayette, Indiana.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 1996		3. REPORT TYPE AND DATES COVERED Final Subcontract Report	
4. TITLE AND SUBTITLE The Laconia, New Hampshire, Bottom Ash Paving Project Vol. 1 Environmental Testing Report				5. FUNDING NUMBERS (C) XAE-3-13245 (TA) WM41.1010	
6. AUTHOR(S) T. Eighmy, D. Gress, D. Crimi, S. Hasan, S. Karpinski					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Environmental Research Group University of New Hampshire Durham, New Hampshire 03824-3591				8. PERFORMING ORGANIZATION REPORT NUMBER DE96000547	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401				10. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/TP-430-20959	
11. SUPPLEMENTARY NOTES NREL technical monitor: Philip Shepherd, (303) 275-2929					
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161				12b. DISTRIBUTION CODE UC-1414	
13. ABSTRACT (Maximum 200 words) Report documents a study on the successful use of grate ash from a waste-to-energy facility for aggregate substitute in an asphalt binder course pavement as part of a demonstration project. As part of the demonstration, a test section and a control section were built. the report concludes that the use of grate as or bottom ash from waste-to-energy facilities in pavement is an acceptable use of this light-weight aggregate substitute.					
14. SUBJECT TERMS solid waste management, waste-to-energy plants, pavements, ash, ash paving				15. NUMBER OF PAGES 300	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT		

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102