and/or very high wheel loads are not recommended to be used with these pavements due to their reduced surface strengths (compared to traditional AC or PCC), questionable durability under aircraft loads, and high FOD potential. Because limited recent data were available for the surface types presented, as these materials are not generally used for modern airfield pavement construction, historical values were examined. Because of this, additional research including full-scale field validation is required to determine if changes are required for the materials described. The evaluation procedures summarized in Table 3 should be used for conservative estimates of flight operations, and the pavement should be inspected after every aircraft pass, as these procedures have not been fully validated through field testing.

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Sustainable Utilization of MSWI Bottom Ash as Road Construction Materials, Part II: Chemical and Environmental Characterization

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Abstract

Incineration of municipal solid waste (MSW) is a common technology that converts solid waste into energy. In European and Asian countries, municipal solid waste incineration (MSWI) ash has been beneficially utilized by separating the bottom ash from fly ash and using them as road construction materials. Generally, MSWI bottom ash, classified as nonhazardous materials, is used to replace either cement or fine aggregate in asphalt and concrete mixtures. In this study, chemical and microstructural analyses of MSWI bottom ash ('as received' samples) produced from a Refuse Derived Fuel (RDF) plant in Florida were conducted. The characterization method included energy dispersive X-ray spectroscopy (EDS) and X-ray diffraction (XRD) methods. Subsequently, leaching behaviors of bottom ash-mixed asphalt and concrete mixtures (for milled asphalt and crushed concrete applications) were investigated. The Synthetic Precipitation Leaching Procedure (SPLP) testing method was used for the leaching investigation.

INTRODUCTION

In 2011, the U.S. produced 251 million tons of municipal solid waste (MSW) and its management involved 53.8% of landfilling, 34.5% of recycling and composting, and 11.7% of incineration (USEPA 2012). Incineration with energy recovery has received a growing attention. As byproduct of MSWI, about 80 to 90% of MSW by weight is bottom ash (BA) and about 10 to 20% is fly ash (FA) (Chandler et al. 1997). The US's current practice is to combine both BA and FA to lower toxicity and to meet the environmental criterion as non-hazardous material, and all combined ashes are being disposed in landfills (Hasselriis 2012). Many Asian and European countries have successfully utilized MSWI BA in areas of road base, asphalt, and concrete pavements. They separate FA and BA and only FA is disposed as hazardous waste because of its high concentrations of toxic metals and salt (Wiles et al. 1999; ISWA 2006; ISWA 2008; Vehlow 2012). Those studies also investigated the leaching behaviors of MSWI BA in the runoff from landfill and road application sites. Use of MSWI ashes as partial replacement of fine or coarse aggregate in HMA and PCC has been studied and life-cycle assessment was also investigated associated with reduction of CO₂ and energy consumption in pavement systems (Vehlow 2012). MSWI BA is generally considered as nonhazardous material while MSWI FA contains significantly high amount of soluble salt (i.e., Na, K, Ca, Cl) and toxic elements (i.e., Pb, Zn, Cr, Ni, Cu) (Quina et al. 2011; Kida et al. 1996). Thus, the reuse of MSWI BA in HMA and PCC can be a promising alternative.

The objective of this study is to evaluate how much leachate can be reduced when combined in asphalt and cement matrix. Thus, raw BA 'as received' was used as the control sample. This study presents and discusses material characterization of MSWI BA 'as received' by using petrographic analysis tool such as EDS and XRD. The leaching characteristics of major alkaline elements (e.g., Ca, Al, Si, Na, and K) and minor trace heavy metals (e.g., Cu, Fe, Mg, Ti, and Zn) from the BA-combined HMA and PCC were investigated by Synthetic Precipitation Leaching Procedure (SPLP) tests (US EPA 1994). The test results are discussed and compared with the drinking water standards, the Secondary Maximum Contaminants Level (SMCL) (US EPA 2009).

EXPERIMENTAL METHODS

Petrographic Analysis

Petrographic analysis, EDS and XRD, was conducted following ASTM C295. Chemical and mineralogy analyses were performed on the BA by using the EDS and XRD, respectively.

SPLP Batch Test

MSWI BA obtained from a RDF facility in Florida was oven dried at 110 °C for 2 hours. The BA whose particle size is smaller than sieve No. 4 (4.45 mm) was used to replace fine aggregate in HMA with replacement percentage of 0, 10, 20, 30, and 40%. Due to the limited amount of the BA, Marshall Mix Design was employed to make smaller specimens (4-in. diameter). The optimum binder content was 5.7% for HMA with no BA; thus, this binder content was used throughout. Limestone meeting the Superpave aggregate requirement was used as virgin aggregate in the mixture. The BA-combined HMA specimens were then crushed to obtain sample size greater than 9.5 mm which were subject to standard SPLP tests.

The BA was sieved out to have its particle size ranged from 4.75 mm to 75 μ m, which is the requirement for the fine aggregate in PCC. Sand with particle size passing 4.75 mm was used as fine aggregate and limestone with nominal maximum size of 19 mm was used as coarse aggregate. According to ASTM C 192, five different sets of concrete specimens (100 × 200 mm²) with a water-to-cement (w/c) ratio of 0.5 were casted. The replacement percentage of fine aggregate by the BA was 10, 20, 30, or 50 %. The concrete specimen (0% BA) was wet-cured for compressive strength tests (not presented in this paper); thus, its leachability condition is different from other specimens. Furthermore, chemical compositions of cement and concrete have been well characterized over past several decades. Therefore, leaching test on the concrete specimen was not conducted in this study. All the specimens were then de-molded and air-cured for 28 days, which was for the leaching test. The hardened concrete specimens were then crushed to obtain particle sizes ranging from 20 to 40 mm.

SPLP batch tests were conducted to assess the leaching behavior of the BA in HMA and PCC when exposed to stormwater infiltration. HMA specimens containing the BA were then crushed to obtain sample size greater than 9.5 mm for SPLP tests. On the other hand, the hardened concrete specimens were crushed to obtain particle sizes ranging from 20 to 40 mm. Extraction fluid was prepared by mixing sulfuric and nitric acids to obtain a solution with a pH of 4.2 to simulate stormwater east of the Mississippi river. The High Density Polyethylene (HDPE) vessels containing a leaching solution and samples at solid-to-liquid ratio of 1:20 were agitated in a rotary tumbler at 30 rpm for 24 hours. All SPLP extracts were then filtered out by using a 0.25- μ m filter paper under 350 kPa pressure, preserved with nitric acid at pH < 2, and stored at 4 °C. Leaching tests were conducted in triplicate. Major alkaline elements and trace

heavy metal concentrations in the elute were determined with inductively coupled plasma optical emission spectrometry (ICP-OES). A total of ten elements, Al, Ca, Na, Si, and K (major alkaline elements) and Cu, Fe, Mg, Ti, and Zn (minor trace elements and heavy metals) were chosen to be evaluated in this study.

RESULTS AND DISCUSSIONS

EDS and XRD

Chemical compositions in element form and mineralogical components are summarized in Fig. 1. The BA contains Si, Ca, Al, Na, K, and Fe at major concentrations and Ti, Mg, Cu, Cr, and Zn at minor concentrations (Speiser et al. 2000; Bayuseno et al. 2010; Lam et al. 2010). The EDS results show that the major alkaline elements of the BA are Ca, Si, Al, Na, and K, the minor elements are Mg, Fe, and S, with heavy metal contents of Ti, Cu, and Zn. The XRD result shows major mineral phases in the BA, such as portlandite (Ca(OH)₂), quartz (SiO₂), and calcite (CaCO₃) and minor compounds are calcium aluminate hydrate (Ca₂Al(OH)₇·5H₂O), jaffeite (Ca₆(Si₂O₇)(OH)₆), and tricalcium aluminate (Ca₃Al₂O₆) (see Fig. 1). The XRD results are found to be in agreement with the EDS result.

Element	MSWI BA (% by weight)	1. C. 2. Ce	AH: $[Ca_2Al(OH)_7.5]$ $a(OH)_2$	H ₂ O] Ca(OH) ₂
0	45.19	4 4 4 C	uartz: SiO ₂ aCO ₂	
Na	3.90	5. Ja	ffeite	
Mg	1.70	2 6. C.	$3A: Ca_3Al_2O_6$	
Al	4.60	6		
Si	8.00			
Р	0.90			
S	3.70			
Cl	2.00			
K	0.87			
Ca	25.30	have have here here have here here here here here here here he		
Ti	1.38	and the second sec	Marsh.	
Fe	1.10		- wy when when the the	44.6
Cu	0.80			and another start for the
Zn	0.56			70 00
Total	100	0 10 20 30 40 5 2 Theta (degree	ee)	70 80

Fig '	1	Petrographic	analysis	FDS	data (left)) and XRD	data	(right)	
rig.	L	i eu ographic	allalysis.	EDS	uala (IEIL	ј апи акd	uata	(Hight)	1

Leaching of the BA-Combined HMA

As a result of acidic leaching using synthetic stormwater solution of pH 4.2 for 1 day, BA, which is generally considered as alkaline (Chandler et al. 1997), shows the pH of 10.32, whereas the pH of HMA itself was observed to be 10.06. Hence, HMA containing 10, 20, 30, and 40% of the BA provides intermediate pH values of 10.20, 10.83, 10.74, and 10.97, respectively.

All elements typically showed the lowest concentration for HMA specimens containing the lowest BA contents. The concentration of the elements increased relatively linearly with increasing the BA content as shown in Fig. 2. With increasing the BA contents, Ca, Al, and Na are released in greater quantities because the amount of asphalt to encapsulate the alkaline elements is reduced, which means insufficient asphalt coating. For the most part, the concentrations from BA-mixed HMA are similar or less than the control (referred as BA alone).

The concentration of released Al from HMA with 40% BA was significantly reduced by 6.3 times from 34223.2 to 5409.9 μ g/L compared to the control (Fig. 3b). Also, the concentration

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of released Na and Ca from HMA with 20% BA were reduced from 8216.4 to 3510.3 μ g/L by 2.3 times and from 46961.5 to 25745.5 μ g/L by 1.8 times, respectively, compared to the control. (Fig.s 2a, 2d). High concentrations of Ca were possibly from the limestone (CaCO₃) which is coarse aggregate in the HMA. Limestone may be disintegrated during the crushing process of the HMA; thus, broken limestone aggregate could be available for leaching at high alkaline pH conditions. A similar observation was observed by Legret et al. (1999). The concentration of released Si from the HMA with 40% BA was higher than that in the control; however, 4.4 times less Si was released from the HMA with 10% BA compared with the control. Release of K shows an irregular trend with the increased content of BA; however, the release of K from the HMA containing the BA is still less than that of the control.



Fig. 2 Effect of BA contents for releasing major alkaline elements from HMA with BA.

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Minor heavy metals, which are Cu, Fe, Mg, Ti, and Zn, show different leaching behavior from the major elements (Fig. 3). Generally, the release of Cu and Fe increases slightly with increasing the BA content. Ti and Zn are slightly reduced in the lower contents of BA (e.g., 10 and 20% of BA) and then increase again in higher contents of the BA (e.g., 30 and 40%). One of potential reasons of this trend, exhibiting an optimum addition of BA, is attributed to the adhesiveness of the HMA that can capture the minor elements to impede release into the solution, as also observed by other researchers (Xue et al. 2009; Chen et al. 2008). In contrast, the release of Mg increases up to 20% BA addition and then reduces with higher addition of BA.



Fig. 3 Effect of BA contents for releasing heavy metals from HMA with BA.

Significant reduction in the release of Cu is observed in the HMA containing 40% BA compared to the control (from 45.50 to 7.28 µg/L). Leachate concentrations of Fe (4.78 ~ 1.92 µg/L) and Mg (475.85 ~ 182.62 µg/L) from the HMA containing BA are similar or less compared to the control. On the other hand, the release of Ti (0.12 ~ 0.52 µg/L) and Zn (6.51 ~ 0.63 µ/L) from the HMA containing BA appears similar or higher than those of the control. Thus, Ti and Zn are believed to be originated from both HMA and BA.

Leaching of the BA-Combined PCC

Both BA alone and concrete are alkaline in nature. After 1 day of batch leaching test by using a synthetic rain water solution with pH 4.2, the leachate pH of different PCC containing 0, 10, 20, 30, and 50% of BA are 12.05, 11.18, 11.50, 12.17, and 11.98, respectively. BA alone shows pH of 11.62.

For Ca, Al, Na, Si and K, the released concentrations after 1 day increased with increasing the BA content (Fig. 4). Significantly less release of Al and Si was observed for the BA-combined PCC compared to the control (BA alone). Leachate concentrations of Al and Si for the control exhibited 34223.2 and 886.7 μ g/L. For the PCC containing 40% BA, the concentrations of Al and Si were 6065.4 and 181.3 μ g/L, respectively. The concentration of K (17180.7 μ g/L) released from the PCC containing 20% BA was considerably lower than that of the control (37570.5 μ g/L). The concentration of Na, however, was higher in the PCC containing more than 20% BA (11828.7 μ g/L) compared to the control (8216.4 μ g/L) because Na is abundant in PCC. Since the major components of cement paste (e.g. calcium silicate hydrate, Ca(OH)₂, and ettringite) have the potential for alkaline leaching, especially Ca (del Valle-Zermeño 2013), both PCC and BA are responsible for the high Ca release (approx. 50000 μ g/L).

Leaching of Cu, Fe, Mg, Ti, and Zn appears to follow two types of patterns with increasing the BA content after 1 day (Fig. 5). Since these elements are possibly released from both BA and PCC, the behavior of leaching for the minor elements can be more complicated than that of the major elements (Bin-Shafique et al. 2006). For Cu and Mg, the concentration increased with increasing BA content in the PCC. Ca as minerals are believed to provide adsorption sites to encapsulate metals into the PCC (Sabbas et al. 2003); thus, reduced leaching was observed. Cu concentration was ranged from 45.5 μ g/L (for the control) to 5.8 μ g/L while Mg concentration was ranged from 475.9 μ g/L (for the control) to 35.5 μ g/L. The release of Zn, however, appears not to decrease significantly (varied between 0.6 to 1.5 μ g/L) between the PCC without BA and the BA-combined PCC due to its amphoteric high leaching behavior at high pH conditions.

On the other hand, the concentration of released Fe fluctuated between 4.8 and 12.1 μ g/L. Also, Ti fluctuated between 0.1 (for the BA-combined PCC) to 0.3 μ g/L (for the control). Leaching behaviors of Fe and Ti are not sensitive to the BA content. The PCC itself contains Fe and Ti as an integrated component (Mindess et al. 2003) and heavy metals can be released from the PCC; thus, higher leaching of Fe and Ti from the BA-combined PCC was observed compared to the PCC alone. The PCC containing 50% BA showed significant increase of leaching for most heavy metals.



Fig. 4 Effect of BA contents for releasing major alkaline elements from PCC with BA.





COMPARISON WITH THE STANDARDS

Leaching test results were compared with the U.S. drinking water standard, the secondary maximum contamination level standards (SMCLs) in this study (US EPA 2009), in order to check environmental risk associated with the use of MSWI BA in milled-HMA and crushed-PCC applications. However, it is important to note that the SMCL is quite strict and may not be perfect for road construction materials; thus, more appropriate criterion needs to be established in the US.

BA-Combined HMA

The average concentration of Cu, Fe, and Zn from BA and BA-combined HMA are far below their corresponding SMCLs (Fig. 6). Peak concentration of Cu found in the BA was in the range of $35-45 \mu g/L$, which is insignificant, compared to SMCL (1000 $\mu g/L$). Similarly, the peak concentration of Fe appears not to exceed 6 $\mu g/L$ whereas SMCL value is 300 $\mu g/L$. Although the leaching of Zn from the BA is minimal, the HMA containing 20% BA exhibits a comparatively higher extent of leaching in the range of 0.63–6.5 $\mu g/L$; however, this is still well below the SMCL of 5000 $\mu g/L$. On the other hand, a large amount of Al leaching occurred with the BA and BA-combined HMA specimens. The BA exhibited the peak concentration of 41727.6 $\mu g/L$ and the HMA containing 40% BA showed 13480.9 $\mu g/L$. Dubey and Townsend (2007) also observed Al exceeding the drinking water standard.



Fig. 6 Leaching concentrations of priority elements from HMA containing BA compared to SMCLs.

BA-Combined PCC

The average concentration of Cu, Fe, and Zn (except Al) from the BA and BA-combined PCC are also far below the SMCLs (Fig. 7). The concentration of Cu was maximum with the control (BA alone), ranging from 70.1 to 22.9 μ g/L, which is negligible compared to the SMCL (1000 μ g/L). The maximum concentration of Zn was found in the PCC containing 20% BA, and it was 18.3 μ g/L, which is much lower than the SMCL of 5000 μ g/L. The maximum concentration of Fe was found to be 16.5 μ g/L in the PCC containing 50% BA, which is still well below the SMCL (300 μ g/L). However, the release of Al from all the specimens including the control