

ENVIRONMENTAL TESTING OF MUNICIPAL SOLID WASTE ASH-AMENDED ASPHALT

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ABSTRACT

As part of an on-going investigation of beneficial uses of ash from the H-POWER facility, a municipal solid waste combustor that burns refuse derived fuel on the island of Oahu in Hawaii, the upramp to the municipal solid waste tipping floor was paved with a 2 inch top course of 5% ash-amended asphalt, and the downramp was paved with a 2 inch top course of control asphalt.

Combined ash (~ 60% bottom ash/~40% flyash) was collected, tested for TCLP metals, and found to be representative of typical H-POWER combined ash. The ash was then 3/8 inch screened and analyzed for total metals and environmentally leachable metals by the Synthetic Precipitation Leaching Procedure (SPLP, pH 4.2). The ash-amended and control asphalt were both subjected to standard engineering tests. It was found that the ash-amended asphalt met the City and County of Honolulu and State of Hawaii mix requirements. Such tests included a Marshall test, an asphalt content test, a gradation analysis, a specific gravity test, and a compaction test using the Rice Method. To investigate any potential environmental effects, both pavements have been water washed twice a month since October, 1998, and soils in the areas where runoff water collects have been analyzed once a month. Wash water has been analyzed for total suspended soils, dissolved metals (12 metals of interest),

chloride, and hardness. Soil has been analyzed for total metals and SPLP metals, chloride and hardness. Test cores of both pavements have been analyzed for total metals and SPLP leachable metals, chloride and hardness. To accelerate the potential effects of weathering, test cores of pavement were broken and subjected to a serial leaching test by placing them in SPLP solution which has been analyzed and replaced monthly. In addition, intact test cores have been subjected to alternating cycles of submersion in SPLP solution and exposure to sunlight, rain, and wind with leachate tested monthly. Metal content and environmental leaching characteristics of the combined ash, the ash-amended asphalt and the control asphalt are presented, as are data from the first three months of the environmental testing program.

INTRODUCTION

The H-POWER waste-to-energy facility is a large refuse derived fuel (RDF) facility on the island of Oahu in Hawaii. The H-POWER facility takes in annually about 630,000 tons of municipal solid waste (MSW). The RDF is fired in two boilers producing about 326,000 megawatt hours of electric power and about 107,000 tons of wet ash per year. About 60% of the ash is bottom ash that fall off the grates into a water bath at the bottom of the boilers. The remaining ash is fly ash, which is carried out of the combustion chamber in the flue gas and collected in the

electrostatic precipitator. Each boiler is also equipped with a lime slurry scrubber for removal of acid gas materials. A bottom ash metal removal system has also recently been constructed that removes metal, glass, and stone greater than 3/8 inch in diameter and separates the metal into ferrous and nonferrous fractions.

For each ton of MSW disposed of at the H-POWER facility, sufficient electricity is produced to preclude combustion of approximately 60 gallons of fuel oil that would otherwise need to be imported to the island. Reduction of the volume of MSW by roughly 90% also conserves valuable landfill space. Still, the combined ash must currently be landfilled, and the capacity of the single landfill on the island is decreasing. Thus, the City and County of Honolulu is interested in identifying beneficial uses of the H-POWER combined ash. Diversion of combined ash from the landfill by beneficially re-using it would extend the lifetime of the landfill and confer additional benefits by decreasing the materials costs associated with the beneficial uses. This paper considers one of several beneficial uses currently under study: the partial substitution of combined ash for natural aggregate in asphalt manufacture. Other beneficial uses under study include the use of combined ash as daily cover at the City's currently operating MSW landfill and use of combined ash in the closure of an abandoned landfill.

HISTORICAL EXPERIENCE WITH MWC ASH IN PAVING APPLICATIONS

Municipal Waste Combustion (MWC) ash is widely used in Europe in road construction as compacted road base; structural fill in wind barriers, sound barriers, and highway ramps; and in asphalt applications (Kosson et al., 1996). In fact, approximately one-half of the MWC bottom ash generated in Germany is used in road construction (Stegemann and Schneider, 1991).

Similarly, in the Netherlands, there are more than ten years of experience with the use of MWC fly ash as a substitute for natural aggregate in asphalt in road construction (Hudales, 1994). The leaching behavior of asphalt containing MWC fly ash has been tested by order of the Dutch Ministry of Transport, Public Works, and Water Management according to the tank diffusion Dutch leaching test NVN 5432. No differences were found in the leaching of metals between asphalt pieces containing MWC fly ash compared to natural aggregates, and ash-amended asphalt passes the requirements for aggregates dictated in the draft Dutch Building Materials decree.

Since 1988, much asphalt containing MWC bottom ash has been produced and applied in about ten pilot projects. The production of asphalt was executed without problem.

There were no differences in the paving of test and control asphalts, and the pavements all performed well (Eymael et al., 1994).

There has also been considerable experience with the use and testing of ash-amended pavement in the United States. Gress et al. (1993) summarized selected paving projects in the United States in which MWC ash was used as a partial substitute for aggregate in asphalt pavement. Kosson et al. (1994) also summarized MWC combustor ash utilization projects in the United States. Their work stemmed from a cooperative agreement with the U.S. EPA on identification of the issues associated with MWC residue utilization and the development of recommendations for utilization criteria. These researchers presented, as an example, the proposed utilization of MWC ash in the binder course for asphalt pavement. Based on tank leaching experiments of MWC ash in a variety of asphalt pavements, they concluded that the use of MWC ash in asphalt would be "environmentally protective based on conservative assumptions" (Kosson et al., 1994, 1996).

In a recent paving demonstration project in the United States, a 600 meter section of U.S. Route 3 in the City of Laconia, New Hampshire was paved with MWC bottom ash as 50% of the required aggregate in the binder course pavement (Musselman et al., 1994). Roadway runoff, surface water, and groundwater were monitored. Groundwater was collected in suction lysimeters installed 1.5 to 3 meters beneath the pavement and in groundwater monitoring wells. The asphalt and the pavement performed well over the two year observation period, and environmental sampling showed no increases in chemical constituents compared to the control pavement that were attributable to the use of the MWC ash. Bench scale monolith leaching tests over 64 days were also performed. According to Musselman, et al. (1994), monolith leaching tests have all indicated that release rates of chemical constituents are low and occur at levels similar to those for natural aggregates.

In Massachusetts, the Department of Environmental Protection recently issued a Beneficial Use Permit for the use of MWC ash as an amendment in asphalt paving of roads. Supporting data for this permit included bench scale leaching experiments and environmental sampling of a test road.

ENVIRONMENTAL TESTING PROGRAMS PREVIOUSLY EXECUTED

The release of chemical constituents to the environment has been demonstrated on numerous occasions not to be correlated with the total concentration of the constituents

in the material (van der Sloot, 1991). Thus, total metal analyses do not yield useful information about leaching potential, and specific leaching tests should be performed. A number of leaching tests have been used to test raw MWC ash, stabilized MWC ash, and MWC ash-amended asphalt and cement products. These range from single batch extraction tests, column tests, monolith tank tests, and field lysimeters of different designs. Single batch extraction tests, such as EP-TOX, TCLP, SPLP, and the similar procedures developed by the Swiss, French, and German governments do not allow an extrapolation to long term effects, nor do they provide information about leaching mechanisms (van der Sloot, 1991). Column tests are useful only for granular materials. Accordingly, they would be useful if MWC ash were proposed for use as structural fill, but not for use as an amendment in pavement. For ash-amended pavement, the most appropriate leaching tests are the monolith tank tests and the field lysimeter tests. Such tests have been performed by many investigators, with slight variations. Several examples from the literature are described below, as is a brief description of leaching mechanisms.

Leaching of chemical constituents has been shown to occur by two mechanisms, depending on the application. In diffusion controlled leaching, the pores of the products fill with water. Dissolution of metals occurs, but the dissolved constituents can reach the environment only after diffusion through the pore structure of the material. The rate limiting step is diffusion. In tank leaching tests, diffusion leaching is measured and quantified. The other leaching mechanism is percolation. This mechanism occurs when there is a flow of water through a granular material. Diffusion also occurs, but it is not the rate limiting step. The overall leaching rate is dependent on the rate of percolation. Column leaching tests measure and quantitate percolation leaching.

Release through leaching may either be percolation controlled or diffusion controlled. Percolation controlled leaching occurs when the material is granular and is used in an application having significant infiltration. Diffusion controlled leaching occurs when the material is either monolithic and durable or is compacted granular material with low permeability or with an overlying barrier preventing infiltration (Kosson et al, 1994). With MWC ash in asphalt pavement, tank leaching tests should be done, because leaching would be diffusion controlled (Kosson, et al. 1994).

Numerous researchers recommend tank leaching tests to estimate the rate of metal leaching from ash-amended pavement pieces. "The tank leaching test ... is a good characterization method for the leaching behaviour of

monolithic materials as it provides knowledge on release controlling parameters and allows prediction of release at longer time scales by the leaching parameters derived from the test results" (van der Sloot et al., 1994). Such tank tests have been field validated. For instance, from tank leaching experiments over a period of up to three years, diffusion controlled release of chemical constituents from coal ash-amended asphalt was observed. A core sample of asphalt that was applied in 1966 was later analyzed to validate the assumption in a field situation that leaching was, indeed, diffusion controlled. The measured leaching depth of metals in the concrete could be explained by Fick's second law of diffusion using literature values for the effective diffusion coefficient (van der Wegen and van der Plas, 1994).

Numerous tank leaching methods have been described. For instance, Dutch method NEN 7345 (formerly NVN 5432) resembles the American Nuclear Society method ANSI6.1. In the Dutch method, the liquid to solid ratio is 5, the specimen is submerged, and leachate is removed after varying time points up to 64 days. Eymael et al. (1994); Hudales (1994); Kosson et al. (1994); Eighmy et al. (1995); Gress et al. (1992); Whitehead et al. (1993); and Kosson et al. (1996) all report tests of ash-amended asphalt pieces with the Dutch method or a modification thereof.

Van der Sloot has modified the procedure and validated it with cement-stabilized MWC fly ash and other materials using a shorter time (16 days). In a similar test, Bialucha et al. (1994) placed a 2 kg test specimen in 30L of deionized water in propylene or glass tank for 24 hours. The liquid to solid ratio was 10.

To evaluate the leaching of chemical constituents from cement stabilized MWC combined ash proposed for placement directly in coastal water, Hjelmar et al. (1994) performed tank leaching assays with ocean water. Monolithic 6 cm³ specimens were suspended in a closed seawater-filled polypropylene tank by a nylon string. The water (0.9 L) was replaced by new seawater at varying time intervals from 0.7 to 47 days.

The U.S. EPA Program for Evaluation of Treatment and Utilization Technologies for Municipal Waste Combustor Residues uses a Monolith Leach Test to assess the release of chemical species from treated and untreated residues. 4 cm diameter by 4 cm high cylindrical monoliths are prepared and tested. These monoliths are extracted by contacting distilled water for up to 64 days. Contacting water is replaced at 1, 2, 4, 8, 16, 32, and 64 days and analyzed. The leach test is a modified version of the ANSI 16.1 test (Kosson et al, 1994).

Thus, monolith leaching tests are useful to evaluate the fundamental leaching behavior of ash-amended pavement. However, the total immersion of samples in water is a more aggressive test of leaching potential than will exist in the field, because pore spaces will not be saturated in the field situation (Musselman, et al, 1994). Thus, such tests should be considered conservative and health-protective.

Field test lysimeter tests have also been conducted. For instance, 12 tons of MWC ash-amended asphalt pavement was manufactured with 25% ash/75% natural aggregate. The mix was paved, compacted, and broken up after one week with a backhoe into large pieces (palm sized to 2 by 3 foot plates). These pavement pieces were placed into a 20 cubic yard double-lined roll-off container. Leachate originating from natural rainfall was collected and analyzed (Gress et al., 1995; Whitehead et al., 1993). Releases of metals from the ash-amended pavement measured in the field lysimeter were two orders of magnitude lower than the releases from the raw MWC ash in a control lysimeter. Good agreement was seen comparing the monolith tank leaching test results and the field lysimeter test results.

ENVIRONMENTAL TESTING OF H-POWER COMBINED ASH-AMENDED PAVEMENT

Before approving the use of H-POWER combined ash in asphalt manufacture, it must be demonstrated to the Hawaii Department of Health that the beneficial use is environmentally acceptable. One of the major issues associated with this beneficial use of H-POWER combined ash is the potential leaching of the metals contained in the ash from the roadway materials (Kosson et al., 1994; Kosson et al., 1996; Eighmy and van der Sloot, 1994.).

To test the environmental consequences of using H-POWER combined ash as a partial substitute for natural aggregate in asphalt, the upramp to the municipal solid waste tipping floor was paved with a 2 inch top course of 5% ash-amended asphalt, and the downramp was paved with a 2 inch top course of control asphalt. There are two goals of the testing program: (1) to determine if there is a significant increase in the release of metals from ash-amended test pavement compared to control pavement, and (2) if there is an increased release, to obtain data that can be used in a human and ecological risk assessment to determine if estimated risks are acceptably low. If the tests reveal no statistically significant increase in the release (or toxicity) of metals, it is neither possible nor appropriate to perform risk assessment calculations on the release of metals from ash-amended asphalt during pavement use. The test program is being conducted in accordance with an Operation Plan and Scope of Work

which has been approved by the Hawaii Department of Health.

To determine if the ash-amended pavement might degrade and release metal-containing particulates or dissolved metals, affecting soil and surface water in the area adjacent to a hypothetical road paved with the material, data on the effects of surface run-off were gathered from the pilot roadways by periodically washing the ramps with city water and collecting and analyzing run-off water and soil/sediment in areas where run-off collects. During the nine month test period, the ramps are not being cleaned with a vacuum sweeper. Instead, detritus is being hand removed from the ramps daily.

Natural patterns of surface water run-off from rainfall events have been observed for both ramps. In both cases, water flows to the inside curb because of the slopes of the ramps and the onto a specific area of the lawn in the front of the plant. In both areas, noticeable sedimentation is visible at the bottom of the ramp and on the lawn where particles deposit. All particles present on the ramps collect in these two areas, regardless of whether they are derived from pavement degradation, from material dropping off of trucks as they pass, or from dust from nearby industries that deposits on the ramps. Baseline soil/sediment samples were collected before the ramps were paved at several locations where surface run-off collects from both ramps. After paving, four test and four control samples are being collected monthly for nine months. Any pavement-derived particle-bound metals that might have worn away due to pavement degradation under normal use patterns might be expected to cause a time-dependent increase in the measured levels of metals in the soils/sediments compared to the baseline levels, if the release of metals from the ash-amended pavement were significant.

In theory, actual stormwater run-off could be collected from the facility on the facility lawn using the site typography as a natural collection device. However, because natural rainfall is unpredictable, the ramps are being washed with city water twice a month, and samples are collected within 10 minutes of the washing at the bottom of each ramp. Water is consistently applied from the truck's sprayers. Baseline wash water samples were collected before the ramps were paved at the bottom of each ramp. In addition, samples of city water were analyzed for dissolved metals as control samples. After paving, samples of wash water are being collected twice a month at both ramps for nine months and analyzed for total suspended solids and dissolved metals.

It should be anticipated that metals will be detected in soil/sediment and wash water samples in the areas where

surface run-off collects from both the test and the control roadways. A large database exists on the results of column leaching tests of natural aggregates, monolith leaching tests of specimens of pavement constructed with natural aggregate, and field lysimeter tests with pavement constructed with natural aggregate. These results clearly indicate that natural materials will leach metals *albeit* at low rates. In addition, it would not be unexpected to anticipate that metal particulates originating from any number of natural and industrial sources might deposit atop the test and control pavement. Accordingly, the goal of this environmental testing is to determine if the presence of metals in surface run-off differs significantly between the test and control pavement.

METHODS AND PROCEDURES

Roughly 5 tons of combined ash, as typically disposed, were collected every day for a total of five days. A separate, dedicated ash trailer replaced the usual ash collection trailer for a single period on each of the five days to allow ash to be collected for the asphalt study. Two combined ash samples were taken each day within one hour of ash collection. Each of these ten samples were submitted to O'Brien and Gere Laboratories, Inc. of Syracuse, New York for total metals analysis and TCLP analysis. It is important that TCLP data on the collected combined ash be directly comparable to the historical TCLP data. Accordingly, fly ash and bottom ash samples were separately collected and mixed, with metal pieces removed using the established H-POWER protocol for TCLP testing.

After the combined ash was demonstrated to be comparable to historical H-POWER combined ash, it was 3/8 inch screened. Ten random samples were collected and split into two sets of ten 5 kg samples. One set was submitted to O'Brien and Gere Laboratories, Inc. of Syracuse, New York for total metals, Synthetic Precipitation Leaching Method (pH 4.2) metals, pH, chloride, and hardness. The other set was submitted to Construction Engineering Laboratories, Inc. of Pearl City, Hawaii for asphalt mix design and performance testing.

Approximately 34 tons of asphalt containing 5% screened H-POWER combined ash was manufactured by Grace Pacific at their Kapolei, Hawaii double barrel asphalt batch plant. The combined ash was off-loaded directly from the H-POWER ash trailer into a front end loader at the Grace Pacific property. The front end loader added the screened H-POWER combined ash to the process line into the heated chamber at the entry point that is used to add crushed glass and recycled asphalt, called the "RAP Feeder." Because the combined ash was 17% moisture, no fugitive dust was

created during addition of the screened ash to the asphalt process.

Control and test asphalt standard test cores (4 inch diameter by 2-2.5 inch thickness) were prepared on the day of asphalt manufacture by Construction Engineering Laboratories, Inc. of Pearl City, Hawaii. Four control and four ash-amended asphalt test cores were submitted to O'Brien and Gere Laboratories, Inc. of Syracuse, New York for total metals, Synthetic Precipitation Leaching Method (pH 4.2) metals, pH, chloride, and hardness. The remaining asphalt test cores were subjected to serial leaching at the H-POWER facility in accordance with a scope of work approved by the Hawaii Department of Health.

Twenty-five liter graduated polypropylene vats with tops and spigots were obtained from Nalgene Company. Asphalt test cores were either placed into the vats intact for the intermittent immersion test or they were broken into pieces with a sledge hammer for the constant immersion test. Test cores were broken into 5-10 large pieces, but numerous smaller pieces were also formed. All material was placed in the vat. For each vat, 10 liters of SPLP extraction solution #1 was prepared in accordance with Section 5.4.1 of EPA Method 1312 by titrating the solution with the concentrated sulfuric/nitric acid mixture to pH 4.2 using a portable pH meter that was standardized to pH 4 and pH 7. For the intermittent immersion test, the test cores were placed on plastic covered screens placed over the vats and exposed to sunlight, wind, and rain.

When sampling the leachate, the vats were washed with a spray of water and/or wet paper towels to remove dust and debris from top and sides of vats. The spigots were washed with deionized water to remove debris. The pH was measured and recorded. The volume of each vat was brought to 10 L if necessary, and the leachate was mixed fully using a large polypropylene stirring paddle. After settling, the sample was collected with cheesecloth placed between the spigot and the sample bottle to avoid the collection of particulate matter and algae in the sample bottle. For vats open to rainfall, the amount of rainwater present was measured with a ruler, and the pH was measured. The volume of the vat was brought to 4 L with deionized water, and the contents were well mixed. After settling, the pH was measured again and the sample was collected as above. Monthly leachate samples were collected in laboratory-provided labeled nitric-acid preserved polyethylene bottles without field filtration and submitted in insulated coolers via overnight delivery to O'Brien and Gere Laboratories, Inc. of Syracuse, New York for analysis of total metals, chloride, and hardness.

After sample collection, the test cores from the intermittent immersion tests were removed with gloves and placed in labeled ziplocked polyethylene bags. Leachate samples were discarded, and the vats were washed with tap water using gloves, paper towels and/or a brush to remove the algae buildup. The vats were given a final deionized water rinse before either preparing the SPLP extraction fluid #1 for the next month or placing the pavement core on the plastic screen atop the vat.

For the constant immersion test, large pieces of asphalt were removed with gloves and placed in labeled ziplocked polyethylene bags. Leachate from the constant immersion vats containing broken asphalt samples required special care. Leachate solutions were carefully decanted to allow small asphalt particles to settle. The vat was washed with tap water several times with gloves and/or a brush to remove as much of the algae as possible. The vats were drained carefully leaving several cm of water in the bottom to avoid the loss of small asphalt particles.

Bi-monthly pavement wash water samples were collected in laboratory-provided labeled polyethylene bottles without field filtration and submitted in insulated coolers via overnight delivery to O'Brien and Gere Laboratories, Inc. of Syracuse, New York for analysis of total suspended solids, dissolved metals, pH, chloride, and hardness. Wash water samples were also collected in laboratory-provided polyethylene cubitainers and held in insulated coolers containing blue icepacks and submitted to Ogden Environmental and Energy Services Bioassay Laboratory of San Diego, California for acute toxicity testing with *Ceriodaphnia dubia* and *Pimephales promelas*.

Monthly soil/sediment samples were collected with a stainless steel trowel from the top two inches of the soil/sediment horizon. Samples were placed in a stainless steel bowl, and vegetative matter and rocks were removed. The samples were placed in laboratory-provided labeled glass jars and submitted in insulated coolers via overnight delivery to O'Brien and Gere Laboratories, Inc. of Syracuse, New York for analysis of total metals, Synthetic Precipitation Leaching Method (pH 4.2) metals, pH, chloride, and hardness. Equipment was decontaminated after each collection by washing with Alconox detergent, deionized water, and acetone.

RESULTS

TCLP analyses were executed solely to ensure that the combined ash used in the pilot test was typical ash from the facility. TCLP test results were comparable to the results of quarterly TCLP test results from recent years (data not shown). Thus, the collected ash was typical of H-POWER

combined ash. Total metal data for historical samples, combined ash as collected, and screened combined ash as used in asphalt manufacture are shown in Table 1. Inspection of the data also demonstrates that the combined ash used in the pilot test was very similar in metal concentrations to typical combined ash from this facility.

The screened combined ash that was used in the manufacture of ash-amended asphalt was analyzed by the Synthetic Precipitation Leaching Procedure (SPLP) using the pH 4.2 extractant, because such data may be useful in performing a life-cycle risk assessment of the use of H-POWER combined ash as an amendment to asphalt. Data are shown in Table 2.

Control and ash-amended asphalt test cores were crushed and analyzed both for total metals and SPLP metals for characterization purposes. As anticipated, metals of concern, such as arsenic, cadmium and lead are present in both control pavement and test pavement, as shown in Table 3. Metals are present in natural aggregate materials and in bitumen. Because of the heterogeneity of combined ash, natural aggregate, and bitumen and because of the inherent difficulty in sampling such heterogeneous mixtures, the substitution of 5% of the natural aggregate with 5% H-POWER combined ash does not necessarily increase the metal concentration of the pavement in a statistically significant manner. As shown in Table 4, metals are tightly bound in the matrix of the asphalt and are not appreciably leached using the SPLP method at pH 4.2.

Pavement wash water was analyzed on two occasions prior to the test period (baseline samples) and bi-monthly after the ash-amended and control pavements were laid. Table 5 shows the data for the first eight post-paving wash events. For data summarization purposes, one-half of the sample quantitation limit was used as a surrogate concentration for samples which were reported as "non-detect" by the laboratory. To date, there are no statistically significant differences between control and test pavement wash water at the $P=0.05$ level using two-tailed t tests assuming equal variances. When comparing baseline data to post-paving data, several metals were statistically significantly *lower* in the wash water after the new pavements were laid compared to the old pavements. For instance, on the up-ramp, which received the ash-amended pavement, arsenic, copper, and total suspended solids were *lower* in the wash water from the test pavement compared to the baseline wash water from the washing of the old pavement.

In January, 1999, the wash water from both the control and test pavements were also subjected to acute aquatic toxicity testing with the waterflea (*Ceriodaphnia dubia*) and the

fathead minnow (*Pimephales promelas*). As shown in Table 6, there are no significant differences between the control and test groups.

Soil/sediment samples in run-off collection areas were analyzed on two occasions prior to the test period (baseline samples) and monthly after the ash-amended and control pavements were laid. Table 7 shows the data for the first three post-paving soil sampling events. For data summarization purposes, one-half of the sample quantitation limit was used as a surrogate concentration for samples which were reported as "nondetect" by the laboratory. To date, when test and control pavement run-off area soils are directly compared, arsenic, barium, cadmium, copper, mercury and zinc are statistically significantly higher on the *control* side and chromium and selenium are statistically significantly higher on the *test* (ash-amended) side. When comparing baseline data to post-paving data, several metals were statistically significantly *lower* in the soil after the new pavements were laid compared to the baseline data. For instance, on the up-ramp side, which received the ash-amended pavement, arsenic, barium, nickel, and selenium were significantly *lower* in the soil samples after the test pavement was installed. Similarly, on the down-ramp side, selenium was significantly *lower* in the soil samples after the control pavement was installed. These data do not demonstrate that the presence of combined ash in asphalt causes an increase in metal leaching.

The above soils were also analyzed for SPLP metals, hardness, and chloride as shown in Table 8. SPLP aluminum, chromium, copper, lead, zinc, and chloride are statistically significantly higher on the *control* side and no metal is elevated in leachates from the test soils. When comparing baseline data to post-paving data, several metals were statistically significantly *lower* in the SPLP soil leachate after the new pavements were laid compared to the baseline data. For instance, on the up-ramp side, which received the ash-amended pavement, barium, chromium, copper, and zinc were significantly *lower* in the soil SPLP leachate samples after the test pavement was installed. Similarly, on the down-ramp side, barium and zinc were significantly *lower* in the soil SPLP leachate samples after the control pavement was installed. Only hardness and pH were significantly higher in soil SPLP leachate samples after the test pavement was installed, and only aluminum and pH were significantly higher in soil SPLP leachate samples after the control pavement was installed. Again, these data do not demonstrate that the presence of combined ash in asphalt causes an increase in metal leaching.

Table 9 shows the results from the first two sampling events for the bench scale simulated weathering experiments with intact and broken pavement cores. In the constant immersion experiment in which broken pavement cores are constantly submerged in SPLP extractant solution which is renewed each month, few metals were detected in the leachate solution. Only aluminum, arsenic, copper, zinc, hardness, and chloride were detected. With the limited dataset, only aluminum, hardness, and chloride were statistically significantly elevated in the ash-amended pavement leachate. In the intermittent immersion experiment in which intact pavement cores are intermittently exposed to sun, wind and rain or submerged in SPLP extractant solution, few metals were detected in the leachate solution. Only aluminum, copper, zinc, hardness, and chloride were detected in ash-amended pavement. No parameters were statistically significantly different when control and ash-amended pavements were compared.

DISCUSSION

An environmental test program is underway to compare the environmental leaching of metals from test asphalt that contains 5% H-POWER combined ash and control pavement that contains only natural aggregate. Leaching of metals from pavement *in situ* is monitored by washing the pavement bi-monthly and analyzing the wash water for dissolved metals, pH, chloride and hardness and for total suspended solids. Soil/sediment in natural run-off collection areas is also monitored monthly, because any metals released from the pavement by whatever mechanism would be expected to accumulate in these locations. Preliminary statistical comparisons of data collected to date demonstrate that the ash-amended asphalt does not leach metals in a manner that is statistically different from normal control asphalt. The program will continue for a total period of nine months, and more sophisticated statistical methods will be employed at that time to compare control asphalt to ash-amended asphalt.

Leaching of metals from pavement *ex situ* is monitored by simulating the long term effects of sunlight, wind, and rain on control and ash-amended asphalt test cores in field lysimeters. Broken pavement cores are being serially leached by being continuously submerged in SPLP extractant at pH 4.2, which is renewed monthly. Intact pavement cores are intermittently submerged in SPLP extractant or placed in contact with sunlight, wind and rain, each on a monthly basis. In the former case, the SPLP leachate is analyzed and in the latter case, the collected rainwater is analyzed. As above, preliminary statistical comparison of data collected to date demonstrate that the ash-amended asphalt does not leach metals in a manner

that is statistically different from normal control asphalt. The program will continue for a total period of nine months and more sophisticated statistical methods will be employed at that time to compare control asphalt to ash-amended asphalt.

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Material	Sample No.	Moisture (%)	Loss on Ignition (%)	Organic Content (%)	Chloride (%)	Sulfate (%)	Other
Bottom Ash	BA-1	12.5	15.2	0.5	0.1	0.2	
Bottom Ash	BA-2	11.8	14.8	0.4	0.1	0.2	
Bottom Ash	BA-3	13.2	16.1	0.6	0.1	0.2	
Bottom Ash	BA-4	12.9	15.5	0.5	0.1	0.2	
Bottom Ash	BA-5	11.5	14.3	0.4	0.1	0.2	
Bottom Ash	BA-6	13.8	16.8	0.7	0.1	0.2	
Bottom Ash	BA-7	12.1	15.0	0.5	0.1	0.2	
Bottom Ash	BA-8	11.9	14.6	0.4	0.1	0.2	
Bottom Ash	BA-9	13.5	16.3	0.6	0.1	0.2	
Bottom Ash	BA-10	12.3	15.3	0.5	0.1	0.2	
Bottom Ash	BA-11	11.7	14.5	0.4	0.1	0.2	
Bottom Ash	BA-12	13.1	16.0	0.6	0.1	0.2	
Bottom Ash	BA-13	12.6	15.4	0.5	0.1	0.2	
Bottom Ash	BA-14	11.4	14.2	0.4	0.1	0.2	
Bottom Ash	BA-15	13.6	16.5	0.7	0.1	0.2	
Bottom Ash	BA-16	12.4	15.2	0.5	0.1	0.2	
Bottom Ash	BA-17	11.8	14.4	0.4	0.1	0.2	
Bottom Ash	BA-18	13.3	16.2	0.6	0.1	0.2	
Bottom Ash	BA-19	12.7	15.6	0.5	0.1	0.2	
Bottom Ash	BA-20	11.6	14.3	0.4	0.1	0.2	

TABLE 1
 ANALYTICAL DATA
 FOR BOTTOM ASH

Sample No.	Moisture (%)	Loss on Ignition (%)	Organic Content (%)	Chloride (%)	Sulfate (%)	Other
BA-1	12.5	15.2	0.5	0.1	0.2	
BA-2	11.8	14.8	0.4	0.1	0.2	
BA-3	13.2	16.1	0.6	0.1	0.2	
BA-4	12.9	15.5	0.5	0.1	0.2	
BA-5	11.5	14.3	0.4	0.1	0.2	
BA-6	13.8	16.8	0.7	0.1	0.2	
BA-7	12.1	15.0	0.5	0.1	0.2	
BA-8	11.9	14.6	0.4	0.1	0.2	
BA-9	13.5	16.3	0.6	0.1	0.2	
BA-10	12.3	15.3	0.5	0.1	0.2	
BA-11	11.7	14.5	0.4	0.1	0.2	
BA-12	13.1	16.0	0.6	0.1	0.2	
BA-13	12.6	15.4	0.5	0.1	0.2	
BA-14	11.4	14.2	0.4	0.1	0.2	
BA-15	13.6	16.5	0.7	0.1	0.2	
BA-16	12.4	15.2	0.5	0.1	0.2	
BA-17	11.8	14.4	0.4	0.1	0.2	
BA-18	13.3	16.2	0.6	0.1	0.2	
BA-19	12.7	15.6	0.5	0.1	0.2	
BA-20	11.6	14.3	0.4	0.1	0.2	

TABLE 1
COMBINED ASH TOTAL METAL CONCENTRATIONS
(mg/kg)

Metals	Historical		Collected Ash		Screened Ash		All Data	
	Aluminum	NA		34,700 +/-	12,212 (n= 10)	42,100 +/-	19,157 (n= 10)	38,400 +/-
Arsenic	43 +/-	12 (n= 14)	68 +/-	19 (n= 10)	86 +/-	19 (n= 10)	63 +/-	24 (n= 34)
Barium	322 +/-	163 (n= 14)	346 +/-	83 (n= 10)	359 +/-	34 (n= 10)	340 +/-	114 (n= 34)
Cadmium	27 +/-	8 (n= 58)	28 +/-	7.1 (n= 10)	35 +/-	10 (n= 10)	28 +/-	9 (n= 78)
Chromium	65 +/-	20 (n= 58)	52 +/-	7.2 (n= 10)	69 +/-	7.8 (n= 10)	64 +/-	18 (n= 78)
Copper	NA		1,772 +/-	2,522 (n= 10)	1,022 +/-	611 (n= 10)	1,397 +/-	1,827 (n= 20)
Lead	2,283 +/-	973 (n= 58)	1,860 +/-	672 (n= 10)	2,730 +/-	732 (n= 10)	2,286 +/-	930 (n= 78)
Mercury	10 +/-	2.2 (n= 14)	7.9 +/-	1.8 (n= 10)	8.1 +/-	2.7 (n= 10)	9.0 +/-	2.5 (n= 34)
Nickel	72 +/-	72 (n= 58)	57 +/-	12 (n= 10)	70 +/-	16 (n= 10)	70 +/-	63 (n= 78)
Selenium	0.7 +/-	0.3 (n= 14)	1.4 +/-	0.7 (n= 10)	1.8 +/-	0.9 (n= 10)	1.3 +/-	0.8 (n= 34)
Silver	5.9 +/-	2.1 (n= 14)	6.4 +/-	2.2 (n= 10)	7.2 +/-	2.1 (n= 10)	6.4 +/-	2.2 (n= 34)
Zinc	NA		2,670 +/-	460 (n= 10)	3,970 +/-	770 (n= 10)	3,320 +/-	909 (n= 20)

mean +/- standard deviation (number of samples)

NA = Not available.

TABLE 2
SPLP DATA
H-POWER COMBINED ASH
(mg/L)

Metals	Screened Ash Used in Asphalt	
	May, 1998	
SPLP Aluminum	5.9 +/-	5.5 (n= 10)
SPLP Arsenic	0.025 +/-	0.000 (n= 10)
SPLP Barium	1.52 +/-	0.11 (n= 10)
SPLP Cadmium	0.013 +/-	0.027 (n= 10)
SPLP Chromium	0.005 +/-	0.000 (n= 10)
SPLP Copper	0.057 +/-	0.063 (n= 10)
SPLP Lead	0.19 +/-	0.30 (n= 10)
SPLP Mercury	0.0001 +/-	0.0000 (n= 10)
SPLP Nickel	0.025 +/-	0.000 (n= 10)
SPLP Selenium	0.025 +/-	0.000 (n= 10)
SPLP Silver	0.005 +/-	0.000 (n= 10)
SPLP Zinc	0.041 +/-	0.060 (n= 10)
Chloride	1972 +/-	814 (n= 10)
Hardness	1530 +/-	267 (n= 10)
SPLP pH	11.3 +/-	0.78 (n= 10)

mean +/- standard deviation (number of samples)

TABLE 3
ASPHALT TOTAL METAL DATA
(mg/kg)

Analytes	Ash-Amended Asphalt		Control Asphalt	
	Aluminum	7220 +/-	1080 (n= 5)	4080 +/-
Arsenic	6.7 +/-	1.3 (n= 5)	6.3 +/-	10 (n= 5)
Barium	56 +/-	21 (n= 5)	32 +/-	28 (n= 5)
Cadmium	3.8 +/-	0.8 (n= 5)	6.3 +/-	8.7 (n= 5)
Chromium	40 +/-	14 (n= 5)	42 +/-	20 (n= 5)
Copper	182 +/-	61 (n= 5)	157 +/-	67 (n= 5)
Lead	194 +/-	54 (n= 5)	104 +/-	139 (n= 5)
Mercury	0.60 +/-	0.14 (n= 5)	0.32 +/-	0.45 (n= 5)
Nickel	260 +/-	42 (n= 5)	320 +/-	67 (n= 5)
Selenium	0.76 +/-	0.21 (n= 5)	0.90 +/-	0.37 (n= 5)
Silver	0.60 +/-	0.22 (n= 5)	0.80 +/-	0.67 (n= 5)
Zinc	416 +/-	103 (n= 5)	263 +/-	335 (n= 5)

mean +/- standard deviation (number of samples)

TABLE 4
ASPHALT LEACHATE DATA
(mg/L)

Analytes	Ash-Amended Asphalt		Control Asphalt	
	Hardness	87.5	(n= 2)	26.5
SPLP Arsenic	< 0.05	(n= 2)	< 0.05	(n= 2)
SPLP Barium	< 0.1	(n= 2)	< 0.1	(n= 2)
SPLP Cadmium	< 0.01	(n= 2)	< 0.01	(n= 2)
SPLP Chromium	< 0.01	(n= 2)	< 0.01	(n= 2)
SPLP Copper	< 0.01	(n= 2)	0.0225	(n= 2)
SPLP Lead	< 0.005	(n= 2)	0.00375	(n= 2)
SPLP Mercury	< 0.0002	(n= 2)	< 0.0002	(n= 2)
SPLP Nickel	< 0.05	(n= 2)	< 0.05	(n= 2)
SPLP Selenium	< 0.05	(n= 2)	< 0.05	(n= 2)
SPLP Silver	< 0.01	(n= 2)	< 0.01	(n= 2)
SPLP Zinc	0.03	(n= 2)	0.025	(n= 2)
SPLP Final pH	10.45	(n= 2)	10.05	(n= 2)
Chloride	40	(n= 2)	4.5	(n= 2)

mean (number of samples)

* No standard deviation is given due to the small number of samples.

TABLE 5
PAVEMENT WASH WATER CONCENTRATIONS
BIMONTHLY FIELD WASHING
(mg/L)

Metals	Baseline	
	Test	Control
Aluminum, filtered	0.088 +/- 0.075 (n = 4)	0.088 +/- 0.075 (n = 4)
Arsenic, filtered	0.0076 +/- 0.0048 (n = 4)	0.0046 +/- 0.0015 (n = 4)
Barium, filtered	0.05 +/- 0 (n = 4)	0.05 +/- 0 (n = 4)
Cadmium, filtered	0.005 +/- 0 (n = 4)	0.005 +/- 0 (n = 4)
Chromium, filtered	0.005 +/- 0 (n = 4)	0.00625 +/- 0.0025 (n = 4)
Copper, filtered	0.035 +/- 0.006 (n = 4)	0.070 +/- 0.023 (n = 4)
Lead, filtered	0.014 +/- 0.009 (n = 4)	0.0061 +/- 0.0031 (n = 4)
Mercury, filtered	0.0001 +/- 0 (n = 4)	0.0001 +/- 0 (n = 4)
Nickel, filtered	0.025 +/- 0 (n = 4)	0.025 +/- 0 (n = 4)
Selenium, filtered	0.0025 +/- 0 (n = 4)	0.0025 +/- 0 (n = 4)
Silver, filtered	0.005 +/- 0 (n = 4)	0.005 +/- 0 (n = 4)
Zinc, filtered	0.54 +/- 0.38 (n = 4)	0.37 +/- 0.21 (n = 4)
Hardness	NA	NA
TSS	4100 +/- 1906 (n = 4)	2888 +/- 2576 (n = 4)
Chloride	NA	NA
pH	NA	NA

Metals	Post-Paving	
	Test	Control
Aluminum, filtered	0.05 +/- 0.013 (n = 16)	<0.1 (n = 16)
Arsenic, filtered	0.004 +/- 0.0021 (n = 16)	0.005 +/- 0.003 (n = 16)
Barium, filtered	<0.1 (n = 16)	<0.1 (n = 16)
Cadmium, filtered	<0.01 (n = 16)	<0.01 (n = 16)
Chromium, filtered	0.006 +/- 0.002 (n = 16)	<0.01 (n = 16)
Copper, filtered	0.011 +/- 0.011 (n = 16)	0.017 +/- 0.015 (n = 16)
Lead, filtered	0.007 +/- 0.006 (n = 16)	0.005 +/- 0.003 (n = 16)
Mercury, filtered	<0.0002 (n = 16)	<0.0002 (n = 16)
Nickel, filtered	<0.05 (n = 16)	<0.05 (n = 16)
Selenium, filtered	0.0027 +/- 0.0006 (n = 16)	<0.005 (n = 16)
Silver, filtered	<0.01 (n = 16)	<0.01 (n = 16)
Zinc, filtered	0.51 +/- 0.41 (n = 16)	0.38 +/- 0.37 (n = 16)
Hardness	193 +/- 74 (n = 14)	196 +/- 52 (n = 14)
TSS	893 +/- 601 (n = 16)	1559 +/- 1,423 (n = 16)
Chloride	146 +/- 22 (n = 14)	138 +/- 22 (n = 14)
pH	6.21 +/- 0.57 (n = 14)	6.4 +/- 0.47 (n = 14)

mean +/- standard deviation (number of samples)

NA = Not available.

**TABLE 6
PAVEMENT WASH WATER
ACUTE BIOASSAY RESULTS SUMMARY**

Species and Test Type	Waterflea (<i>Ceriodaphnia dubia</i>)	
	Test	Control
	4 replicates, 5 animals	4 replicates, 5 animals
	(% survival)	(% survival)
Control (0% test material)	100	100
6.25 % test material	100	100
12.5%	100	95
25%	100	100
50%	70	95
100%	50	0 ¹

Species and Test Type	Fathead Minnow (<i>Pimephales promelas</i>)	
	Test	Control
	2 replicates, 10 animals	2 replicates, 10 animals
	(% survival)	(% survival)
Control (0% test material)	85 ²	100
6.25 % test material	95	90
12.5%	95	100
25%	85	100
50%	80	90
100%	85 ³	80

Notes:

1. Excessive debris observed; may have impacted filtering ability and survival.
2. Control mean survival below the standard acceptability of 90%; duplicated controls from the same batch of animals exhibited 100% survival, confirming health of test organisms.
3. Replicate containers initiated on subsequent days rather than concurrently. Test data and water quality results are comparable.

TABLE 7
SOIL TOTAL METAL CONCENTRATIONS
(PAVEMENT RUNOFF RECEIVING AREA)
(mg/kg)

Metals	Baseline			
	Test		Control	
Aluminum	28,545 +/-	14,060 (n= 11)	24,000 +/-	8,198 (n= 11)
Arsenic	38 +/-	13 (n= 11)	41 +/-	16 (n= 11)
Barium	99 +/-	43 (n= 11)	219 +/-	66 (n= 11)
Cadmium	3.6 +/-	2.5 (n= 11)	6 +/-	2.7 (n= 11)
Chromium	238 +/-	62 (n= 11)	161 +/-	48 (n= 11)
Copper	85 +/-	23 (n= 11)	252 +/-	160 (n= 11)
Lead	79 +/-	67 (n= 11)	466 +/-	457 (n= 11)
Mercury	0.35 +/-	0.29 (n= 11)	0.79 +/-	0.67 (n= 10)
Nickel	242 +/-	135 (n= 11)	208 +/-	111 (n= 11)
Selenium	5.6 +/-	4.1 (n= 11)	3.8 +/-	1.5 (n= 11)
Silver	2.6 +/-	2.9 (n= 11)	4.4 +/-	2.2 (n= 11)
Zinc	337 +/-	169 (n= 11)	1,025 +/-	707 (n= 11)

Metals	Post-Paving			
	Test		Control	
Aluminum	19,900 +/-	9,259 (n= 12)	25,250 +/-	13,302 (n= 12)
Arsenic	23.7 +/-	7.6 (n= 12)	34 +/-	10 (n= 12)
Barium	68 +/-	22 (n= 12)	183 +/-	44 (n= 12)
Cadmium	2.3 +/-	0.81 (n= 12)	4.9 +/-	3.0 (n= 12)
Chromium	221 +/-	71 (n= 12)	151 +/-	52 (n= 12)
Copper	103 +/-	19 (n= 12)	233 +/-	100 (n= 12)
Lead	119 +/-	26 (n= 12)	369 +/-	447 (n= 12)
Mercury	0.41 +/-	0.17 (n= 12)	0.84 +/-	0.60 (n= 12)
Nickel	137 +/-	53 (n= 12)	185 +/-	72 (n= 12)
Selenium	2.4 +/-	0.61 (n= 12)	1.5 +/-	0.43 (n= 12)
Silver	1.33 +/-	0.33 (n= 12)	3.5 +/-	4.2 (n= 12)
Zinc	432 +/-	89 (n= 12)	768 +/-	442 (n= 12)

mean +/- standard deviation (number of samples)

TABLE 8
SOIL SPLP LEACHATE CONCENTRATIONS
(PAVEMENT RUNOFF RECEIVING AREA)
(mg/L)

Metals	Baseline			
	Test		Control	
Hardness	60 +/-	14 (n= 11)	82 +/-	62 (n= 11)
SPLP Aluminum	11 +/-	17 (n= 11)	4.5 +/-	5.3 (n= 11)
SPLP Arsenic	0.025 +/-	0.000 (n= 11)	0.029 +/-	0.014 (n= 11)
SPLP Barium	0.53 +/-	0.46 (n= 11)	0.44 +/-	0.28 (n= 11)
SPLP Cadmium	0.005 +/-	0.000 (n= 11)	0.005 +/-	0.000 (n= 11)
SPLP Chromium	0.038 +/-	0.051 (n= 11)	0.018 +/-	0.02 (n= 11)
SPLP Copper	0.015 +/-	0.01 (n= 11)	0.06 +/-	0.039 (n= 11)
SPLP Lead	0.014 +/-	0.018 (n= 11)	0.028 +/-	0.036 (n= 11)
SPLP Mercury	0.0001 +/-	0.0000 (n= 11)	0.0001 +/-	0.0000 (n= 11)
SPLP Nickel	0.057 +/-	0.063 (n= 11)	0.031 +/-	0.014 (n= 11)
SPLP Selenium	0.025 +/-	0.000 (n= 11)	0.025 +/-	0.000 (n= 11)
SPLP Silver	0.005 +/-	0.000 (n= 11)	0.005 +/-	0.000 (n= 11)
SPLP Zinc	0.15 +/-	0.07 (n= 11)	0.16 +/-	0.054 (n= 11)
SPLP Final pH	6.8 +/-	0.8 (n= 11)	7.2 +/-	0.4 (n= 11)
Chloride	15 +/-	16 (n= 9)	54 +/-	47 (n= 9)

Metals	Post-Paving			
	Test		Control	
Hardness	83 +/-	16 (n= 12)	86 +/-	102 (n= 12)
SPLP Aluminum	1.10 +/-	0.72 (n= 8)	14.9 +/-	15.3 (n= 8)
SPLP Arsenic	<0.05	(n= 12)	<0.05	(n= 12)
SPLP Barium	<0.1	(n= 12)	<0.1	(n= 12)
SPLP Cadmium	<0.01	(n= 12)	<0.01	(n= 12)
SPLP Chromium	0.005 +/-	0.001 (n= 12)	0.038 +/-	0.041 (n= 12)
SPLP Copper	0.0067 +/-	0.0025 (n= 12)	0.05 +/-	0.029 (n= 12)
SPLP Lead	0.007 +/-	0.005 (n= 12)	0.021 +/-	0.018 (n= 12)
SPLP Mercury	0.0002 +/-	0.0005 (n= 12)	0.00018 +/-	0.00020 (n= 12)
SPLP Nickel	<0.05	(n= 12)	0.048 +/-	0.039 (n= 12)
SPLP Selenium	<0.05	(n= 12)	<0.05	(n= 12)
SPLP Silver	0.007 +/-	0.007 (n= 12)	0.0063 +/-	0.0043 (n= 12)
SPLP Zinc	0.044 +/-	0.020 (n= 12)	0.098 +/-	0.060 (n= 12)
SPLP Final pH	8.4 +/-	1.2 (n= 12)	8.8 +/-	1.21 (n= 12)
Chloride	5.9 +/-	2.6 (n= 12)	78 +/-	119 (n= 12)

mean +/- standard deviation (number of samples)

TABLE 9
BENCH EXPERIMENT SPLP EXTRACTS
ASHPALT CORES
(mg/L)

Analytes	Constant Immersion Experiment			
	Ash-Amended		Control	
Aluminum	0.33 +/-	0.13 (n = 4)	0.063 +/-	0.025 (n = 4)
Arsenic	0.0046 +/-	0.0015 (n = 4)	< 0.005	(n = 4)
Barium	< 0.1	(n = 4)	< 0.1	(n = 4)
Cadmium	< 0.01	(n = 4)	< 0.01	(n = 4)
Chromium	< 0.01	(n = 4)	< 0.01	(n = 4)
Copper	0.0075 +/-	0.0029 (n = 4)	0.0063 +/-	0.0025 (n = 4)
Lead	< 0.005	(n = 4)	< 0.005	(n = 4)
Mercury	< 0.0002	(n = 4)	< 0.0002	(n = 4)
Nickel	< 0.05	(n = 4)	< 0.05	(n = 4)
Selenium	< 0.005	(n = 4)	< 0.005	(n = 4)
Silver	< 0.01	(n = 4)	< 0.01	(n = 4)
Zinc	0.028 +/-	0.010 (n = 4)	0.06 +/-	0.06 (n = 4)
Hardness	111 +/-	51 (n = 4)	36 +/-	13 (n = 4)
Chloride	97 +/-	50 (n = 4)	33 +/-	9 (n = 4)

Analytes	Intermittent Immersion Experiment			
	Ash-Amended		Control	
Aluminum	0.075 +/-	0.029 (n = 4)	0.06 +/-	0.03 (n = 4)
Arsenic	< 0.005	(n = 4)	< 0.005	(n = 4)
Barium	< 0.1	(n = 4)	< 0.1	(n = 4)
Cadmium	< 0.01	(n = 4)	< 0.01	(n = 4)
Chromium	< 0.01	(n = 4)	< 0.01	(n = 4)
Copper	0.041 +/-	0.039 (n = 4)	0.024 +/-	0.015 (n = 4)
Lead	< 0.005	(n = 4)	< 0.005	(n = 4)
Mercury	< 0.0002	(n = 4)	< 0.0002	(n = 4)
Nickel	< 0.05	(n = 4)	< 0.05	(n = 4)
Selenium	< 0.005	(n = 4)	< 0.005	(n = 4)
Silver	< 0.01	(n = 4)	< 0.01	(n = 4)
Zinc	0.050 +/-	0.008 (n = 4)	0.048 +/-	0.021 (n = 4)
Hardness	69 +/-	26 (n = 4)	49 +/-	0.96 (n = 4)
Chloride	69 +/-	45 (n = 4)	38 +/-	4 (n = 4)

mean +/- standard deviation (number of samples)