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**DETOXIFICATION AND GENERATION OF USEFUL PRODUCTS FROM COAL
COMBUSTION WASTES**

Final Technical Report

Work Performed Under Contract No. FC22-88PC88910

**For
U.S. Department of Energy
Pittsburgh Energy Technology Center
Pittsburgh, Pennsylvania**

**By
Arkansas Tech University
Russellville, Arkansas**

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Revised 11-21-90

FINAL TECHNICAL REPORT TO THE
U.S. DEPARTMENT OF ENERGY

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Products from Coal Combustion Wastes

Introduction:

Electric utilities are on the brink of a new era in waste disposal problems that will stem from newly enacted acid rain legislation and pressure from the environmental community to reduce all emissions including sulfur dioxide. In order to meet these new requirements, power plants will be engaged in practices ranging from fuel switching to the installation of complete scrubber systems. The ultimate effect of an overall reduction in emissions will be an increase in the quantity and type of solid waste that will need to be disposed of by coal-fired power plants. This research project addresses the issue of how to effectively dispose of flyash, bottom ash, and desulfurization sludge through the generation of chemically-hardened material that could potentially be used as a cement or as a synthetic aggregate.

In other parts of the world where local raw materials are scarce (notably in Japan and areas of Europe), by-products from the combustion of coal are used extensively for building materials. These building materials have a variety of forms and many of them are high strength. If a similar strategy were adopted in the U.S. to take waste products from the coal-fired power plants and generate synthetic cement/aggregates from these wastes, then many areas with inadequate ash disposal sites would benefit. The cost of generating this chemically formed aggregate would likely be offset by the reduced cost of disposing of the waste products at the power plant site.

One method of disposing of ash is to utilize it to generate useful products; however, only about 20 percent of all ash that is generated can be

utilized, principally for cement manufacture (Schively, 1977). In addition, the pattern of utilization varies from state to state. In Florida, for example, nearly all flyash that is generated from coal-burning power plants is consumed by the cement industry and virtually none is available for other uses.

Depending on the type of burner used, between 20 and 80 percent of the ash in coal will leave a coal-fired power plant as flyash with the remainder forming bottom ash. Scrubbing of the flue gasses to remove sulfur produces flue gas desulfurization sludge (DSG) consisting principally of impure gypsum. These by-products generate environmental problems because of their chemical composition and the volume of material that must be disposed of. The large volumes of ash and DSG that must be handled on or near the site represent only a minimal problem in rural areas, but in urban areas lack of space and/or geological conditions make disposal very difficult, if not impossible.

Review of the Literature:

Uses for flyash as a pozzolan (i.e., a siliceous material which, when lime is added to it, will precipitate insoluble cementitious silicates) have long been recognized and a large number of techniques utilizing flyash have been described (Bucklen, et al, 1965; Faber, et al, 1976). Research in flyash utilization has been primarily external to the United States (Ravina, 1979). Little information has been published about the relative strengths of flyash lime cements; however, a mixture of gravel, flyash, and slaked lime derived from a dolomite gave compressive strengths of 162 and 194 kg/cm² after 7 and 14 days (Webster and Smith, 1971). Ground blast furnace slag having properties very similar to flyash was mixed with lime and cured for two weeks producing a product that had a compressive strength of 100 kg/cm² (Yamamoto, et al, 1977). The effect of strengthening agents on flyash and ground slag cement mixes is unknown. Silica

gel and lime have been used as binders to produce lightweight building materials out of flyash; however, strengths for such material were not reported (Oates, 1974). Mixtures of calcium oxide and calcium chloride are known to enhance both the tensile and compressive strengths of portland cements and there is no reason to believe that it would not be equally as effective on flyash cements (Simeonov and Dzhabarov, 1978).

Mixtures of power plant flyash, quicklime and gypsum (or other sulfate containing materials) as an activator were found to have a compressive strength of approximately 100 kg/cm² which could be increased to 200-300 kg/cm² by heat treating (Grzymek and Malolepszy, 1973). Binders made from lignite ash, ground slag, and calcium sulfate hydrate were cured under hydrothermal conditions and found to create a cement having compressive strengths ranging between 50 and 400 kg/cm² (Savinkina and Logvinenko, 1974). A composition of calcium sulfate hemihydrate, clay, and flyash was found to give a hardened product with a compressive strength of 670 kg/cm² and a bending strength of 132 kg/cm² (Baselsen, 1977). Mixtures of desulfurization gypsum and granulated slag have been used as a soil cement (Hasaba and Torii, 1979). Similar soil stabilization cements can be generated from flyash, gypsum, and a small amount of either portland cement, ground blast furnace slag, or calcium hydroxide. When this mixture was mixed with soil in amounts of only 3½ percent it gave compressive strengths of up to 40 kg/cm² after 28 days (Soc. Des Ciments Francais). All of the flyash/gypsum/lime mixtures have the common characteristic of forming not only calcium silicate hydrates and calcium aluminate hydrates but also ettringite as a binder (Lucas, 1980).

Granulated blast furnace slag was mixed with gypsum, calcium hydroxide, and water and stirred at 50-100°C to produce ettringite fibers. When these fibers were compacted at 170°C and 200 kg/cm² after mixing with 25 percent organic pulp,

a product was obtained with a bending strength of 80 kg/cm^2 (Kondo, et al, 1979). Ettringite fibers were also obtained from a mixture of blast furnace slag, anhydrite, calcium hydroxide and water agitated at $50\text{-}100^\circ\text{C}$ (Kondo and Fujisawa, 1974). Ground blast furnace slag and mixtures of gypsum and flue gas desulfurization gypsum along with sodium hydroxide, potassium hydroxide or calcium hydroxide can be used to make ettringite (Chudo, et al, 1978). Ettringite fibers can also be generated using aluminous cement, gypsum, quicklime and water (Caspar and Gaillard, 1980). Fibers of gypsum can also be crystallized directly through the reaction of sodium sulfate and calcium chloride at an elevated temperature and pH (Sueddeutsche Kalkstickstoff, 1976). The strength of cement can also be increased through the generation of ettringite by the addition of aluminum sulfate and calcium chloride (Simeonov and Dzhabarov, 1973). Ettringite fibers can be directly mixed with gypsum to produce high strength, high fire resistant wallboard and also mixed with siloxanes and compacted to produce extremely high strength, high density wallboards with a compressive strength of 90 kg/cm^2 (Kaga, et al, 1976; Oguri and Hashimi, 1973; Kubo and Sedo, 1977).

Cement can be rapidly hardened by the addition of gypsum and calcium chloride, gypsum and aluminum chloride, calcium fluoro-aluminate, or gypsum and aluminum sulfate producing compressive strengths of greater than 100 kg/cm^2 (Nakagawa, et al, 1977; Simeonov and Dzhabarov, 1977; Ichimura, et al, 1979). Mixtures of ettringite and gypsum fibers along with organic fibers have been hardened using calcium alumino-sulfates, aluminum hydroxide/calcium oxide, and pozzolan/sodium silicate mixtures (Kanno and Higaski, 1977; Hayashi, 1976; Mineshita, et al, 1977; Mineshita and Imai, 1979). In addition to the hardening of ettringite cements some research has been performed on hardening red mud from bauxite processing. The red mud contains iron hydroxides and calcium silicates

which when mixed with calcium hydroxide and a sulfate (such as sodium sulfate, potassium sulfate, or gypsum) gave compressive strengths of up to 83 tons/m² after seven days (Mori and Kitsugi, 1974). Hardening agents for solidifying soils can be generated from separate solutions of sodium silicate and a suspension of gypsum and calcium hydroxide which when mixed will set in the soil (Nitto Chemical Industry Company, 1980). A high strength cement may also be generated from a mixture of portland cement and flyash hardened with a sodium oxalate/sodium silicate solution. This mixture gave a compressive strength of 51 and 248 kg/cm² after one day and year respectively (Fujiko, 1980). Mixtures of lime and residue from pyrite roasting and ferruginous slags developed strengths ranging from 92 to 156 kg/cm² after autoclaving (Mukhamedbaeva, et al, 1972). Porous lightweight products were obtained with aluminum hydroxides and phosphoric acids which gave materials with compressive strengths ranging from 23 to 70 kg/cm² (Abyzov and Kir'yanova, 1979).

In tests of immobilization of ash from the incineration of sewage sludge (containing cadmium, lead, and chromium), slag cements were found to be superior in suppressing the dissolution of heavy metal ions from the hardened material and also had superior compressive strengths (Kawashima, et al, 1976). Sludges from coal combustion (flyash and desulfurization gypsum) were used as a cementing matrix for phosphate-rich sewage sludge and a solidified material was obtained that reduced the amount of phosphate leaching from the sewage sludge significantly (Akers Consulting Services, Ltd., 1977). A special cement containing ettringite and calcium silicates was found to fix very high amounts of mercury, cadmium, lead, chromium, arsenic, and cyanide (Uchikawa, 1978). Some fixation of heavy metals in cement mixtures is also found to be a characterization of precipitation as heavy metals hydroxides by the calcium hydroxide in the cement (Asano and Konishi, 1978).

Both flyash and bottom ash composition will vary with the original ash composition of the coal that was burned. Typical bulk flyash and bottom ash compositions from the Four Corners Generation Plant are shown in Table 1 (Roffman, et al, 1977). These same authors give the concentrations of trace elements in the coal, bottom ash, and fly ash. Trace element contents and enrichment ratios for bottom ash and flue gas desulfurization sludge have been published (National Academy of Science, 1980). In a study of flyash from New Zealand coals, the composition of both acid soluble and acid insoluble fractions were determined (Bibby, 1977). The principle acid soluble fraction consists primarily of alkali components of the ash, especially calcium and boron. Distribution (and concentration) of elements in bottom ash, flyash, and flue gas has also been calculated (Schsitzgebel, et al, 1975; U.S. Environmental Protection Agency, 1975) and the average trace element content of ash from coals in different regions of the United States has also been tabulated (Abernethy, et al, 1969).

Research Objectives:

The objectives of the proposed research were to find optimum mixtures of flyash, bottom ash, and flue gas desulfurization sludge (DSG) that could be hardened through a pozzolanic reaction into a flyash or ettringite cement that will have high strength and low leachability of heavy metals. The specific goals of this study were: (1) to study the hardness of mixtures of flyash, bottom ash, and DSG treated with lime and other hardening agents; (2) to determine the optimum solids content, setting time, moisture content, and post setting treatments that will yield the greatest strength and hardness out of these mixtures; and (3) to determine the leachability of the synthetic material as a measure of its ability to retain absorbed and/or entrained toxic metals.

TABLE 1
Composition of Coal, Bottom and Flyash

<u>Constituent</u>	Major and Minor Constituents (%)		<u>Bottom Ash</u>
	<u>Coal</u>	<u>Flyash</u>	
	3.0	27.4	26.2
Al ₂ O ₃			
	5.7	57.2	59.1
SiO ₂			
	0.08	0.68	0.6
MgO			
	0.55	3.8	3.9
Fe ₂ O ₃			
	0.22	1.4	1.3
Na ₂ O			
	0.15	0.9	0.93
K ₂ O			
	0.72	4.5	5.0
CaO			
	0.19	1.5	1.4
TiO ₂			
		3.3	1.2
Ignition Loss			
Ash	11.2		

Materials and Methods:

Flyash, bottom ash, and DSG from Ohio Edison, flyash and bottom ash from the White Bluff Power Plant of Arkansas Power and Light, and flyash from a Tennessee Valley Authority power plant were obtained. These samples provided waste materials from high sulfur Eastern coal, low sulfur Western coal, and an intermediate mix, respectively.

The DSG slurry was decanted and the settled solids scooped out of the bucket and placed in an oven where they were dried at approximately 60°C for 48 hours. This resulted in a porous, blocky material which could be ground very rapidly in a pulverizer. The resulting lightweight powder had +95 percent passing a 100 mesh screen. The bottom ash was also dried at less than 60°C, crushed to -2 mm, and then passed through a pulverizer and reduced to +80 percent passing a 100 mesh screen. The flyash was already -100 mesh and no further crushing or grinding was performed on it. After drying and pulverizing, the samples were stored in buckets until they were ready for mixing with the hardening agents.

Hardening Tests:

An initial set of 120 tests of hardening agents using mixtures of lime, lime plus calcium chloride, lime plus aluminum sulfate, lime plus aluminum sulfate plus sodium silicate in combination with flyash, bottom ash, and DSG and mixtures of Ohio Edison flyash, bottom ash, and DSG were carried out. Tests of water slurries of DSG, flyash, and bottom ash indicated the following pH:

DSG	8.80
Flyash	3.00
Bottom Ash	7.58

The weights of flyash, DSG, and bottom ash and hardening agents used in the 120 tests are given in Appendix A.

The dry ground flyash, DSG, and bottom ash were mixed with the powdered chemical reagents and placed in ziplock bags. They were thoroughly mixed by shaking the powdered components together. Between 50 and 100 ml of distilled water was then added to each bag until a plastic slurry was achieved. The amount of water added varied depending on the content of DSG, with less water being required for the somewhat coarser bottom ash and for the relatively non-absorbent flyash. The bags were then sealed and placed in boxes to harden at room temperature.

The results of the initial hardening tests were somewhat disappointing. After 24 hours, only the flyash and bottom ash and mixtures thereof had shown any significant hardening. Mixtures containing DSG remained in a plastic or semi-hardened state. At the end of one week, some additional hardening had taken place but the DSG continued to act as an inhibitor to the hardening process.

The initial hardening tests indicated that the DSG tended to act as a hardening inhibitor rather than an accelerator. This problem was traced to a very low calcium sulfate content and very high calcium sulfite content of the material. The solubility of calcium sulfate is 0.209 grams per 100 cc of water whereas the solubility of calcium sulfite is only 0.0043 grams per 100 cc of water. This low solubility inhibits the conversion of the sulfite to sulfate in the reacting products and inhibits the growth of ettringite.

The second and subsequent hardening tests contained added calcium sulfate dihydrate so that ettringite would be able to form rapidly during the initial hydration and acted as a cement to hold the calcium sulfite together until its delayed reaction could take place.

Fresh coal flyash and bottom ash was ground to -300 mesh and new mixes for hardening tests (based on the initial hardening tests) were prepared (Appendix B). The mixes were allowed to harden for one month and were then removed from

the sample cups and subjected to crushing tests. A subsample of the material was retained for cation exchange capacity testing.

Expansion and contraction of the mixes during hardening led to cracking of one test samples (Appendix C). While some mixtures had excellent hardness, they were relatively low strength because of this cracking.

The original mixes were not pulverized beyond -100 mesh and had strengths ranging from 6.3 kg/cm² to 96.4 kg/cm² (Table 2). All but one of the unground tests had strengths below 30 kg/cm². After grinding to -300 mesh there was a significant increase in strength in all but one case (Table 3).

Chemical Analysis:

Chemical analyses of the fly and bottom ash from Ohio Edison were provided by the Company. Chemical, physical and EP toxicity tests are reported in Tables 4-6.

Mineralogical Analysis of Flyash and Hardened Products:

Examination of air dried DSG, flyash and pulverized bottom ash was carried out using packed powder mounts on an x-ray diffractometer. The DSG consists entirely of calcium sulfite dihydrate and does not appear to contain any gypsum (Figure 1a and 1b). The bottom ash revealed only glassy phases; however, the flyash contained distinct peaks for quartz, mullite, and hematite (Figure 2).

Examination of the reaction products indicated the formation of ettringite, calcium monosulfate hydrate, an unknown hydrated phase, and minor calcite. A mix of 1 part flyash and 1 part bottom ash to 5 parts DSG treated with 10% lime showed distinct formation of ettringite, a very minor formation of a hydrated unknown phase, and formation of calcite (Figure 3). The same mix ratio treated with 10% lime and calcium chloride as a hardening accelerator showed the complete disappearance of the ettringite peak and essentially no formation of calcite.

TABLE 2

Hardening Data - Underground Mixtures

Sample	Ohio Coal Ash	Water	Compressive Strength	CBC mg/100g
A003-1	8g FA + 2g CaO	26%	6.42 kg/cm ²	16.6
A008-1	8g FA + DSG + GYP + 2g CaO	37%	7.23 kg/cm ²	11.1
A028-1	8g FA + DSG + GYP + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	41%	16.06 kg/cm ²	0.5
A030-1	8g BA + DSG + GYP + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	39%	25.3 kg/cm ²	0.5
TVA Coal Ash				
A039-1A	8g FA1 + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	39%	25.29 kg/cm ²	12.8
A039-1B	8g FA2 + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	39%	25.29 kg/cm ²	12.8
White Bluff Coal Ash				
A055-1	8g BA + 2g CaO	22%	7.37 kg/cm ²	5.5
A059-1	8g BA + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	26%	10.62 kg/cm ²	2.8
A065-1	8g (BA + DSG + GYP) + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	38%	6.33 kg/cm ²	9.4
A067-1	8g FA + 2g CaO	28%	30.00 kg/cm ²	2.8
A075-1	8g FA + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	26%	96.35 kg/cm ²	-

TABLE 3

Hardening Data - Pulverized Mixtures

<u>Sample</u>	<u>Ohio Coal Ash</u>	<u>7 Day</u>	<u>30 Day Compressive Strength</u>
A003-1	8g FA + 2g CaO	very hard-few small cracks	47.4 kg/cm ²
A008-1	8g FA + DSG + GYP + 2g CaO	extremely hard, no cracks	118.4 kg/cm ²
A028-1	8g FA + DSG + GYP + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	extremely hard, no cracks	112.5 kg/cm ²
A030-1	8g BA + DSG + GYP + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	extremely hard, no cracks	47.4 kg/cm ²
<u>TVA Coal Ash</u>			
A039-1A	8g FA1 + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	extremely hard-few small cracks	29.6 kg/cm ²
A039-1B	8g FA2 + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	extremely hard-few small cracks	29.6 kg/cm ²
<u>White Bluff Coal Ash</u>			
A055-1	8g BA + 2g CaO	hard, many small cracks	29.6 kg/cm ²
A059-1	8g BA + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	extremely hard, no cracks	17.3 kg/cm ²
A065-1	8g (BA + DSG + GYP) + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	extremely hard, no cracks	11.9 kg/cm ²
A067-1	2g FA + 2g CaO	extremely hard, no cracks	41.4 kg/cm ²
A075-1	8g FA + 2g CaO + Al ₂ (SO ₄) ₃ + Na ₂ SiO ₃	extremely hard, no cracks	23.7 kg/cm ²

TABLE 4

A.H. SAMMIS PLANT - ASH ANALYSIS

Toxic Substances: (fly ash only)
EP Toxicity Test - mg/L

Date	Location	Arsenic	Barium	Cadmium	Chromium	Lead	Mercury	Selenium	Silver
	Hazardous Waste Limits	(5.0)	(100)	(1.0)	(5.0)	(5.0)	(0.2)	(1.0)	(5.0)
	Solid Waste Limits	(1.5)	(30)	(0.30)	(1.5)	(1.5)	(0.06)	(0.3)	(1.5)
	Drinking Water Standards	(0.05)	(1)	(0.010)	(0.05)	(0.05)	(0.002)	(0.01)	(0.05)
Feb. 19, 1988	1-4 precip	0.009	0.24	<0.01	<0.02	<0.05	<0.002	0.093	<0.01
Feb. 19, 1988	5-7 precip	0.26	0.22	0.01	0.04	<0.05	<0.002	0.051	<0.01

TABLE 5

W.H. SAMMIS PLANT - ASH ANALYSIS

Chemical Composition - %

Date	Location	Ash Type	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	P ₂ O ₅	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	MnO ₂	Total
Feb 19 1988	1-4 north	fly	42.23	15.28	35.96	0.16	1.69	0.56	1.16	0.20	2.49	0.26	<0.01	99.99
Feb 23 1988	1-4 north	bottom	58.92	25.99	9.75	0.08	1.48	0.49	0.89	0.16	2.20	0.02	<0.01	99.98
Feb 19 1988	5-7 south	fly	40.14	12.98	42.82	0.08	0.77	0.78	0.58	0.29	1.15	0.40	<0.01	99.99
Feb 23 1988	5-7 south	bottom	47.21	18.21	28.92	0.13	0.95	1.63	0.91	0.30	1.72	<0.01	<0.01	99.98

TABLE 6

W.H. SAMMIS PLANT - ASH ANALYSIS

Physical Properties

Date	Location	Ash Type	Loss on Ignition (%)	Wet Seive 325 Mesh % Passing	Bulk Density g/cc
Feb 19 1988	1-4 north	fly	8.9	80.4	1.96
Feb 23 1988	1-4 north	bottom	17.1	-	1.80
Feb 19 1988	5-7 south	fly	1.5	69.0	2.31
Feb 23 1988	5-7 south	bottom	4.7	-	2.30

Figure 1. (A) Air dried desulfurization gypsum sludge. Packed powder mount, $\text{CuK}\alpha$. Specimen is essentially pure $\text{CaSO}_3 \cdot 2\text{H}_2\text{O}$. (B) Gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ reference specimen. Same conditions as A.

Figure 2. Packed powder mount of flyash, $\text{CuK}\alpha$. Peaks for crystalline phases of mullite, quartz, and hematite are indicated.

Figure 3. 1 part flyash, 1 part bottom ash (pulverized) and 5 parts desulfurization gypsum sludge (DSG) reacted with 10% lime. Slide mount, CuK α . Peaks assignable to reaction products are indicated.

The suppressing action of calcium chloride in the formation of these minerals has not been reported previously, although calcium chloride is known to be an accelerator in concrete setting (Figure 4).

The addition of 10% lime plus aluminum sulfate to the test mix generated the greatest amount of ettringite and some minor monosulfate and calcite (Figure 5). Addition of lime, aluminum sulfate, and sodium sulfate as hardeners to the same mix generated considerably less ettringite but also generated monosulfate, an unknown hydrated phase, and some calcite (Figure 6). It is possible that some tobermorite phases were generated; however, these could not be detected. A number of unsuccessful attempts were made to synthesize pure ettringite and calcium monosulfate hydrate; however, the mixtures obtained were always contaminated with either calcite or gypsum as reaction products. A literature review of the synthesis of these components has been conducted and an attempt will be made to generate pure reference materials for later work.

Cation Exchange Capacity (CEC) of the Hardened Ash Mixtures:

The CEC of the hardened mixtures was determined using ammonium absorption and measuring the retained ammonium with an ammonia specific ion electrode. This technique is simple, rapid, and essentially free of interferences. The CEC's of various hardening mixtures are given in Appendix D. CEC's ranged from 0.5 meq/100 g to 16.6 meq/100 g. For comparison purposes, a montmorillonitic clay has a CEC that is typically 110 meq/100 g. The relatively low CEC of these mixtures is thought to reflect the relatively small amount of cation exchanger generated as hardening agents. If for example, only 10% of ettringite or tobermorite were generated during hardening and this 10% component represented all of the cation exchanger, then the CEC's reported would actually be fairly high on a unit weight basis. Further testing of mixes with higher ratios of ettringite and tobermorite will be needed to determine the true CEC of the

Figure 4. 1 part flyash, 1 part bottom ash (pulverized) and 5 parts desulfurization gypsum (DSG) reacted with 10% lime plus CaCl_2 accelerator. Slide mount, $\text{CuK}\alpha$.
Note the absence of reaction products.

Figure 5. 1 part flyash, 1 part bottom ash (pulverized) and 5 parts desulfurization gypsum (DSG) reacted with 10% lime and $\text{Al}_2(\text{SO}_4)_3$ accelerator. Slide mount, $\text{CuK}\alpha$. Peaks for reaction products are indicated on the diffractogram. Note the apparent presence of calcium monosulfate hydrate.

Figure 6. 1 part flyash, 1 part bottom ash (pulverized), and 5 parts desulfurization gypsum (DSG) reacted with 10% lime and $\text{Al}_2(\text{SO}_4)_3$ and sodium silicate accelerators. Slide mount, $\text{CuK}\alpha$. Reaction products are indicated on the diffractogram. Note the presence of an unidentified hydrous phase and calcium monosulfate hydrate.

hardening agents. Selectivity of the hardening agents is unknown at this time and will be tested during the leaching phase.

XRF Analysis of Heavy Metal Sorption Capacity:

Stock solutions containing 10, 50, and 100 ppm of As, Co, Cu, Ni, Se, Zn, and Hg were prepared from 1000 ppm standard solutions supplied by Chemical Manufacturing Co., Gardena, California, and by Alpha Analytical Labs, Newark, New Jersey. These standards were in a matrix of dilute HCl and HNO₃. The pH of the solutions was:

10 ppm	2.50
50 ppm	1.80
100 ppm	1.60

These pH's reflect the acid matrix of the standards. Fifty ml of the stock solution was equilibrated for 1 hour with 1 g of crushed, hardened mixture. Approximately 5 ml of the equilibrated solution was poured into an XRF cup, covered with 0.25 mil mylar film and analyzed in a Norelco XRF spectrograph. Analytical lines and settings used are in Table 7.

All analyses were performed using a scintillation detector and a count time of 100 seconds.

Calculation of concentration was from standards after subtraction of background counts. Detection limits were below 30 ppm on the elements analyzed.

Results of the sorption tests are reported in Figures 7-15 and Appendix E. In general, the anions As and Se were lightly adsorbed. Zn and Cu were variable but demonstrated intermediate adsorption. Hg was also variable but tended to be highly adsorbed. Only Co and Ni were adsorbed completely at all treatment levels.

There was some desorption at higher treatment levels, especially for As and Se. This was probably caused by the higher acidity of the solution used to sorb the heavy metals on the hardened material (see Table 8). Much of the adsorption

TABLE 7

Analytical Lines and Settings for
XRF Analysis of Heavy Metal Sorption

<u>ELEMENT</u>	<u>λ</u>	<u>Li F Analyzer Setting (2θ°)</u>
As	1.177	34.00
Co	1.790	52.79
Cu	1.542	45.03
Pb	1.175 (L α)	33.93
Ni	1.659	48.66
Se	1.106	31.89
W	1.479	43.02
Zn	1.436	41.80
Hg	1.24 (L α)	35.90

TABLE 8
pH of Metal Adsorption Tests

<u>Sample No.</u>	<u>10 ppm</u>	<u>50 ppm</u>	<u>100 ppm</u>
A003-1	11.4	10.2	1.5
A008-1	11.5	9.0	1.4
A028-1	9.4	4.1	1.5
A030-1	11.2	3.9	1.6
A055-1	11.2	10.0	3.9
A059-1	10.8	7.5	3.4
A065-1	11.0	6.8	3.1
A067-1	11.2	10.5	4.3
A075-1	10.2	8.7	4.2

Figure 7. Absorption of heavy metals on hardened mixture A003-1. 8g FA + 2g CaO

Figure 8. Adsorption of heavy metals on hardened mixture A008-1. 8g FA + DSG + GYP + 2g CaO

Figure 9. Adsorption of heavy metals on hardened mixture A028-1.
 8g FA + DSG + GYP + 2g $[\text{CaO} + \text{Al}_2(\text{SO}_4)_3 + \text{Na}_2\text{SiO}_3]$

Figure 10. Adsorption of heavy metals on hardened mixture A030-1.
 8g BA + DSG + GYP + 2g [CaO + $\text{Al}_2(\text{SO}_4)_3$ + Na_2SiO_3]

Figure 11. Adsorption of heavy metals on hardened material A055-1.
8g BA + 2g CaO. (Hg value is probably anomalous)

Figure 12. Adsorption of heavy metals on hardened material A059-1.
 8g BA + 2g [CaO + Al₂(SO₄)₃ + Na₂SiO₃]

Figure 13. Adsorption of heavy metals on hardened material A065-1.
 8g (BA + DSG + GYP) + 2g [CaO + Al₂(SO₄)₃ + Na₂SiO₃]

Figure 14. Adsorption of heavy metals on hardened material A067-1.
8g FA + 2g CaO

Figure 15. Adsorption of heavy metals on hardened material A075-1.
 8g FA + 2g $[\text{CaO} + \text{Al}_2(\text{SO}_4)_3 + \text{Na}_2\text{SiO}_3]$

may be attributed to a precipitation reaction caused by the alkalinity of the hardened materials.

Results and Discussions:

The hardness tests provided satisfactory evidence that cementing agents (including torbermorite and ettringite) can be generated in flyash, bottom ash, and desulfurization sludge. The degree of cementation is dependent on several factors including (1) fineness (surface area) of the ash and DSG; (2) uniformity of mixing of the hardening agents; (3) moisture content of the mix; (4) formation of carbonates during drying cycles; and (5) the degree of cracking caused by formation of shrink-swell components (mostly ettringites). The amount of shrink-swell appears to control the strength (but not the hardness) of the mix. Many samples that crumbled before testing produced granules that were quite hard and crush resistant.

Strengths of unpulverized mixtures ranged from 0 to 96 kg/cm². Strengths for pulverized mixes ranged from 11 to 118 kg/cm². This compares well with ranges of such mixes reported previously in the literature. Various forms of heat treating are known to generate compressive strengths up to 400 kg/cm² in such mixes; however, for simple air-curing the values are typically clustered around 100 kg/cm².

Cation exchangers were generated during hardening; however, the percentage of these materials in the hardened product was relatively low. CEC's ranged from 0.5 meq/100 g to 16.6 meq/100 g.

Adsorption tests of heavy metals has demonstrated that the hardened materials have excess capacity to adsorb heavy metals. This demonstrates that under worst case conditions (high acidity) the hardened materials are stable and would not release toxins to the environment.

This project has demonstrated that diverse mixtures of coal-fired power plant wastes can be hardened satisfactorily. The problem of cracking of the mixtures will have to be overcome before structural use of the hardened products can be realized. For simple disposal, such as road underlayment, the hardened product should be more than adequate.

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APPENDICES

APPENDIX A

Proportions of Fly Ash, Bottom Ash, and Desulfurization Gypsum (DSG) Sludge and Hardening Agents Used in Test of Ohio Edison Waste Products. Hardening Results:
 N = Nil (Plastic after 1 week), W = Weakly Hardened,
 M = Moderately Hardened, H = Hardened (Resists Crushing)

Power Plant By-Product Tested	Lime Ca(OH) ₂			1 Part Lime/1 Part Calcium Chloride Ca(OH) ₂ /CaCl ₂		
	1 g	5 g	10 g	1 g	5 g	10 g
100 g Fly Ash	N	W	W	N	W	M
100 g DSG Sludge	N	N	N	N	N	N
100 g Bottom Ash	N	M	W	N	W	M
50 g Fly Ash + 50 g DSG Sludge	N	N	N	N	N	N
20 g Fly Ash + 80 g DSG Sludge	N	N	N	N	N	N
50 g Fly Ash + 50 g Bottom Ash	N	N	N	N	N	N
50 g Bottom Ash + 50 g DSG Sludge	W	N	N	N	N	N
20 g Bottom Ash + 80 g DSG Sludge	N	N	N	N	N	N
33 g Fly Ash + 33 g Bottom Ash + 34 g DSG Sludge	N	N	N	N	N	N
14 g Fly Ash + 14 g Bottom Ash + 72 g DSG Sludge	N	N	N	N	N	N

Power Plant By-Product Tested	5 Parts Lime/1 Part Aluminum Sulfate 5 Ca(OH) ₂ /1Al ₂ (SO ₄) ₃			5 Parts Lime/1 Part Aluminum Sulfate/2 Parts Sodium Silicate 5 Ca(OH) ₂ /1Al ₂ (SO ₄) ₃ /2 Na ₂ SiO ₃ 35H ₂ O		
	1 g	5 g	10 g	1 g	5 g	10 g
100 g Fly Ash	N	N	W	N	H	H
100 g DSG Sludge	N	N	N	N	N	N
100 g Bottom Ash	N	N	W	W	M	H
50 g Fly Ash + 50 g DSG Sludge	N	N	N	N	N	N
20 g Fly Ash + 80 g DSG Sludge	N	N	N	W	M	H
50 g Fly Ash + 50 g Bottom Ash	N	W	W	N	N	N
50 g Bottom Ash + 50 g DSG Sludge	N	N	N	N	N	N
20 g Bottom Ash + 80 g DSG Sludge	N	N	N	N	N	N
33 g Fly Ash + 33 g Bottom Ash + 34 g DSG Sludge	N	N	N	N	N	W
14 g Fly Ash + 14 g Bottom Ash + 72 g DSG Sludge	N	N	N	N	N	W

Proportions of Fly Ash, Bottom Ash, and Desulfurization
Gypsum (DSG) Sludge and Hardening Agents Used in
Test of Ohio Edison Waste Products. Hardening Results (after 60 days)
N - Nil (Plastic after 1 week), W - Weakly Hardened, M - Moderately
Hardened, H - Hardened (Resists Crushing), VH - very hard (resists
breaking and crushing under heavy pressure)

	Lime			Lime CaCl ₂			Lime Al ₂ (SO ₄)			Lime AlSO ₄ Na Silicate		
	1	5	10	1	5	10	1	5	10	1	5	10
FA	W	W	M	N	W	H	N	N	H	W	H	VH
BA	W	H	VH	M	H	VH	N	W	W	W	H	VH
DSG	N	W	H	N	M	H	N	W	H	W	M	M
1:1 FA/DSG	N	W	M	N	W	M	N	W	W	N	W	H
5:1 FA/DSG	N	M	H	N	W	M	N	W	M	N	H	VH
1:1 FA/BA	N	N	W	N	W	H	N	N	W	M	H	VH
1:1 BA/DSG	N	M	H	N	W	H	N	N	W	W	M	VH
5:1 BA/DSG	N	M	H	N	W	H	N	W	M	N	M	VH
1:1:1 FA/BA/DSG	N	N	W	N	W	H	N	N	N	N	H	VH
1:1:5 FA/BA/DSG	N	W	M	N	W	H	N	W	H	N	H	VH+

APPENDIX B

Flyash/Bottom Ash Mixtures for the Second Series of Hardening Tests

OHIO COAL ASH

Sample #		Water
A001	90g FA* + 10g CaO*	28%
A002	80g BA* + 20g CaO	22%
A003	80g FA + 20g CaO	26%
A004	90g BA + 10g CaO	21%
A005	90g DSG + Gyp 10g CaO	44%
A006	80g DSG + Gyp 20g CaO	45%
A007	90g FA + DSG* + Gyp* + 10g CaO	42%
A008	80g FA + DSG + Gyp + 20 g CaO	37%
A009	90g BA + DSG + Gyp + 10g CaO	36%
A010	80g BA + DSG + Gyp + 20g CaO	35%
A011	90g FA + 10g A*	34%
A012	80g FA + 20g A	36%
A013	90g BA + 10g A	29%
A014	80g BA + 20g A	29%
A015	90g DSG + Gyp + 10g A	50%
A016	80g DSG + Gyp + 20g A	47%
A017	90g FA + DSG + Gyp + 10g A	42%
A018	80g FA + DSG + Gyp + 20g A	42%
A019	90g BA + DSG + Gyp + 10g A	44%
A020	80g BA + DSG + Gyp + 20g A	53%
A021	90g FA + 10g B*	32%

A022	80g FA + 20g B	32%
A023	90g BA + 10g B	24%
A024	80g BA + 20g B	28%
A025	90g DSG + Gyp + 10g B	49%
A026	80g DSG + Gyp + 20g B	48%
A027	90g FA + DSG + Gyp + 10g B	42%
A028	80g FA + DSG + Gyp + 20g B	41%
A029	90g BA + DSG + Gyp + 10g B	39%
A030	80g BA + DSG + Gyp + 20g B	--

TVA COAL ASH

Sample		Water
A031	90g FA + 10g CaO	39%
A032	80g FA + 20g CaO	36%
A033	90g FA + DSG + Gyp + 10g CaO	42%
A034	80g FA + DSG + Gyp + 20g CaO	41%
A035	90g FA + 10g A	38%
A036	80g FA + 20g A	46%
A037	90g FA + DSG + Gyp + 10g A	45%
A038	90g FA + 10g B	40%
A039	80g FA + 20g B	39%
A040	80g FA + DSG + Gyp + 20g A	41%
A041	90g FA + DSG + Gyp + 10g B	45%
A042	80g FA + DSG + Gyp + 20g B	41%
A043	90g FA2 + 10g CaO	42%
A044	80g FA2 + 20g CaO	40%
A045	90g FA2 + DSG + Gyp + 10g CaO	44%
A046	80g FA2 + DSG + Gyp + 20g CaO	41%

A047	90g FA2 + 10g A	42%
A048	80g FA2 + 20g A	45%
A049	90g FA2 + DSG + Gyp + 10g A	44%
A050	80g FA2 + DSG + Gyp + 20g A	41%
A051	90g FA2 + 10g B	42%
A052	80g FA2 + 20g B	37%
A053	90g FA2 + DSG + Gyp + 10g B	--
A078	80g FA2 + DSG + Gyp + 20g B	--

WHITE BLUFF COAL ASH

A054	90g BA + 10g CaO	21%
A055	80g BA + 20g CaO	22%
A056-A	90g BA + 10g A	29%
A056-B	90g BA + 10g A	26%
A057	80g BA + 20g A	27%
A058	90g BA + 10g B	25%
A059	80g Ba + 20g B	26%
A060	90g [BA + DSG + Gyp] + 10g CaO	34%
A061	80g [BA + DSG + Gyp] + 20g CaO	35%
A062	90g [BA + DSG + Gyp] + 10g A	37%
A063	80g [BA + DSG + Gyp] + 20g A	39%
A064	90g Ba + DSG + Gyp + 10g B	36%
A065	80g [BA + DSG + Gyp] + 20g B	38%
A066	90g FA + 10g CaO	22%
A067	80g FA + 20g CaO	28%
A068	90g FA + DSG + 10g CaO	37%
A069	80g FA + DSG + 20g CaO	35%

A070	90g FA + 10g A	32%
A071	80g FA + 20 g A	34%
A072	90g FA + DSG + Gyp + 10g A	36%
A073	80g FA + DSG + Gyp + 20g A	43%
A074	90g FA + 10g B	27%
A075	80g FA + 20g B	26%
A076	90g FA + DSG + Gyp + 10g B	43%
A077	80g FA + DSG + Gyp + 20g B	41%

*FA=Fly Ash

BA=Bottom Ash

DSG=Desulfurization Sludge

GYP=Gypsum

CaO=Lime

APPENDIX C

Test Sample Characteristics from the Second Series of Hardening Tests

Sample:

A001 - Sample is hard. Does not demonstrate shrinkage or expansion cracks.

A002 - Hard. Cup is bulged from approximately 10% expansion.

A003 - Cup is split from approximately 20% expansion. Sample is hard and demonstrates very minor surface cracking.

A004 - Exhibits minor shrinkage (after an apparent expansion because the cup is slightly bulged).

A005 - Hard. Demonstrates minor surface cracking and spalling but no apparent shrinkage or expansion.

A006 - Demonstrates some surface expansion and spalling of the surface. There is a ring around the surface of the cup where it expanded more than the body of the mix.

A007 - Demonstrates considerable surface cracking and spalling and expansion of the surface layer.

A008 - Demonstrates minor expansion. There is some cracking evident. No surface spalling.

A009 - Demonstrates considerable cracking. Some minor surface spalling, minor expansion.

A010 - Hardened. Does not demonstrate appreciable surface cracking or expansion. No apparent shrinkage.

A011 - Demonstrates minor shrinkage after apparent expansion. No surface cracking, no spalling.

A012 - Demonstrates minor, probably less than 5%, expansion followed by some shrinkage. No surface spalling although the surface is somewhat soft.

A013 - Demonstrates considerable shrinkage. No surface cracking.

A014 - Demonstrates minor expansion and cracks. Surface is irregular, somewhat soft.

A015 - Demonstrates considerable expansion, surface spalling, and very deep cracks.

A016 - Demonstrates no appreciable expansion; however, the surface has spalled and there are a considerable number of fine cracks throughout the body of the material.

- A017 - Demonstrates severe surface spalling and severe cracking, although expansion appears to be only about 5%.
- A018 - Demonstrates minor surface spalling, considerable cracking, no apparent expansion or shrinking.
- A019 - Demonstrates severe surface spalling, severe surface cracking and cracking through the body of the material. Extreme expansion or contraction not evident in the cup.
- A020 - Demonstrates some shrinkage, minor surface spalling, minor cracking.
- A021 - Sample is crumbly, soft, surface is spalled, probably cracked, although it is difficult to tell. No expansion or shrinkage is evident.
- A022 - Sample appears to have expanded approximately 10%. Minor surface spalling, mostly in the center of the sample and some cracking is evident.
- A023 - Specimen has severe surface cracking and spalling. Sample appears to have undergone minor expansion.
- A024 - Specimen is fairly hard. Minor surface spalling and some cracking is evident.
- A025 - Specimen is hard. Appears to have been some expansion followed by shrinkage. Minor surface spalling, minor cracking apparent.
- A026 - Considerable surface spalling. No expansion or shrinkage apparent. Considerable cracking of the sample.
- A027 - Hard. There is minor surface spalling, no cracking is evident. Sample appears to have minor shrinkage.
- A028 - Appears to have expanded approximately 10%. There is considerable minor surface spalling. Underneath the surface layer are fairly large cracks.
- A029 - Appears to have expanded and then shrunk. There is only minor surface spalling but considerable cracking of the sample.
- A030 - Has surface spalling. Does not appear to have expanded. There is apparently some shrinkage on drying. Minor cracking.
- A031 - Has shrunk considerably. There is no evidence of cracking, there is some minor surface spalling.
- A032 - Has very minor surface spalling. Sample is hard, does not appear to have been either shrinkage or expansion.
- A033 - Hard. Does not appear to have either expanded or shrunk. Minor surface spalling, minor cracking.
- A034 - Hard. There is very minor cracking, no evident surface spalling.

A035 - Has very minor surface spalling, appears to have minor shrinkage and very minute cracking.

A036 - Minor surface spalling. Sample is hard, does not appear to be cracked.

A037 - Considerable surface spalling. Formation of crystalline crust and cracks throughout.

A038 - Has crumbled into small fragments. Appears to be cracked throughout. Does not appear to have either expanded or contracted; however, it is falling apart.

A039 - Hard. Exhibits very minor surface spalling. No evident cracking. Does not appear to have shrunk or expanded.

A040 - Appears to have shrunk. Sample is reasonably hard. Does not show surface cracking or spalling.

A041 - Shows considerable surface spalling. Minor cracking, although it is hard to determine with all of the spalling. Does not appear to have shrunk or expanded.

A042 - Appears to have expanded approximately 10% with most of the expansion concentrated to the surface of the sample. Sample has minor surface spalling and extensive deep cracking.

A043 - Does not show surface spalling or cracking. Does not appear to have expanded or contracted.

A044 - Shows very minor surface spalling. No cracking is evident. Sample does not appear to have shrunk or expanded.

A045 - Does not show expansion or contraction. Very minor cracking and no surface spalling evident.

A046 - Shows considerable shrinkage with one large crack extending completely across the specimen. Sample is very soft.

A047 - Shows minor surface spalling, no cracking. Does appear to be some minor shrinkage. Sample is reasonably hard.

A048 - Hard. Shows very minor surface spalling, no cracking. No evidence of expansion or shrinkage.

A049 - Appears to have expanded slightly with most of the expansion at the top of the sample. Surface has minor spalling but very extensive deep cracking.

A050 - Shows minor expansion of the surface. There is minor spalling and considerable number of surface cracks.

A051 - Soft. Shows no evidence of shrink or swell. Surface is spalling. There is minor cracking.

A052 - Shows no evidence of surface spalling or cracking; however, it is very

soft.

A054 - Hard. Does not appear to have expanded or contracted. Does not show surface spalling or cracking.

A055 - Shows extreme expansion, probably 20% because the sample burst the cup, does not show surface spalling, does not show surface cracking.

A056A - Does not show expansion or contraction. Very minor surface spalling and one crack.

A053 - Shows considerable surface spalling but no cracking is in evidence. Does not appear to have expanded or contracted.

A077 - Shows minor surface spalling, considerable cracking. Sample appears to have expanded 10%.

A078 - Shows a loose powdery surface, considerable spalling, no cracking is evident. No expansion or contraction is evident, sample is fairly hard.

A058 - Shows minor expansion of the surface. The surface is fairly loose. There is minor spalling. Sample is soft.

A057 - Shows considerable expansion, approximately 10%, perhaps a little more. Does not show surface spalling; however, there are several large deep cracks in the sample.

A056B - Shows approximately 5% expansion. Sample has no surface spalling evident; however, it has a considerable network of fine cracks throughout it.

A059 - Shows approximately 5% expansion with the bottom layer having expanded 10%. Sample shows minor surface spalling, considerable fine crack network throughout.

A060 - Shows approximately 5% expansion. Sample has some surface spalling and very minor fine cracking.

A061 - Shows no evidence of expansion or contraction. Minor surface spalling and no cracking is evident.

A064 - Shows minor expansion followed by contraction. Sample is extensively spalled on the surface. Has considerable deep cracks.

A063 - Shows approximately 5% expansion with most of it concentrated near the surface of the sample. Surface has very minor spalling and considerable fine cracks.

A062 - Shows minor expansion, probably less than 5%. Sample has minor surface spalling and considerable fine surface cracks.

A065 - The surface is completely covered by a fibrous mineral so it is impossible to determine whether there is any cracking or not. Sample does not appear to have expanded and is hard.

A066 - Sample appears to have expanded approximately 5%. Surface has very minor spalling, considerable fine cracking with a few cracks that are deep.

A067 - Has expanded approximately 20%. Surface has minor spalling and considerable fine cracks.

A070 - Shows no surface spalling, no surface cracks, does not appear to have expanded or contracted.

A069 - Shows approximately 10% expansion, minor surface spalling, very minor fine cracking.

A068 - Has very minor expansion, probably 1-2% mostly at the surface, shows very minor surface spalling and very fine minor cracks.

A071 - Has approximately 2-3% expansion mostly concentrated near the surface of the sample, does not show spalling, and has very, very minor fine cracking across the surface.

A072 - Does not appear to have expanded. Sample has minor surface spalling, considerable fine cracking.

A073 - Appears to have expanded 1-2% as minor surface spalling, considerable cracking arranged in a radial pattern.

A074 - Appears to have expanded 1-2%. Surface has very minor spalling and minor fine cracking.

A075 - Appears to have expanded approximately 5%. Sample has not spalled, surface has extremely minor fine cracking.

A076 - Appears to have expanded approximately 5%, most concentrated near the top of the sample. Sample has minor surface spalling and considerable cracking radiating from the center of the sample.

APPENDIX D

Cation Exchange Capacities for Various Hardening Mixtures

Sample #	Mixture	H ₂ O	CEC meq/100 g
A002	80g BA* + 20g CaO*	22%	8.3
A003	80g FA* + 20g CaO	26%	16.6
A006	80g DSG* + Gyp* 20g CaO	45%	5.5
A008	80g FA + DSG + Gyp + 20 g CaO	37%	11.1
A010	80g BA + DSG + Gyp + 20g CaO	35%	2.8
A012	80g FA + 20g A*	36%	2.8
A014	80g BA + 20g A	29%	2.8
A016	80g DSG + Gyp + 20g A	47%	3.9
A018	80g FA + DSG + Gyp + 20g A	42%	3.9
A020	80g BA + DSG + Gyp + 20g A	53%	2.8
A022	80g FA + 20g B*	32%	5.5
A024	80g BA + 20g B	28%	3.9
A026	80g DSG + Gyp + 20g B	48%	2.8
A028	80g FA + DSG + Gyp + 20g B	41%	0.5
A030	80g BA + DSG + Gyp + 20g B	--	0.5
A032	80g FA1 + 20g CaO	36%	3.9
A034	80g FA1 + DSG + Gyp + 20g CaO	41%	5.5
A036	80g FA1 + 20g A	46%	2.8
A039	80g FA1 + 20g B	39%	12.8
A040	80g FA1 + DSG + Gyp + 20g A	41%	6.1
A042	80g FA1 + DSG + Gyp + 20g B	41%	5.5
A044	80g FA2 + 20g CaO	40%	5.5
AC46	80g FA2 + DSG + Gyp + 20g CaO	41%	5.5

A048	80g FA2 + 20g A	45%	5.5
A050	80g FA2 + DSG + Gyp + 20g A	41%	2.8
A052	80g FA2 + 20g B	37%	2.8
A078	80g FA2 + DSG + Gyp + 20g B	--	2.8
A055	80g BA + 20g CaO	22%	5.5
A057	80g BA + 20g A	27%	2.8
A059	80g Ba + 20g B	26%	2.8
A061	80g [BA + DSG + Gyp] + 20g CaO	35%	2.8
A063	80g [BA + DSG + Gyp] + 20g A	39%	2.8
A065	80g [BA + DSG + Gyp] + 20g B	38%	9.4
A067	80g FA + 20g CaO	28%	2.8
A069	80g FA + DSG + 20g CaO	35%	1.7
A071	80g FA + A	34%	1.7
A073	80g FA + DSG + Gyp + 20g A	43%	1.7
A075	80g FA + 20g B	26%	--
A077	80g FA + DSG + Gyp + 20g B	41%	0.5

* BA=Bottom Ash

CaO=Lime

FA=Fly Ash

DSG=Desulfurization Sludge

Gyp=Gypsum

A=3 parts CaO + 1 part $Al_2(SO_4)_3$

B=3 parts CaO + 1 part $Al_2(SO_4)_3$ + 1 part Na_2SiO_3

APPENDIX E

Adsorption of Heavy Metals by Hardened Product

Sample No.	PPM Added	PPM Adsorbed						
		As	Co	Cu	Ni	Se	Zn	Hg
A003	10	10	10	10	10	10	10	10
A008	10	5	10	10	10	10	10	10
A028	10	10	10	10	10	10	10	10
A030	10	10	10	10	10	5	8	10
A055	10	9	10	10	10	10	10	10
A059	10	5	10	10	10	7	10	10
A065	10	9	10	10	10	10	8	10
A067	10	10	10	10	10	10	10	10
A075	10	7	10	10	10	8	8	10
A003	50	10	50	50	50	14	21	40
A008	50	15	50	50	50	15	25	50
A028	50	11	50	50	50	28	20	50
A030	50	0	50	45	50	3	31	50
A055	50	38	50	43	50	15	20	42
A059	50	0	50	40	50	13	20	50
A065	50	10	50	45	50	2	26	50
A067	50	40	50	50	50	17	22	46
A075	50	8	50	42	50	14	25	45
A003	100	11	100	100	100	12	33	71
A008	100	6	100	100	97	22	45	100
A028	100	10	100	100	100	21	22	100
A030	100	8	100	76	100	21	53	100
A055	100	35	100	76	100	40	27	0
A059	100	3	100	40	100	13	19	100
A065	100	3	100	100	100	9	34	100
A067	100	17	100	70	100	43	7	62
A075	100	19	100	33	100	42	14	89

END

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