Measurement and Stabilization of Waste-to-Energy Ash–Concrete Expansion in Seawater

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Combustion residues from waste-to-energy systems can be stabilized with portland cement to form offshore artificial reefs that augment fishing harvests. To use secondary raw materials from waste-to-energy systems for beneficial applications, the stabilized material must maintain its structural integrity in a marine environment. The current study compared the rates of expansion of ash–concrete with selected combinations of bottom ash and/or scrubber residue, examined changes in mineral phases during exposure to seawater, and assessed mechanisms for reducing expansion. The rate of expansion of ash–concrete prepared with bottom ash alone or with scrubber residue was approximately 1.5 times the rate of expansion of mortar. Superficial structural degradation of these materials in seawater was not observed. Ash–concrete prepared with scrubber residue alone exhibited significant expansion and structural deterioration after 80 days of exposure. Bubbling in ash–concrete with scrubber residue provided physical evidence of gas formation. Hydrating scrubber residue at a moisture content of 30% for 5 days prior to stabilization reduced expansion by a factor of 3 and mitigated bubbling and cracking that was observed in ash–concretes with scrubber residue. Ettringite, associated with expansion of conventional concrete, was present in hydrated scrubber residue but not in scrubber residue. Hydrating the scrubber residue may limit expansion by facilitating the formation of gypsum and ettringite and the liberation of gas prior to stabilization.

Introduction

Waste-to-energy systems have been incorporated into municipal solid waste management programs throughout the world as an alternative to landfill disposal. The State of Florida currently has the largest capacity for municipal solid waste combustion in the United States (*1*). Combustion is a viable alternative in regions with high per capita solid waste generation rates, limited landfill space, and high groundwater because it reduces the volume of solid waste by 90% and weight by 75% (*2*). Combustion ashes can be stabilized with portland cement to form solid concrete blocks that can be used as offshore artificial reefs to augment commercial and recreational fishing harvests and increase primary productivity and diversity in marine habitats damaged by pollution or over-exploitation (*3–5*). Laboratory studies have indicated that stabilized combustion ashes, referred to as ash–concrete, can retain their physical integrity in seawater for extended periods of exposure with minimal chemical leaching (*6, 7*).

The current study focuses on the use of two residuals from municipal waste-to-energy systems: bottom ash, which is the collection of residues that remain on the combustion grate, fall through the grate, or become entrained in the boiler, and flue gas scrubber residue that may contain small amounts of fly ash and boiler ash. These materials have physical properties and absorption capacities similar to lightweight structural aggregates and, when stabilized with Type II portland cement, form moderate strength lightweight concretes. To be used for beneficial applications as offshore artificial reefs, ash–concrete must maintain its structural integrity in a marine environment. Although the compressive strengths of the ash–concrete increased during 1 year of exposure to seawater in previous studies by Kalajian et al. (*2*), expansion of ash–concrete with bottom ash and scrubber residue was 3–4 times that reported for Type II portland cement concrete and was within the range of Type I concrete. Hydrating the scrubber residue at a moisture content of 30% for 5 days reduced expansion of ash–concrete during setup and within the first 48 h of curing.

Superficial structural degradation of the ash–concrete was not observed during exposure to seawater. However, continued expansion may threaten the future integrity of the material and facilitate chemical leaching. The current study provides a more comprehensive examination of expansion in ash–concrete than previous studies and focuses on the relative effectiveness of hydrating scrubber residue prior to stabilization as a potential method for reducing long-term expansion. The specific objectives of the study were to compare the rates of expansion of selected ash–concretes in seawater, to examine changes in the mineralogy of scrubber residue due to hydration, and to examine the progress of chemical and mineralogical processes in ash–concrete during exposure to seawater using X-ray diffraction and scanning electron microscopy with energy-dispersive X-ray analysis.

Materials and Methods

WTE Ashes. The composition of municipal solid waste varies with location, season, collection patterns, and recycling activities (*2, 7*). Bottom ash was obtained from the Waste-to-Energy Plant in Pinellas County, Florida, during the spring season. Metals were extracted from the ash and sold for reuse prior to shipping. Therefore, the current research is applicable to similar resource recovery facilities that postprocess their ash. Further processing of bottom ash was conducted manually in the laboratory to remove batteries, nails, unburned paper, and large pieces of glass. Elemental compositions and major calcium compounds in the bottom ash and scrubber residue were determined in independent investigations by Yoo (*7*) and Fanning (*8*) and are summarized in Table 1. The purpose of presenting the silicon, aluminum, and calcium contents is to indicate that the materials contained stabilization elements. Concentrations of most elements were similar to or lower than values for comparable facilities (*9*) with the exception of silicon, which was slightly enriched in bottom ash. The moisture content was 9.8–12% prior to mixing determined by the ASTM C566-78 method (*10*).

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TABLE 1. Elemental Composition and Relative Abundance of Major Calcium Compounds in Bottom Ash and Scrubber Residue (7, 8)

element	bottom ash	scrubber residue
Si (%)	22 ± 1	19 ± 1
Ca (%)	7.7 ± 0.9	8.6 ± 0.7
Al (%)	2.8 ± 0.1	6.5 ± 0.9
Fe (%)	6.8 ± 0.1	3.4 ± 0.1
Mg (%)	0.9 ± 0.09	1.80 ± 0.07
Zn (%)	0.40 ± 0.04	0.40 ± 0.03
Pb (μg/g)	1700 ± 20	1200 ± 17
Cu (μg/g)	2100 ± 140	1100 ± 77
Cr (μg/g)	201 ± 6	403 ± 22
Ni (μg/g)	160 ± 17	250 ± 13
Cd (μg/g)	24 ± 8	30 ± 4
major Ca compds (relative abundance)	calcite[a] > ettringite[b]	calcite > anhydrite[c]

[a] $CaCO_3$. [b] $(Ca_6Al_2(SO_4,SiO_4,CO_3)_3(OH)_{12})$. [c] $(CaSO_4)$.

Flue gas scrubber residue, which may have contained small amounts of fly ash and boiler ash, was obtained from the Bridgeport Connecticut Resource Recovery Plant and stored in a sealed 5-gal drum. Elemental compositions and major calcium compounds are presented in Table 1 (7, 8). Calcite and anhydrite were the most abundant calcium species. Calcium, released from dirt, clay, and dust during combustion, reacts with sulfur dioxide to form anhydrite. Calcium hydroxide, introduced in the scrubbing chamber, reacts with carbon dioxide and sulfur dioxide to form calcite, calcium sulfite hemihydrate, and gypsum (7). Enrichment of aluminum in scrubber residue is attributed to condensation of $AlCl_3$, from the reaction of molten Al with HCl, onto suspended particles (7). The moisture content of the scrubber residue was 6.6−11.1% prior to mixing determined by the ASTM C566-83 method (10). Engineering properties of the bottom ash and scrubber residue were determined in an independent investigation by Wu (11).

Hydrating the scrubber residue at a 30% moisture content for 5 days prior to mixing dramatically decreased expansion during the first 48 h of curing in previous studies (2). Scrubber residue was hydrated or "prewetted" with tap water under the same conditions for the current study. The wetted material liberated heat but did not set. The moisture content ranged from 27.2 to 28.8% prior to mixing.

Mix Designs. Type II portland cement was used in all mixes because of its moderate sulfate resistance and suitability for seawater applications. Mix designs are presented in Table 2. Six aggregate combinations were used in the study: (1) bottom ash, (2) bottom ash and scrubber residue, (3) bottom ash and prewetted scrubber residue, (4) Ottawa sand and scrubber residue, (5) Ottawa sand and prewetted scrubber residue, and (6) Ottawa sand (mortar). Aggregate combinations with scrubber residues and Ottawa sand were used to isolate chemical processes associated with scrubber residue because Ottawa sand was a chemically inert material with an extremely low affinity for water (12). Mortar was used as a control mix.

Fabrication and Curing. Six concrete blocks were fabricated with each mix according to ASTM C157-80 and C490-83a (10). Steel molds with dimensions of 2.54 cm × 2.54 cm × 15.875 cm (1 in. × 1 in. × 6.25 in.) were cleaned to remove surface corrosion and were lubricated with a silicone spray prior to block fabrication. Steel gage studs were set so their principal axis coincided with the principal axis of the test block.

Mixing of the mortar followed ASTM C305-82. Mixing of the ash−concretes followed ASTM C192-81 with two modifications (10). First, all ashes were dry mixed with cement to break up large clumps of ash and obtain a uniform mix. Second, ash−concretes with scrubber residue were mixed continuously for 5 min without the recommended rest period because of the tendency to flash set. Master Builder's Rheobuild superplasticizer (25 oz/100 lb of cement) was used to improve the workability of the mixes. Concrete was placed in approximately two equal layers in the molds by simultaneous vibration and tamping.

Curing in the molds was permitted for 2 days after fabrication in a control chamber at a constant temperature of 25 °C. A wet fabric cover was placed over the molds to facilitate hydration. Ash−concrete and mortar blocks were removed from the molds after 2 days and placed in separate plastic containers that contained a saturated lime solution for the remainder of the 28-day curing period in the control chamber. Addition of lime ensures adequate calcium for the formation of hydration products that contribute to concrete density and strength development. A 28-day curing period was chosen to ensure adequate strength development (2). After the 28-day curing period, blocks were placed in 2 L of Atlantic Ocean seawater in the control chamber. The seawater was changed weekly for the 95-day duration of the study.

Analytical Methods. The lengths and weights of all blocks were measured weekly during exposure to seawater. Lengths were measured with a micrometer for measurements between 6 and 7 in. with a resolution of one ten-thousandth of an inch. The micrometer was aligned against the steel gage studs in each block, and the length along the principal axis of the block was measured. Six test blocks were fabricated with each mix design. Length measurements were repeated three times and then averaged for each block. In almost all cases, the variation between length measurements of a block did not exceed two ten-thousandths of an inch. The percent expansion was calculated for each block relative to its length after 28 days of curing but prior to immersion in seawater (0 days of exposure to seawater). The expansion percentages for the six test blocks were averaged to determine the average percent expansion and standard deviation for each mix design. The results are presented below as a time series of average percent expansion for each mix design.

Weights were measured to the nearest tenth of a gram with a top loading balance. Weight measurements were repeated three times and then averaged for each block. The percent weight gain was calculated for each block relative to its weight after 28 days of curing but prior to immersion in seawater. The measurements for the six test blocks were averaged to determine the average percent weight gain for each mix design.

Changes in the mineralogy of scrubber residue due to hydration and the progress of chemical and mineralogical processes in the ash−concretes after 1, 28, and approximately 95 days of exposure to seawater were examined using X-ray diffraction and scanning electron microscopy with energy-dispersive X-ray analysis. Analysis of ash−concrete with Ottawa sand and scrubber residue was performed only after 92 days of exposure and was not conducted on the bottom ash−concrete. The duration of the experiment was selected to examine the kinetics of expansion after a sufficient period of exposure while accommodating the scheduling of the equipment in the laboratories where the studies were conducted (National Aeronautics and Space Administration's Materials Science Laboratory and Harris Semiconductor Corporation). Cross-sections of blocks were first ground with an aluminum oxide mortar and pestle and sieved with a 100-mesh nylon sieve to remove quartz if they contained Ottawa sand. Samples were then examined with an optical microscope to identify changes in color, texture, and composition and to select samples for X-ray diffraction analysis. Magnifications used for the scanning electron microscopy studies were selected to produce the best resolution of each sample.

TABLE 2. Ash–Concrete and Mortar Mix Designs[a]

| | mix designation and composition (% by wt) | | | | | |
component	BA	BA-SR	BA-pwSR	OS-SR	OS-pwSR	mortar
bottom ash	66.40	43.25	43.25			
scrubber residue/prewetted scrubber residue		18.53	18.53	18.98	18.98	
Ottawa sand				44.28	44.28	72.50
water	16.60	18.34	18.34	16.45	16.45	9.07
Type II portland cement	16.60	19.51	19.51	19.98	19.98	18.13
superplasticizer	1.0	0.37	0.37	0.31	0.31	0.27

[a] BA, bottom ash; SR, scrubber residue; pwSR, prewetted scrubber residue; OS, Ottawa sand.
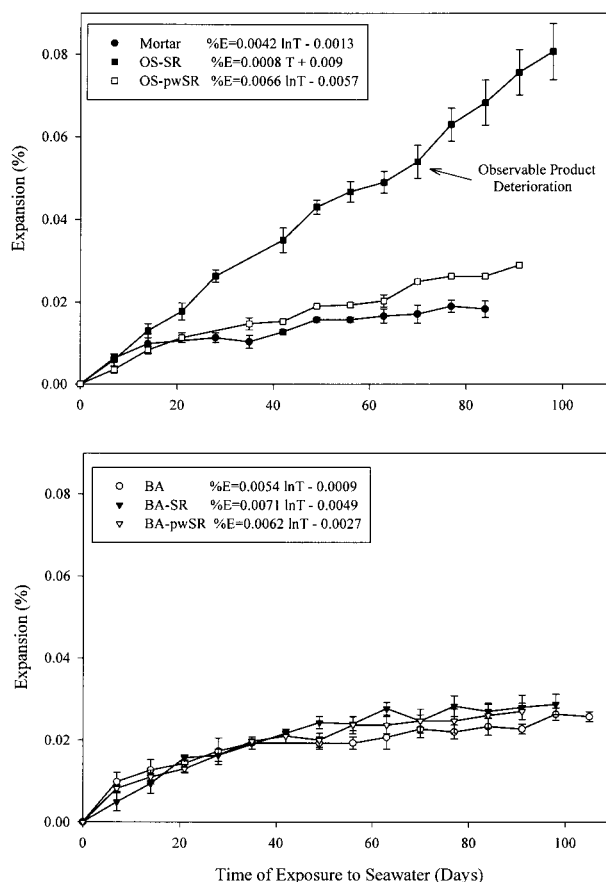
FIGURE 1. Average expansion of ash–concrete and mortar during exposure to seawater.

FIGURE 2. Average weight gain of ash–concrete and mortar during exposure to seawater.

Results and Discussion

Expansion. Expansion of each mix as a function of time of exposure to seawater is presented in Figure 1. Mortar had the lowest expansion at an average of 0.0183% after 84 days of exposure. Expansion of mixes with bottom ash, bottom ash and scrubber residue, bottom ash and prewetted scrubber residue, and Ottawa sand and prewetted scrubber residue was 0.0257%, 0.0287%, 0.0270%, and 0.0290%, respectively, after approximately 98 days of exposure. No superficial structural degradation of these ash–concrete blocks was observed.

Kalajian et al. (2) reported expansion of 0.06%, approximately twice that measured in the current study, for ash–concrete with bottom ash and scrubber residue after 100 days of exposure. Expansion in the previous study was initiated relatively rapidly after exposure. Differences in the kinetics of expansion during extended periods of exposure warrant further investigation. The composition of ash residues can va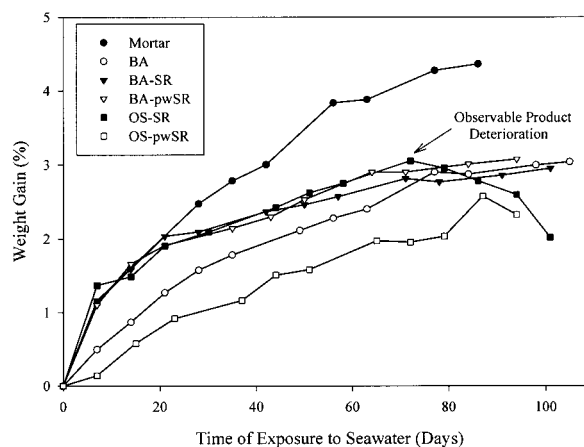ry within the same batch of material because the combustion stream is not homogeneous. Further studies should examine expansion kinetics of ash–concrete with scrubber residue and bottom ash from many batches of material and possibly over different seasons to quantify variability. Ash–concrete that contains scrubber residue sets rapidly. This behavior decreases the workability of the material and can potentially affect its quality if the void fraction is high because the vulnerability to chemical attack in seawater increases with permeability.

Ash–concrete with Ottawa sand and scrubber residue exhibited the greatest expansion, 0.0807%, after approximately 100 days of exposure to seawater. Although the expansion was less than 0.2%, at which Tuthill (13) reported internal disruption of conventional concrete even without apparent structural degradation, loss of material from blocks of ash–concrete with Ottawa sand and scrubber residue began at 0.06% expansion (72 days of exposure). It became more severe as the expansion increased with the sides of the blocks eventually separating from one another. This behavior was observed in all six of the blocks formulated with this mix. As the blocks began to deteriorate, the variability between expansion percentages for the six blocks increased. Consequently, the error bars shown in Figure 1 for this mix design are significantly larger than for other mix designs at later ages.

Weight Gain. Weight gain of each mix as a function of time of exposure to seawater is presented in Figure 2. All materials except mortar and ash–concrete with Ottawa sand and scrubber residue had a weight gain of 2–3% over the duration of exposure to seawater. Ash–concrete with Ottawa sand and scrubber residue had a gradual gain of 3% over 72 days of exposure and then a rapid loss of 1% over the next 28 days. Mortar had a 4–5% gain. Although a standard for the weight gain of conventional concrete in seawater does not exist, freeze–thaw durability studies have shown 1–4% weight gains from water absorption depending upon the void fraction (12). Weight loss is an indicator of structural

TABLE 3. Selected Mineral Phases in Ash—Concrete and Mortar as a Function of Time of Exposure to Seawater

species	time of exposure (days)	relative abundance of mineral phases[a]				
		mortar	BA-SR	BA-pwSR	OS-SR	OS-pwSR
calcium hydroxide	0	M	M	m	-	M
	28	M	M	m	-	m
	end[b]	M	m	M	m	M
brucite	0	ND	ND	ND	-	ND
	28	m	M	M	-	m
	end[b]	M	m	M	m	M
anhydrite	0	t	m	m	-	m
	28	t	M	t	-	m
	end[b]	M	m	M	M	M
calcium sulfite hemihydrate	0	ND	ND	ND	-	ND
	28	ND	ND	ND	-	ND
	end[b]	ND	ND	ND	ND	ND
gypsum	0	m	m	m	-	m
	28	m	M	m	-	m
	end[b]	M	m	M	M	M
ettringite	0	t	M	M	-	M
	28	t	M	M	-	m
	end[b]	M	M	M	M	M

[a] Species with the largest peak from X-ray diffraction analysis was arbitrarily assigned an intentsty of 100. M, major, intensity is 20—99% of peak; m, intensity is 5—19% of peak; t, trace, intensity <5% of peak; ND, not detected; -, not analyzed. [b] End, end of experiment. OS-SR, 92 days; mortar, 84 days; BA-SR, BA-pwSR, and OS-pwSR, 98 days.

TABLE 4. Mineralogy of Scrubber Residues Prior to Stabilization

species	relative abundance of mineral phases[a]	
	scrubber residue	prewetted scrubber residue
calcite	M	M
calcium hydroxide	ND	ND
brucite	ND	ND
anhydrite	M	M
calcium sulfite hemihydrate	M	M
gypsum	M	M
ettringite	ND	M

[a] Species with the largest peak from X-ray diffraction analysis was arbitrarily assigned an intensity of 100. M, major, intensity is 20—99% of peak; m, minor, intensity is 5—19% of peak; t, trace, intensity <5% of peak; ND, not detected.
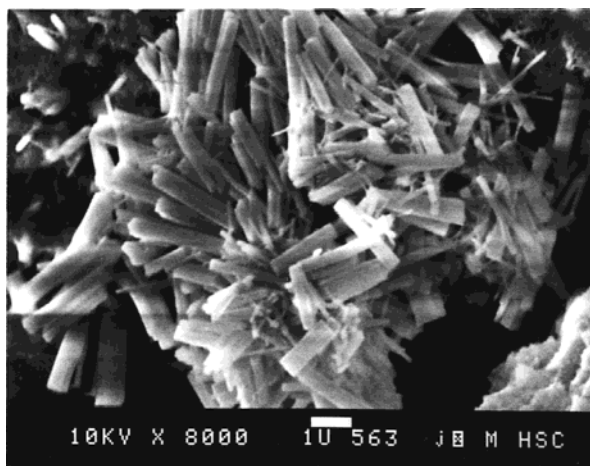

FIGURE 3. SEM photograph of ettringite in ash—concrete with Ottawa sand and prewetted scrubber residue after 98 days of exposure to seawater.

surfaces after 28 days of exposure to seawater. The crust was found only on the surfaces of the blocks and not within the interiors. This material was enriched in magnesium and was confirmed to be brucite. The presence of brucite in conventional concrete exposed to seawater has been documented (14). Seawater is undersaturated with respect to calcium and drives the dissolution of calcium hydroxide (portlandite) in concrete. Magnesium ions diffuse toward the interior of the material and precipitate with hydroxyl ions as brucite. Hockley and van der Sloot (15) found magnesium-enriched encrustations on the surfaces of stabilized coal waste but were not able to identify a crystalline magnesium phase as identified in the current study.

Simultaneous increase in the abundance of brucite, gypsum ($CaSO_4 \cdot 2H_2O$), and ettringite ($Ca_6Al_2(SO_4,SiO_4,CO_3)_3(OH)_{12}$) in mortar is evidence of long-term chemical interaction with seawater. Sulfate attack of mortar leads to the formation of ettringite and gypsum through reactions with calcium ions and hydrated tricalcium aluminate (14). Ettringite may also be formed through the reaction of tricalcium aluminate with chloride ions, which forms chloroaluminate hydrate that is unstable in a sulfate environment and is ultimately converted to ettringite (14). Expansion of conventional concrete from ettringite formation is thought to occur by either or both of the following mechanisms: swelling or crystallization pressure. The morphology of ettringite has been shown by Mehta (16) to depend on the amount of lime in solution. Colloidal ettringite, which forms in saturated lime solutions, has a large surface area and negative surface charge that absorbs a large amount of oriented water. Swelling of colloidal ettringite may occur by interparticle repulsion. Crystallization pressure may occur by topochemical ettringite formation and oriented crystal growth (17). A similar topochemical mechanism may account for expansion from gypsum formation in solutions supersaturated with respect to calcium and sulfate ions (18). Expansion in seawater may be limited by brucite formation, which provides a barrier to diffusion of sulfate and chloride ions, and by the increased solubility of ettringite in a chloride environment.

Ettringite, the second most abundant calcium compound in bottom ash, was a major component of ash—concrete that contained bottom ash. Ettringite was the most abundant compound in ash—concrete with Ottawa sand and scrubber residue and ash—concrete with Ottawa sand and pre-wetted scrubber residue, respectively, after approximately 95 days in seawater. Ettringite in ash—concrete with Ottawa sand and prewetted scrubber residue is shown in Figure 3. The intensity of the ettringite peak in the X-ray diffractogram of
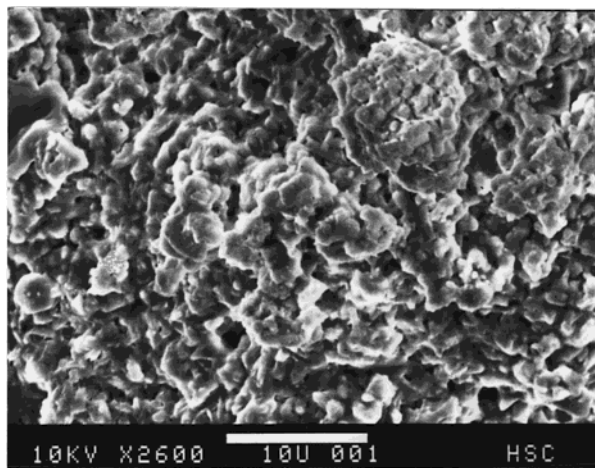
degradation, and weight measurements could be incorporated into a monitoring program.

Mineralogy. A classification system was developed to compare the relative abundance of each mineral phase in a material based on its X-ray diffractogram. Changes in the abundance of species over time should be interpreted in the context of trends because X-ray diffraction analysis does not support absolute quantitative analysis. The mineral with the largest peak was assigned an intensity of 100. Classification of other mineral phases was based on their relative intensities versus the peak. A summary of selected mineral phases found in ash—concrete and mortar as a function of time of exposure to seawater is presented in Table 3 (results for brucite, gypsum, and ettringite discussed in detail below are bolded). A summary of mineral phases found in scrubber residue and prewetted scrubber residue prior to stabilization is presented in Table 4.

Hydration products of ash—concrete were similar to those of conventional concrete. Ash—concrete and mortar were enriched in calcium, silicon, sulfur, and aluminum. Plates of calcium hydroxide and needles of hydrated calcium silicates, ettringite, and gypsum were observed in ash—concrete. A yellow-gray crust appeared on ash—concrete and mortar

FIGURE 4. SEM photograph of scrubber residue prior to stabilization.

ash—concrete with Ottawa sand and scrubber residue was 35% greater than the next most intense peak after 92 days of exposure. Ettringite did not exhibit the same dominant intensity in other mixes. For example, intensities of ettringite and calcite in the X-ray diffractograms of ash—concrete with Ottawa sand and prewetted scrubber residue differed by only 7% after 98 days of exposure.

The significant presence of ettringite and gypsum at early ages in ash—concrete with scrubber residue was not observed in mortar and indicated an additional mechanism for formation besides sulfate attack. Hydrating the scrubber residue at a moisture content of 30% for 5 days prior to stabilization changed the mineralogy of the scrubber residue as well as the kinetics of expansion of the stabilized material. Scrubber residue, shown in Figure 4, and prewetted scrubber residue are amorphous materials that consist of irregular, plate-like structures enriched with calcium, chlorine, and sulfur. Both materials contained calcite, anhydrite, calcium sulfite hemihydrate, and gypsum, but, as shown in Table 4, only prewetted scrubber residue contained ettringite. Although the moisture content of stored scrubber residue was 6—12%, ettringite was only detected with the higher moisture contents used for pre-wetting. Hydration of anhydrite ($CaSO_4$ + $2H_2O$ ↔ $CaSO_4 \cdot 2H_2O$) and calcium sulfite hemihydrate ($CaSO_3 \cdot 0.5H_2O$ + $0.5O_2$ + $1.5H_2O$ ↔ $CaSO_4 \cdot 2H_2O$) forms gypsum. Gypsum hydrates to form ettringite ($3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 32H_2O$) in the presence of aluminate ions. These reactions are accompanied by an increase in the specific volume of solids and the evolution of heat.

Calcium sulfite hemihydrate was detected in both scrubber residue and prewetted scrubber residue but was absent after curing and was assumed to be rapidly and completely hydrated to gypsum. The relative intensity of gypsum in the ash—concrete tended to increase during exposure to seawater probably due to both sulfate intrusion from seawater and slow hydration of anhydrite in scrubber residue to gypsum. Conversion of anhydrite to gypsum in stabilized coal waste blocks was found by Roethel (19). Ettringite can continue to form in ash—concrete with scrubber residue in the presence of sufficient lime and sulfate sources, i.e., gypsum.

Prewetting may also limit the liberation of gas following stabilization that can lead to expansion. Broken and unbroken bubbles were observed in ash—concrete with scrubber residue during examination with an optical microscope. These structures were observed but were much less prevalent in ash—concrete with prewetted scrubber residue. Although physical evidence of gas formation was present, the specific chemical mechanism should be investigated in future studies. For example, hydrogen gas may be liberated when aluminum in scrubber residue is exposed to a highly alkaline environment. Prewetting may facilitate this reaction prior to stabilization, which would limit "bubbling" during the cementation period.

Replacement of Ottawa sand with bottom ash in ash—concrete with scrubber residue was nearly as effective as prewetting for reducing expansion. These results were not consistent with those of Kalajian et al. (2), in which expansion of ash—concrete with bottom ash and scrubber residue was only 33% less than the expansion of ash—concrete with Ottawa sand and scrubber residue in this study at the same age. However, Kalajian et al. did not observe structural deterioration of their material although the expansion was similar in magnitude to that of ash—concrete with Ottawa sand and scrubber residue in this study. Ettringite is more abundant than anhydrite or gypsum in bottom ash. It is possible that concretes with bottom ash are more rigid and able to resist expansive stresses from scrubber residue or that ettringite and other components in bottom ash reduce the exposed surface area for solid-state reactions. Air entraining agents may also stabilize expansion and should be investigated.

Implications. Secondary raw materials from waste-to-energy-systems, such as bottom ash and flue gas scrubber residue, can be used for beneficial applications in a marine environment if the stabilized materials maintain their structural integrity. Expansion of ash—concrete with scrubber residue in seawater may threaten the integrity of the material and facilitate chemical leaching. Hydrating scrubber residue at a moisture content of 30% for 5 days prior to stabilization reduces the rate of expansion in ash—concrete and mitigates structural deterioration of ash—concrete with scrubber residue. The presence of ettringite in prewetted scrubber residue prior to stabilization and the dominance of ettringite in X-ray diffractograms of ash—concrete with Ottawa sand and scrubber residue at later ages suggests that prewetting may limit expansion by facilitating the formation of gypsum and ettringite prior to stabilization. Although the chemical mechanism was not confirmed, physical evidence of bubbling in ash—concrete with scrubber residue suggests that prewetting may also limit expansion by facilitating gas formation prior to stabilization when the ash—concrete is more vulnerable to irreparable fracture from expansive forces.

Literature Cited

(1) Florida Department of Environmental Protection. 1999 Solid Waste Management Report (www.dep.state.fl.us/dwm/documents/swm/swm_99).

(2) Kalajian, E. H.; Jonsson, O. O.; Wu, H.; Nevin, T. *Pinellas County MSW Incineration Ash Ocean Reef Program Engineering Studies*; Submitted to HDR Engineering, Tampa, FL, 1990.

(3) Breslin, V. T.; Tisdell, S. E. *J. Environ. Eng.* **1994**, *120*, 154.

(4) Duedall, I. W.; Champ, M. A. *Oceanus* **1991**, *34*, 94.

(5) Shieh, C. S.; Duedall, I. W. *Chem. Ecol.* **1995**, 295.

(6) Shieh, C. S.; Wei, Y. W.; Duedall, I. W.; Wang, T. *Chem. Ecol.* **1992**, 247.

(7) Yoo, H. Chemical Characterization of Waste-To-Energy Ashes and Stabilized Ash-Concretes. M.S. Thesis, Florida Institute of Technology, Melbourne, FL, 1991.

(8) Fanning, K. A. *Pinellas County Ash Management Assessment Ocean Reef Program Report*; Submitted to HDR Engineering, Tampa, FL, 1989.

(9) U.S. EPA. *Characterization of MWC Ashes and Leachates from Landfills, Monofills, and Co-Disposal Sites*; Versar, Inc.: Springfield, IL, 1987.

(10) ASTM. *Annual Book of Standards*; ASTM: Philadelphia, 1983.

(11) Wu, C. Engineering Properties of Waste to Energy Ash Concrete for Artificial Reef Construction. M.S. Thesis, Florida Institute of Technology, Melbourne, FL, 1989.

(12) Lea, F. M. *Chemistry of Cement and Concrete*; Chemical Publishing Company: New York, 1971.

(13) Tuthill, L. H. *Resistance to Chemical Attack*; ASTM Special Technical Publication 169; ASTM: Philadelphia, 1956.

(14) Mehta, P. K. *Concrete in the Marine Environment*; Elsevier: New York, 1991.

(15) Hockley, D. E.; van der Sloot, H. A. *Environ. Sci. Technol.* **1991**, *25*, 1408.

(16) Mehta, P. K. *Cem. Concr. Res.* **1973**, *3*, 1.

(17) Bentur, A.; Ish-Shalom, M *Cem. Concr. Res.* **1974**, *4*, 709.

(18) Skalny, J.; Mindness, S *Materials Science of Concrete II*; American Ceramic Society: Westerville, OH, 1991.

(19) Roethel, F. J. The Interaction of Stabilized Power Plant Coal Waste with the Marine Environment. Ph.D. Dissertation, State University of New York at Stony Brook, 1981.