Evaluation of leaching of trace metals from concrete amended with cement kiln baghouse filter dust

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ABSTRACT

The production of Portland cement (PC) can result in the release of trace amounts of mercury (Hg) in stack emissions. As a means of controlling Hg stack emissions at Portland cement kiln operations, some facilities have instituted a process known as dust shuttling, where baghouse filter dust (BFD), a partially calcined byproduct, is collected and blended with PC as an inorganic process addition, instead of returning the material to the kiln pyro-process. In response to questions raised regarding environmental impacts of recycling BFD into concrete products, research was performed to investigate the chemical composition of BFD and to assess the potential for leaching of trace metals from concrete products amended with BFD. Leaching of monolithic concrete under submerged conditions was examined as a function of time; concentrations of detected elements were found to be below applicable risk thresholds. Despite elevated Hg in the BFD relative to the PC, no elevated Hg risk was observed. Leachates from raw BFD did exceed risk-based thresholds for Se and V. However, leaching of size-reduced BFD-amended concrete did not show concentrations of these elements above applicable risk based thresholds. The results of this study suggest that the use of BFD as an inorganic process addition, within the percentages currently allowed by US industry standards, does not pose any additional risk with respect to direct human hazard or leaching of trace metals to water supplies.

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1. Introduction

The production of Portland cement (PC) requires a number of air pollution control (APC) technologies to limit emissions and capture particulate matter (PM) during the manufacturing process. Baghouses, as well as other APC devices, are used at locations within the operation to collect dust particles generated during the production of PC. In some cases this material, frequently referred to as cement kiln dust (CKD), is extracted from the system as a waste product as the buildup of alkali salts can reduce final cement product quality (Shoaib et al., 2000). In other cases, the recovered PM is of sufficient quality to be recycled as a mineral additive in the PC manufacturing process or through direct incorporation into the PC (Sikkema et al., 2011); the latter practice is considered to be an inorganic process addition (IPA). Within the United States, the standard specifications for Type I PC (ASTM C150/AASHTO M85)

allow for the use of an IPA up to 5% by mass, as long as the final product specifications are met (ASTM, 2013a,b; AASHTO, 2011). Materials typically used as IPA include limestone, fly ash, bottom ash, slag, cement kiln feed, CKD, and other calcined materials (Taylor, 2008). The partially calcined byproducts collected in a cement kiln baghouse and subsequently recycled are referred to baghouse filter dust (BFD) throughout this study, and differ from CKD which is a more general term for a waste product purposely removed from the cement manufacturing process. BFD can be distinguished from CKD because of the lower content of alkali salts within the material, allowing for its use as an IPA; trace element content of BFD has not yet been reported in the literature, and producing a detailed data set is one objective of the study presented herein.

The promulgation of more stringent air emissions regulations for cement kilns within the US (US-EPA, 2010) has driven a number of kilns to implement modified operational strategies. As a means of controlling mercury (Hg) emissions from cement kiln operations, some facilities have proposed or instituted dust shuttling, a practice that involves the blending of a fixed percentage BFD into the PC for use as an IPA (Sikkema et al., 2011; Wang et al., 2014).

Since Hg is known to partition into a cement plant's BFD (Mlakar et al., 2010), the removal of BFD through use as an IPA provides a mechanism to "bleed" off Hg out of the cement manufacturing operation and thus reduce air emissions. The potential for release of Hg into the environment as a result of products amended with BFD, however, must be addressed. The impacts of the vapor phase release of Hg from plants that have implemented dust shuttling were investigated by the authors in another study (Wang et al., 2014). Previous research has indicated that additional trace metals (As, Ba, Cd, Cr, Pb, Se, V, and Zn) are found in the PM generated by cement kilns, (Haynes and Kramer, 1982; PCA, 1992) and since BFD is produced in a similar manner to CKD, the evaluation of the effects of dust shuttling on the total and leachable concentrations of these trace metals is warranted.

While CKD characterization data are available, both on the raw material (Haynes and Kramer, 1982; PCA, 1992) and on CKD used in mortar and concrete (Siddique, 2006; Kunal et al., 2012), information on the chemical constituents found specifically in BFD used as an IPA are not common; the influences of dust shuttling on the concentrations of trace metals in PM from cement manufacturing are not well reported. The objective of this study is to address the current lack of data with regard to the impact of dust shuttling on the total and leachable concentrations of trace metals in BFD, as well as in Portland cement concrete (PCC) where BFD is used as an IPA. Two previously conducted nationwide (US) surveys characterizing the concentrations of trace elements in CKD and PC (Haynes and Kramer, 1982; PCA, 1992) are used as a benchmark for comparison to the data generated in this study. Bulk and trace elemental concentrations of BFD from a full-scale facility practicing dust shuttling were measured, and a suite of leaching tests were used to assess trace elemental release of the raw material, PC-BFD blends, and PCC products amended with BFD. These results were then compared to risk-based thresholds to determine if measured concentrations might pose a potential risk to human or environmental health under normal use scenarios (the concrete product itself and the crushed concrete recycled as a construction material).

2. Materials and methods

2.1. Sample collection, processing, and laboratory specimen creation

BFD and PC samples were collected from a cement production facility located in Florida, USA. The kiln incorporated a precalciner dry-process system. Samples were collected from the cement kiln over an 11-month period. Samples of BFD and PC from the facility were collected in five-gallon High Density Polyethylene (HDPE) buckets. Four grab samples of BFD and one PC sample were collected: BFD Sample A (collected Oct. 28, 2011), BFD Sample B (collected Dec. 15, 2011), BFD Sample C (collected Feb. 28, 2012), BFD Sample D (collected Aug. 24, 2012), and Cement Sample A (collected Aug. 24, 2012). Prior to use in any experimentation, the materials were homogenized by rotating the storage vessels in an end-over-end fashion for approximately 2 h (Analytical Testing Corporation, DC-20B rotator).

Recent harmonization of cement specifications (AASHTO M85 and ASTM C150) has led to a maximum allowable addition of IPAs (5% by mass) in Type I PC (ASTM, 2013a, 2013b; AASHTO, 2011). A National Cooperative Highway Research Program (NCHRP) study has precluded the use of more than an 8% by mass addition of CKD, due to Loss-On-Ignition (LOI) and insoluble residue limitations (Taylor, 2008). Taking this into account, two PC and BFD blends were created; a blend at 5% BFD and 95% PC by mass and a blend at 10% BFD and 90% PC by mass. These blends represented the maximum allowable concentration of BFD as an IPA in Type I PC, as well as a blend that would serve as a conservative overestimate.

The BDF-PC blends were mixed in a similar fashion to the collected samples prior to use.

Coarse and fine aggregate used to create the PCC specimens were purchased from local suppliers and conformed to ASTM C33 in all concrete mixes. The fine aggregate utilized consisted of silica sand and the coarse aggregate was limestone. All aggregate and cement were characterized for trace metals before use. After batching, PCC specimens were placed in rectangular molds (10.16 cm × 10.16 cm × 25.4 cm), wrapped in plastic sheeting to prevent moisture loss and cured at a temperature of $23 \pm 2°$ C per ASTM C192; PCC samples were cured for a period of 24 h. Although samples were cured for 24 h, it should be noted that concrete has been demonstrated to become less permeable as the hydration process continues: because this experiment was designed to assess the leachability of trace metals from BFD, a 24 h curing period was used as a conservative estimate of a real world scenario. Three PCC specimens of each of the following groups were created; Set A (10% BFD-90% PCC), Set B (5% BFD-95% PCC), and a control set which contained no BFD. All mix design parameters were maintained constant with the exception of the BFD additions and the PC it replaced. The cement content, water to cement ratio, and coarse and fine aggregate additions were 467 kg/m^3, 0.53, 827 kg/m^3, and 661 kg/m^3, respectively. Following the initial 24-h curing period, a portion of the PCC was then size reduced with a jaw crusher to pass a 9.5 mm sieve, in accordance with the maximum particle size requirements outlined in EPA method 1312 (US-EPA, 2007). The size-reduced sample then was used in all batch tests with no further particle size modification. The remaining PCC samples were kept intact for use in monolithic leaching experiments.

2.2. Elemental analysis

Bulk elemental analysis was performed using Scanning Electron Microscopy – Energy Dispersive X-Ray Spectroscopy (SEM-EDS) (JEOL SEM-6400) and X-Ray Diffraction Spectroscopy (XRD) (Philips XPert MRD); the detection limit for the SEM-EDS was 0.1% mass for all elements. Bulk elemental analysis was conducted to verify that the total elemental concentration and mineral forms contained in the BFD were similar to CKD, however it should be noted that this analysis serves only as a semi-quantitative tool for elemental and mineralogical characterization. Total environmentally available (TEA) concentrations of trace metals were determined in accordance with EPA Method 3050b (US-EPA, 2007). To obtain the powered sample required for analysis (Method 3050b) the material was first size reduced using a jaw crusher, and then ground to powder in a ball mill. Following this process the entirety of this material was able to pass a US #10 sieve (2 mm). The sample was then mixed and three aliquots were digested for each of the samples tested. The samples were exposed to multiple additions of nitric acid (15 mL HNO$_3$), hydrogen peroxide (5 mL of 30% H$_2$O$_2$), and hydrochloric acid (10 mL HCL) while being heated at a temperature of 95 ± 5 °C. The remaining solid sample was then removed using filter paper (Whatman 41) and the liquid sample diluted to a volume of 100 mL. Digestates were analyzed for trace metals using Inductively Coupled Plasma – Atomic Emission Spectrometry (ICP-AES) (Thermo-Jarrell Ash Trace 61E).

The digestion procedure to determine Hg speciation was derived from the sequential extraction procedure outlined in EPA Method 3200 (US-EPA, 2005); total Hg concentration was conducted in accordance with EPA Method 7474 (US-EPA, 2007). Five replicates (0.5 g) of each material type (PC, BFD, fine aggregate, and coarse aggregate) were weighed using an analytical balance with a precision of 0.01 mg and placed in polytetrafluoroethylene (PTFE) vials. Ten milliliters of the appropriate extraction solution for each of the Hg species were then added to the PTFE vials. The vials were then capped and heated to 95 ± 5 °C for a period 30 min in a microwave

digestion system (CEM MDS 81D). The extracts were analyzed for Hg by a Hydride Generation – Atomic Fluorescence Spectrometer (HG-AFS) (Aurora Biomed 3300); the detection limit of the HG-AFS was 1 ng-Hg/mL.

2.3. Batch leaching tests

EPA Method 1312 (US-EPA, 2007), the Synthetic Precipitation Leaching procedure (SPLP), was performed on all BFD samples, PCC/BFD blends, and size reduced PCC samples. The SPLP is a batch leaching test which has been used by a number of state and federal regulatory agencies to assess a wastes leaching risk to water supplies (Townsend et al., 2006). The SPLP extraction fluid consists of reagent water adjusted to a pH of 4.25 ± 0.05 by a mixture of 60:40 (%by mass) sulfuric and nitric acid. One hundred grams of solid material was then added to 2.2 L high density polyethylene (HDPE) bottles along with 2 L of the extraction fluid. The samples were rotated for a period of 18 ± 2 h and filtered using a 0.6–0.8 μm glass fiber filter (Whatman GF/F) and a vacuum filtration apparatus.

A pH static leaching test was conducted on BFD sample D and the size-reduced PCC samples to evaluate the effects of pH on the leachabiliy of trace metals. The pH static leaching test was conducted in accordance with the procedures outlined in EPA Method 1313 (US-EPA, 2007). A representative aliquot equating to 20 g of dry sample was placed into 250 mL HDPE bottles with 200 mL of reagent water to achieve a liquid to solid ratio (L/S) of 20:1. Additions of nitric acid (2.0 N) and (1 N) sodium hydroxide were then used to achieve the target pH points. For BFD, Sample D extractions were collected at pH values of 4, 6, 8, and 11; for PCC samples, extractions were taken at pH values of 2, 4, 6, 10, and 12.

EPA Method 1315 (US-EPA, 2007) was conducted on the intact PCC samples; samples were tested following the initial 24-h curing period. All concrete samples, except the control, were amended with BFD Sample D. Method 1315 is a monolithic leaching test which involves immersing a sample in reagent water at a set liquid to surface area ratio (9 ± 1 mL/cm^2), and renewing the reagent water at specified intervals (0.08, 1.0, 2.0, 7.0, 14.0, 28.0, 42.0, 49.0, 63.0 days). Following extraction by EPA Methods 1313 and 1315, leachate samples were filtered with a 0.45-μm membrane filter (PALL GHP) and a vacuum filtration apparatus. For storage prior to analysis, all leachate samples were acidified to a pH <2 with HNO$_3$. Leachate samples were analyzed for trace metals using ICP – AES and for Hg by Cold Vapor – Atomic Florescence Spectroscopy (CV-AFS)(Tekran® Model 2500); the detection limit for CV-AFS was 0.2 ng Hg/L.

2.4. Risk assessment

When evaluating direct human exposure risk, a common approach utilized by many regulatory agencies is to compare total concentrations of wastes materials to applicable risk based thresholds. In this study, the Florida Soil Clean-up Target Levels (SCTLs) (F.A.C, 2005) were used as a basis for evaluation of contaminant levels in the BFD and PC. A similar approach is often taken when assessing the potential risk of a material to leach to water supplies (Townsend et al., 2006). The Florida Groundwater Cleanup Target Levels (GCTLs) (F.A.C, 2005) were used to assess the risk posed by leachate concentrations of trace metals in BFD, PC, and PCC samples.

3. Results and discussion

3.1. Elemental analysis

The results of the bulk elemental analysis on the BFD and PC samples are presented in Table 1. The data indicate that the bulk elemental composition of the BFD and PC collected for this study fall within the ranges seen for historical data of CKD and PC (Haynes and Kramer, 1982; PCA, 1992). The major crystalline phase detected in the BFD through XRF analysis was calcium carbonate; the other mineral forms were minor (<10% wt.) or trace (<1% wt.) constituents. The Hg concentration and speciation in the BFD, PC, and aggregates are shown in Table 2. Organic Hg was below detection limits in all samples and was excluded from subsequent analysis. The total Hg concentration in the BFD samples ranged from 0.91 to 1.52 mg/kg; Sample A was found to have the lowest concentration at 0.91 mg/kg while Samples B, C and D were more closely grouped at 1.43, 1.52, 1.44 mg/kg respectively. Hg concentrations in BFD (mean 1.33 mg/kg) were more than double the mean value (0.66 mg/kg) reported by the Portland Cement Authority in their 1992 characterization of CKD (PCA, 1992). The total Hg concentration in the PC sampled was 0.074 mg/kg, elevated in comparison to the mean (0.0141 mg/kg) value from the previous study (PCA, 1992). The measured concentrations of Hg in the BFD were more than an order of magnitude higher than those in the PC. Increased concentrations of Hg in the PC, with respect to previously characterized values, could be attributed to differences in the Hg content of the feedstock utilized (Sikkema et al., 2011). When using risk based regulatory thresholds to assess the relative hazard that Hg concentrations might pose when being handled throughout production and use, total concentrations of Hg in the PC and BFD were found to be below the FL residential (3 mg/kg) and commercial/industrial (17 mg/kg) SCTLs.

Soluble inorganic Hg (SI-Hg) accounted for 61.5–73.4% of total Hg in the samples, while the remaining percentage 38.5–26.6% was found to be in the non-soluble inorganic (NSI-Hg) phase; SI-Hg has been demonstrated to have increased mobility and toxicity when compared to the NSI-Hg fraction (Langford and Ferner, 1999). Total concentrations of Hg in the BFD were found to be more than an order of magnitude larger than those in the PC, supporting the conclusion that Hg concentrations were enriched in APCRs from cement kilns (Mlakar et al., 2010) as well as the hypothesis that BFD would increase Hg concentrations in PC when used as an IPA. When assessing direct human exposure risk, Hg concentrations in the PC and BFD were found to be below risk thresholds, and although the BFD concentrations were enriched with respect to the PC, maximum allowable replacement percentages would likely dilute these concentrations in the final PC product.

The total trace metal composition of BFD, PC and PCC components are presented in Table 3; previously measured concentrations of CKD (PCA, 1992) are shown for comparison. Concentrations of Ag, Ba, Cd, Cr, Pb, Se in BFD fell at or below the low end of the range values previously reported for CKD (PCA, 1992). Concentrations of As in BFD (20.8 mg/kg) were found to be similar to the mean values (23.8 mg/kg, 18 mg/kg) established for CKD in prior studies (Haynes and Kramer, 1982; PCA, 1992). Measured values of As (50.2 mg/kg) and Cd (4.85) in PC were found to be elevated above previously reported means of 19.0 mg/kg (As) and 0.34 mg/kg (Cd) (PCA, 1992). With the exception of Ag, Hg and Se, the total trace metal content was found to be higher in the PC than the BFD. When comparing these values to regulatory thresholds, the only trace metal which exceeded the Florida SCTLs (18 mg/kg) was As, for both PC and BFD samples. Hg, the element hypothesized to be the most effected by the dust shuttling was enriched in the BFD, but was still found to be below the residential direct exposure standard. When assessing the impact of using BFD as an IPA, the trace metal content determined indicated that the addition of BFD would be unlikely to pose a greater risk to human health than PC alone when added in the currently allowable percentages.

Table 1
Bulk elemental composition of baghouse filter dust and cement samples.

Element	BFD Sample A	BFD Sample B	BFD Sample C	BFD Sample D	BFD Mean	Cement Sample A
Concentration (%wt.)						
Al	1.56	1.75	1.12	1.31	1.44	2.2
C	7.38	14.7	22.6	21.8	16.6	15.3
Ca	56.8	27.6	24.2	24.2	33.2	35.7
Cl	0.28	<0.1[a]	0.09	0.11	0.16	<0.1[a]
Fe	1.65	0.73	0.41	0.6	0.848	2.71
K	0.77	0.35	0.23	0.25	0.40	0.36
Mg	0.17	0.23	0.19	0.2	0.198	0.28
O	27.7	52.1	48.6	49.0	44.3	37.6
S	0.16	<0.1[a]	0.07	<0.1[a]	–	0.63
Si	3.68	2.57	2.37	2.44	2.77	5.23
Ti	0.27	<0.1[a]	<0.1[a]	0.17	–	<0.1[a]

[a] Indicates sample was found to be below instrument detection limits.

Table 2
Mercury concentration and speciation for concrete components.

Material	Total Hg (µg/kg)	Soluble inorganic Hg (µg/kg)	Percent soluble
BFD Sample A	910 ± 60	560 ± 20	61.5
BFD Sample B	1430 ± 70	1050 ± 40	73.4
BFD Sample C	1520 ± 90	990 ± 100	65.4
BFD Sample D	1440 ± 23	1030 ± 100	71.5
Cement Sample A	74.5 ± 6.24	47.02 ± 8.94	63.1
Coarse aggregate	4.32 ± 1.52	2.63 ± 1.16	60.8
Fine aggregate	0.44 ± 0.06	0.33 ± 0.04	73.2

3.2. Monolith leaching

The results of the monolithic leaching test can be utilized to evaluate the trace elemental release of PCC products in their typical material form. The measured Hg concentrations in monolithic leachates were not substantially different than those found in the reagent blanks and were less than 0.2 ng/L. For both control and BFD-amended concrete, Ba and Zn were the only two elements found in concentrations above instrument detection limits. Ba was found in concentrations less than 0.060 mg/L in the first four extractions. The cumulative mass release of Ba was higher in the control (2.62 mg/kg) than in the 5 and 10% BFD amended samples (1.45, 0.88 mg/kg). Ba and Zn did not exceed their respective GCTLs during any of the extraction periods. The release of Zn was observed only during the first 48 h of the test. This suggests that Zn may have been released by an initial surface wash off mechanism (Torras et al., 2011) and not the by the diffusion of this element through the concrete matrix. After the initial surface available Zn was released (either from the typical components of the concrete or the BFD), the remaining Zn was well encapsulated within the concrete microstructure and was not measured above detection limits throughout the remainder of the test. The minimal release of trace metals seen in the monolithic leaching experiment leads to the conclusion that these constituents are encapsulated and immobilized in the concrete matrix. This data can be supported by prior study that has demonstrated that cement enriched with trace metals was found to encapsulate these metals when in its monolith form. Serclerat et al. (Serclerat et al., 2000) found that concrete mortar bars, which had been made from PC with elevated concentrations of Pb, Cr, and Zn, were found to leach low concentrations of these trace metals when immersed in deionized water. The negligible effect that the addition of the BFD had on the release of trace elements from the PCC (in monolithic form) demonstrates there is minimal risk associated with the leaching of trace metals to water supplies from monolithic concrete where BFD is used as an IPA (in the proportions currently allowed by US industry standards).

3.3. Synthetic precipitation leaching procedure

While concrete amended with BFD in its monolithic form is unlikely to present a risk to the public or environment, it is important to investigate the leaching of trace metals from BFD amended concrete when it has been crushed for use in a recycling application. It is common to recycle crushed concrete in a number of beneficial use applications including use as road base or backfill (Tam, 2008). When concrete is placed in these applications, the

Table 3
Trace element content of concrete components.

Element	Cement Sample A	BFD mean (min–max)	CKD[a] mean (min–max)	Coarse aggregate (mean)	Fine aggregate (mean)	SCTL[b]
Concentration (mg/kg)						
Ag	0.149	0.322 (0.216–0.411)	10.5 (4.80–40.7)	<0.1	<0.1	1200
As	50.2	20.8 (17.5–27.6)	18.0 (2.00–159)	0.647	0.113	12
Ba	190	67.8 (42.3–75.6)	172 (35.0–767)	5.07	1.17	130,000
Cd	4.85	1.56 (1.43–1.68)	10.3 (0.1–59.6)	0.135	0.121	1700
Cr	53.4	19.81 (16.9–23.6)	41.0 (8.00–293)	4.84	0.954	470
Pb	90.4	28.48 (17.1–52.7)	434 (34.0–7390)	0.823	1.35	1400
Se	<1.0	4.36 (3.22–5.63)	28.1 (2.68–307)	<1.0	<1.0	11,000
V	136	50.35 (41.0–59.9)	NR	3.00	1.26	10,000
Zn	635	70.94 (51.2–99.6)	NR	4.46	15.0	630,000

[a] Data from Portland cement authority characterization (PCA, 1992).
[b] Florida commercial/industrial soil cleanup target levels (F.A.C., 2005).

loss of the concrete matrix and the increase in material surface area could facilitate the release of previously encapsulated trace metals.

The SPLP is the standard regulatory test used in the US when assessing the risk of a material to leach to water supplies; the results of the SPLP analysis for the BFD, PC, and PC-BFD blends can be seen in Table 4. The final pH of the SPLP extracts did not significantly deviate from the natural pH of the samples (pH when immersed in reagent water at a L/S of 10): BFD (pH_{SPLP} = 11.5; $pH_{natural}$ = 11.8), PC (pH_{SPLP} = 12.8; $pH_{natural}$ = 12.8) and PCC (pH_{SPLP} = 10.8; $pH_{natural}$ = 11.0).

Hg concentrations in the BFD (1.07 µg/L) and PC (0.007 µg/L) were less than the regulatory risk threshold of (2.00 µg/L). Hg leaching from the PC-BFD blends (0.007 µg/L – 5% BFD, 0.008 µg/L – 10% BFD) was comparable to the leachable concentrations from the PC. Ag, As, Cd, and Pb were not detected in any of the samples measured. Though TEA concentrations of As were found to be above the Florida SCTLs for BFD and PC; As concentrations in SPLP leachates were found to be below instrument detection limits. When examining the SPLP concentrations of the BFD-PC blends, only Cr (0.172 mg/L – 5% BFD, and 0.149 mg/L – 10% BFD) was found to leach above its GCTL.

Dissimilar to the BFD, both Se and V were found leach below their respective regulatory thresholds in the PC-BFD blends. Se and Hg were detected in lower total concentrations in the PC than in the BFD, and it can be suggested that leaching may have been decreased by dilution these elements (found in higher concentrations in the BFD) in the BFD-PC blends. Cr release in the blends may largely be due to the contribution of Cr from the PC. Cr leaching from the PC (0.278 mg/L) was found to be elevated above the SPLP concentrations of the BFD (0.025 mg/L), and the total concentrations of Cr in the PC were more than double those in the BFD. Ba release, seen in higher concentrations in the PC (1.22 mg/L) than the BFD (0.440 mg/L) support the greater cumulative mass release seen in the control concrete monolithic specimens.

With respect to leaching, the addition of the BFD was demonstrated to have little effect on the release of Hg (when leachable concentrations of Hg in the blends were compared to the values seen in the PC). In the BFD-PC blends Cr was the only element that leached above its respective risk threshold; this can be attributed to Cr found in the PC (leachable concentrations more than an order of magnitude higher than the BFD). Se and V, which leached above GCTLs in the BFD, were found to be decreased in the blends due to dilution with the PC. These results suggest that although Cr release is elevated with respect to GCTLs for both the PC and BFD-PC blends, the addition of BFD as an IPA did not dramatically alter the leachable concentrations of elements in the final cement product.

The results of the SPLP on the crushed PCC samples are presented in Table 5. All trace metal concentrations were lower than SPLP results for the BFD and PC samples tested, and all SPLP concentrations fell below applicable risk thresholds. Ba, Cr, Hg, and Zn were the only elements found in concentrations above instrument detection limits. Hg SPLP concentrations did not vary significantly between the control and BFD amended concrete and mean values were found to be less than 50 ng/L. Leaching of other trace metals showed little difference between control and BFD amended samples. For example, Cr found in the control SPLP test at 0.0205 mg/L, was measured in Set A (5% BFD) and Set B (10% BFD) at 0.0238 mg/L and 0.0226 mg/L respectively. These results suggest that no substantial influence was seen on the leachability of trace metals as a result of the use of BFD as an IPA (for size reduced PCC). Leachate concentrations from SPLP tests on PCC (both control and BFD amended) were below GCTLs for the elements analyzed, demonstrating that there would be limited risk for leaching of trace metals to water supplies when concrete amended with BFD was recycled and reused.
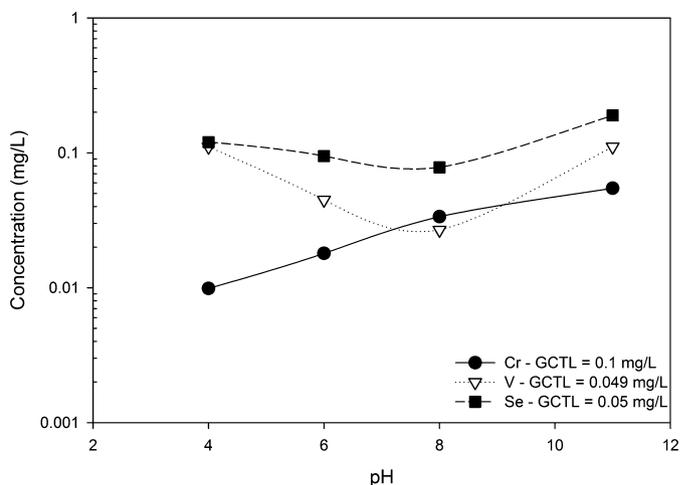

Fig. 1. pH static leaching – baghouse filter dust sample D. Florida Groundwater Cleanup Target Levels (F.A.C., 2005) presented for reference.

3.4. pH static leaching procedure

A pH static leaching test was conducted on the BFD and size reduced PCC (both control and BFD amended samples). This test can be used to better understand how changes to leachate pH during beneficial use applications (such as crushed concrete being disposed of as fill in a water body) may influence leaching. Hg concentrations in BFD leachates for the pH static test leached independent of pH, and all were found to be below 0.750 µg/L (less than the GCTL of 2.0 µg/L).

Fig. 1 presents the BFD pH static leaching curves for Cr, Se, and V. Se found to be elevated above GCTLs in BFD SPLP leachates, displayed an amphoteric leaching trend, with maximum concentrations at high and low pH values. Concentrations of Se did fall below the regulatory threshold at pH values between 8 and 6. V was also elevated above GCTLs in SPLP and Method 1313, displayed a decrease of more than 0.100 mg/L in leachable concentrations from pH 11 to pH 8, followed by a slight increase from pH 8 concentrations at pHs values of 6 and 4. The release of Cr, although below GCTLs, was highest in the basic regime and exhibited a constant decrease as a function of pH. These results indicate that increased leaching of Cr, Se, and V would be expected for the pH range seen in the SPLP tests of the BFD, as well as in the alkaline pH environment of the concrete. The lack of a presence of Se and V during SPLP testing of the BFD amended PCC further supports the hypothesis of the encapsulation of these elements within the concrete matrix, even following size reduction. With respect to the use of BFD in a land application (such as a soil amendment), pH static graphs of Cr, Se and V indicate that if the pH of the leachate were reduced, through applications such as dilution of the BFD with the natural soil, concentrations of these trace elements would also decrease. In some cases, metal leaching will increase with a drop in pH (due to beneficial use conditions), but this was not observed here.

The pH/concentration plots for Cr, Hg, Se and V leached from crushed PCC (both control and BFD amended) samples are presented in Fig. 2. Hg leaching was found to be relatively independent of pH and little difference was seen for control and BFD amended PCC. Unlike the pH static leaching trends observed in the BFD, Cr leaching was seen to increase with decreasing pH. Se leaching differed slightly between control and BFD-amended samples at high pH values; however, a general increase was seen from pH values 10 to 4. V leaching in PCC and BFD-amended PCC did not display any observable trends with respect to pH. Control and BFD-dosed concrete leached similar V concentrations at the majority of the

Table 4
SPLP results for baghouse filter dust, cement, and cement baghouse filter dust blends.

Element	Cement Sample A (mean)	BFD (mean)	5% BFD blend (mean)	10% BFD blend (mean)	GCTL[b]
Concentration (mg/L)					
Ag	<0.0025	<0.0025	<0.0025	<0.0025	0.1
As	<0.0096	<0.0096	<0.0096	<0.0096	0.01
Ba	1.22	0.440 (0.350–0.630)	1.47	1.60	2
Cd	<0.0006	<0.0006	<0.0006	<0.0006	0.005
Cr	0.278	0.0254	0.172	0.149	0.1
Pb	<0.0085	<0.0085	<0.0085	<0.0085	0.015
Se	<0.0155	0.0638 (0.0251–0.0859)	0.0253	0.0232	0.05
V	<0.0014	0.147 (0.0832–0.215)	<0.0014	<0.0014	0.049
Zn	0.057	0.240 (0.0356–0.500)	0.0552	0.0586	5
Hg[a] (ng/L)	7.06	1070 (677–1575)	7.22	8.94	2000

[a] Mercury concentrations are reported in nanograms per liter.
[b] Florida groundwater cleanup target levels (F.A.C., 2005).

Table 5
SPLP results for crushed concrete samples.

Element	Control (mean)	Set A-10% BFD (mean ± std dev)	Set B-5% BFD (mean ± std dev)	GCTL[a]
Concentration (mg/L)				
Ag	<0.0025	<0.0025	<0.0025	0.1
As	<0.0096	<0.0096	<0.0096	0.01
Ba	0.718 ± 0.0327	0.848 ± 0.0191	0.798 ± 0.0145	2
Cd	<0.0006	<0.0006	<0.0006	0.005
Cr	0.0205 ± 0.0005	0.0238 ± 0.0003	0.0226 ± 0.0007	0.1
Pb	<0.0085	<0.0085	<0.0085	0.015
Se	<0.0155	<0.0155	<0.0155	0.05
V	<0.0014	<0.0014	<0.0014	0.049
Zn	0.0318 ± 0.0064	0.0288 ± 0.0079	0.0321 ± 0.0073	5
Hg (ng/L)	36.0 ± 6.9	48.0 ± 5.9	32.0 ± 2.2	2000

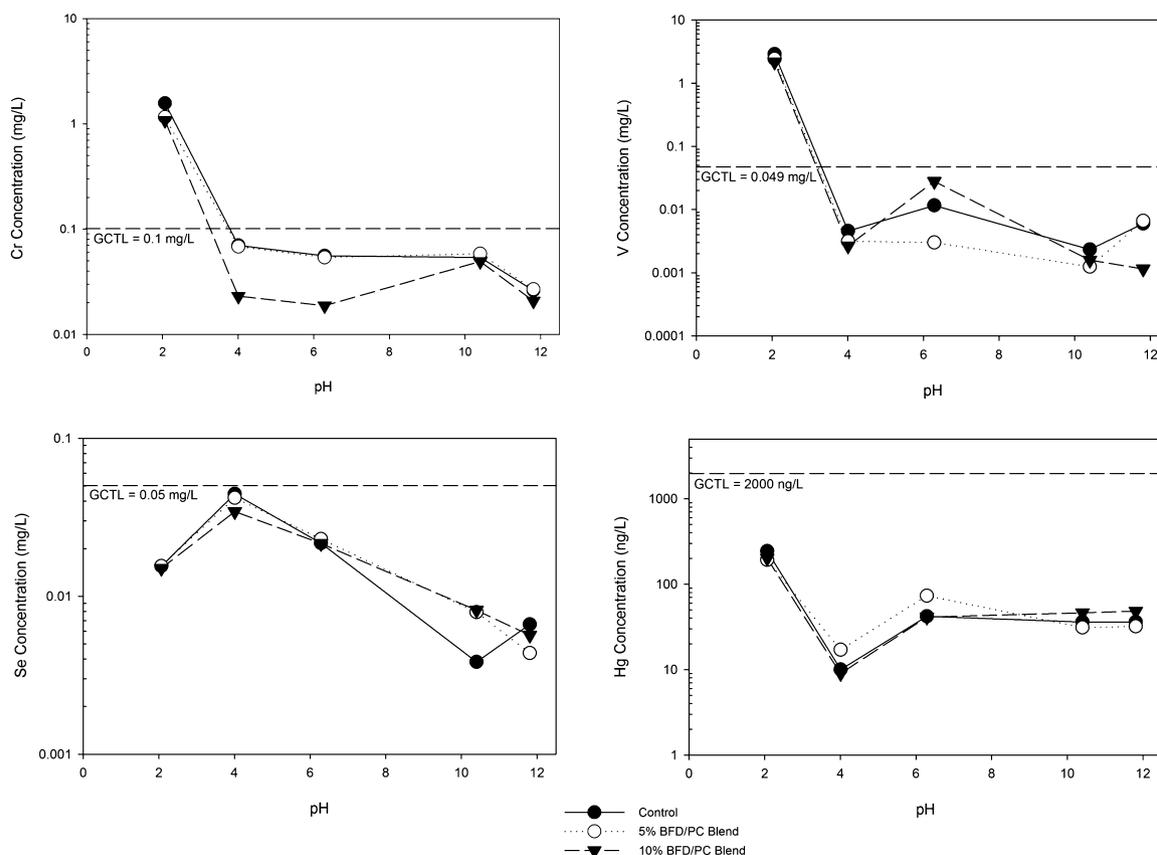[a] Mercury concentrations are reported in nanograms per liter.

Fig. 2. pH static leaching – Portland cement concrete. Florida groundwater cleanup target levels (F.A.C., 2005) presented for reference.

points tested; however, at a pH of 6, leaching of the BFD-amended samples was found to be slightly elevated over that of the controls.

Little difference in the pH dependent leaching, both in concentrations and trends, were seen between control and BFD-amended PCC. Differences in the types of pH leaching trends between the BFD and BFD-amended concrete support the conclusion that these elements are encapsulated in the concrete matrix, altering their leaching characteristics. pH static testing of the PCC indicated that if BFD-amended PCC were to be used in a beneficial use application where the leachate pH was effected (most probably a decrease to the neutral pH region), leachable concentrations of trace elements would most likely still be below GCTLs.

4. Conclusions

The objective of this research was to evaluate the impacts of dust shuttling on the concentrations of trace elements (particularly Hg) in BFD-amended PC and PCC, and to assess if these concentrations might pose a hazard to human health or the environment when used or recycled. When analyzing the total concentration, BFD was found to have elevated levels of Hg with respect to PC. However, these values were still below the set regulatory risk threshold for Hg and would be further decreased when the BFD was mixed with the PC as an IPA. Arsenic was the only element which exceeded its SCTL, but it did so for both the BFD and PC. The total concentration results measured in this study suggest that use of BFD as an IPA poses no greater risk to human health than use of the PC alone.

Leaching of monolithic concrete amended with BFD produced detectable concentrations for only two elements (Ba and Zn), both of which were well below their risk based groundwater contamination threshold. Concentrations of leachable elements in control and BFD-dosed concrete samples did not differ substantially. This suggests that concrete amended with BFD would pose no additional risk of leaching to water supplies when in its monolithic form. To evaluate the potential for trace element release in an application where crushed concrete is recycled, SPLP testing was conducted. Again trace element release from crushed concrete was found to be similar to that of controls, supporting the hypothesis that the size reduction of the BFD-amended concrete did not facilitate the release of trace elements in the BFD, and that crushed concrete amended with BFD would be suitable for recycling in the same matter as conventional PCC.pH static leaching tests were conducted to determine if pH values encountered in the environment might alter the leaching of the BFD or BFD-amended concrete. BFD leachate concentrations of Se, V, and Cr in the pH stat test were found to be elevated in the high pH region seen in the SPLP testing, but were reduced below GCTLs in the neutral pH region. pH static leaching tests of the BFD-amended and control concrete showed minor differences between samples, and concentrations of trace elements were not found to be elevated above GCTLs in the neutral pH region (a scenario which might occur in a beneficial use application).

This data support the conclusion that the addition of BFD to PC as an IPA does not significantly effect the total and leachable concentrations of the final cement product. Although certain trace elements (Hg, Se, V) were present in higher quantities in the BFD, the total concentrations of these elements were reduced through dilution (with the PC) and the concrete matrix was shown to encapsulate these elements when subjected to leaching tests. The results of this study suggest that the use of BFD as an IPA (at the currently allowable percentages) does not pose a greater risk to human or health of the environment than the use of PC alone.

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