Task 6.4 - The Use Of Coal Ash In Ceramics

Topical Report
July - December 1995

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Work Performed Under Contract No.: DE-FC21-93MC30097

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
University of North Dakota
Energy & Environmental Research Center
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TASK 6.4 – THE USE OF COAL ASH IN CERAMICS

1.0 INTRODUCTION

Previous empirical tests at the Energy & Environmental Research Center (EERC) have indicated that coal combustion by-products are a viable starting material for the production of a variety of ceramic products, including brick, tile, and high-flexural-strength ceramics. The EERC has focused on high-temperature properties of coal ashes and has provided valuable insight into ash transformations, fouling, and slagging for the utility industry. It is proposed to utilize the information generated in these past projects to develop material selection criteria and product manufacturing techniques based on scientific and engineering characteristics of the ash. Commercialization of the use of coal combustion by-products in ceramics is more likely to become viable if a quality-assured product can be made, and predictive materials selection is a key component of a quality-assured product.

The objective of this work was to demonstrate the development and production of a ceramic material utilizing coal ash as a key component. Chemical and high-temperature properties of ash were carefully determined with the objective of identifying criteria for materials selection and manufacturing options for ceramic production.

The work was accomplished in four steps, which are summarized below:

1.1 Activity 1

Literature available through previous EERC research was assembled, and additional current literature was identified through computer and manual literature searches. Characterization information on ash used in previous laboratory demonstration of ceramic production was obtained from the Coal Ash Properties Database (CAPD). CAPD does not currently contain information on high-temperature properties of the ash samples represented. Of particular importance are the fusion temperatures of the ash and the types of crystalline phases that form in the ash during sintering.

1.2 Activity 2

The samples were characterized for selected parameters, including bulk chemistry, mineralogy, and ash fusion temperatures.

1.3 Activity 3

Mix designs were developed based on information from previous projects and available literature. Preliminary laboratory specimens were prepared. These specimens were evaluated for key product performance parameters such as flexural strength and water absorption tests.

1.4 Activity 4

A laboratory demonstration of four selected ashes was performed. The products were ceramic bars approximately 3/8 in. × 1¼ in. × 6 in. to facilitate product testing.

The production of a ceramic product was accomplished and a preliminary set of guidelines developed for identification of key criteria to select ash appropriate for use in ceramics.

2.0 RESULTS

2.1 Activity 1 – Literature Search

The literature search was initiated with a review of past research performed at the EERC. This work included the mix design and laboratory-scale production of ceramic tiles, kilned bricks, and high-flexural-strength ceramics. Based on the information reviewed and conversations with industry representatives, it was determined that the ceramic product with the highest commercial potential is likely the high-flexural-strength ceramics with an end use as railroad ties. Previous work in this area showed excellent promise, with the disadvantage being that the fasteners for rails to ties had not been developed for ties made from materials other than wood. Developments in this area in Europe have resulted in successful attachment with a unique fastener, which makes the production of railroad ties from alternative materials more viable.

Appendix A is an annotated bibliography of documentation pertaining to ash use in ceramics. A key publication by Oscar Manz (1984), which discusses the mix designs for flexural strength ceramic with fly ash as one component, is included. Several documents discuss the relevance of chemical composition of fly ash to successful utilization in ceramic materials. From this information, it was determined to investigate fly ash samples with a range of composition for alkali elements (sodium and potassium), since it is generally accepted that a higher alkali content is indicative of lower fusion temperatures for coal ash.

2.2 Activity 2 – Characterization Studies

Four fly ash samples were selected from CAPD based on chemical criteria for fly ash used in the production of mineral wool and high-flexural-strength ceramics. These criteria were: 1) varying sodium or alkali content; 2) iron oxide content of approximately 5%; 3) calcium oxide and SO₃ content varying with the alkali content; and 4) silica and aluminum content varying inversely with the alkali content. Sodium was the primary criterion under consideration. The range reported for sodium oxide was 4.3%–10.1%. Table 1 shows the four fly ashes selected, with elemental analyses from the database. Trends in ash chemistry are noted in the table.

Ash fusion results for the selected samples were not available in CAPD, so ash fusion testing was performed. These results (in an oxidizing atmosphere) are shown in Table 2. The results were quite similar for the four samples, with initial to fluid temperatures ranging from 1164° to 1398°C (2127°–2549°F). The greatest difference in temperature between samples for a given variable was 287° for hemispherical temperature. The identifying information for these samples in CAPD was incomplete, but it can be assumed that Ash 1 and Ash 2 are samples from lignite combustion, while

Ash 3 and Ash 4 can be assumed to be from the combustion of subbituminous coals. Although this investigation was limited to four samples, a larger sample set including more samples of both lignite and subbituminous fly ash might show trends in sodium content and ash fusion temperatures. It is hypothesized that these trends would be noted within a sample set from a single coal type. X-ray diffraction (XRD) was performed to identify minerals present in the samples. XRD results are included in Table 3.

2.3 Activity 3 – Mix Designs

The ash sources used for mix designs and the proportions used in each instance are indicated in Table 4. The quantities of materials used was adjusted to accommodate for the availability of coal ash, but the mix proportions (65% fly ash /35% glass) remained the same in all cases.

The clay used was obtained from the Hebron Brick Company near Dickinson, North Dakota. The clay is described as red-burning plastic clay. This was the same source as the clay used in previous EERC research (Manz, 1984, 1987; Manz and Mitchell, 1985). The clay was air-dried and crushed to -100 mesh prior to use. The glass (Corning) was purchased from Elan Technology in Belleville, New Jersey. It was preground to pass the No. 100-mesh sieve. Its designation is Elan material #11 with an annealing point of 445°C and a working point of 980°C.

2.4 Activity 4 – Laboratory Productions of Ceramics and Testing Results

The materials were blended using a 5-quart mixer (Figure 1). The test mixtures were then extruded (Figure 2) into test specimens (bars approximately $\frac{3}{8}$ in. $\times$ $1\frac{1}{4}$ in. $\times$ 6 in.). The specimens were first air-dried overnight and then oven-dried an additional day at 200°F (93°C).

Figure 1. Five-quart mixer used to blend fly ash-ceramic mixes.

TABLE 1

Fly Ash Chemistry¹

Coal Type	Sample No.	Plant Name	Na ₂ O	K ₂ O	SiO ₂	Al ₂ O ₃	CaO	MgO	Fe ₂ O ₃	SO ₃	Calculated ² Total Alkali	AA ³
Lignite	Ash 1	Hoot Lake, Minnesota	10.05	0.61	27.92	17.08	19.43	4.73	5.37	7.75	10.45	-
	Ash 2	Brett Admixtures, Lampy	8.33	1.01	38.04	18.74	15.83	3.67	4.37	3.55	8.99	5.41
	Ash 3	Ontario Hydro, Ontario	6.10	1.00	47.90	21.90	13.30	2.90	4.90	1.10	6.76	2.9
	Ash 4	Battle River Power, Alberta	4.30	1.00	55.60	19.80	8.80	1.50	5.00	0.35	4.96	0.78

¹ Trends in ash chemistry were as follows:

- Na₂O, CaO, and SO₃ decreasing
- SiO₂ and Al₂O₃ increasing
- Fe₂O₃ constant at approximately 5%

² Na₂O + K₂O expressed as total Na₂O calculated as [Na₂O + .658 (K₂O)].

³ ASTM procedure C311 (available alkali).

TABLE 2

Coal Analysis Lab Ash Fusion Report

Sample No.	Plant Fly Ash	Oxidizing Atmosphere, °C/°F			
		Initial Temp.	Softening Temp.	Hemi. Temp.	Fluid Temp.
Ash 1	Hoot Lake	1266/2311	1334/2433	1350/2461	1371/2500
Ash 2	Brett Admixtures	1203/2197	1294/2361	1364/2487	1398/2549
Ash 3	Ontario Hydro	1164/2127	1180/2156	1205/2200	1261/2301
Ash 4	Battle River Power	1246/2274	1270/2318	1314/2397	1347/2456

TABLE 3

XRD Mineralogies of the Fly Ash Samples

Ash 1	Ash 2	Ash 3	Ash 4
Thenardite Na_2SO_4	Not available	Mullite $\text{Al}_6\text{Si}_2\text{O}_{13}$	Mullite $\text{Al}_6\text{Si}_2\text{O}_{13}$
Merwinite $\text{Ca}_3\text{Mg}(\text{SiO}_4)_2$		Quartz SiO_2	Quartz SiO_2
Quartz SiO_2		Spinel $(\text{Mg,Fe})(\text{Fe,Al})_2\text{O}_4$	Spinel $(\text{Mg,Fe})(\text{Fe,Al})_2\text{O}_4$
Periclase MgO		Anhydrite CaSO_4	
Pyroxene $\text{Ca}(\text{Fe,Mg})\text{Si}_2\text{O}_6$		Periclase MgO	
Spinel $(\text{Mg,Fe})(\text{Fe,Al})_2\text{O}_4$		Lime CaO	
Lime CaO			

After cooling to room temperature, the test specimens were arranged in a high-temperature furnace for firing. The total time for the firing process was 11 hours. The furnace was first ramped, for 7 hours, to a peak temperature of 1040°C and held at this peak temperature for 1 hour. This was followed by a 2-hour ramp to 760°C and held at this temperature for 1 hour. Figure 3 shows the ceramic bars produced for Ashes 1 through 4.

Figure 2. Extruder used to make ceramic bars.

Figure 3. Four bars shown from lowest to highest flexural strength.

TABLE 4

High-Flexural-Strength Ceramics Mix Design ¹				
	Ash 1	Ash 2	Ash 3	Ash 4
Fly Ash, g	1300	800	750	800
Glass (-100 mesh), g	705	434	407	434
Clay (ball), g	106	65	61	65
Water, mL	423	267	235	334

¹ Proportions to be used for laboratory demonstration for optimum mix results.

After firing, the sample specimens were tested for flexural strength and absorption characteristics. The results are given in Table 5. There is no ASTM specification for flexural strength requirements on masonry brick. However, previous experiments at the EERC indicate that typical flexural strength for masonry bricks range from 1000 to 1200 psi. The testing apparatus used for determining flexural strength is shown in Figure 4. The results indicate that all fly ash ceramic bricks successfully met ASTM C67 specifications.

A graphical representation of the results of flexural strength testing vs. ash fusion initial and final temperatures for each ash sample is given in Figure 5. The highest-flexural-strength ceramic had the lowest initial and fluid temperatures. These low initial and fluid temperatures may indicate how well the ash can combine with the remaining ingredients. The maximum curing temperature

was 1040°C, but these results indicate that higher temperatures should be investigated and results compared with ash fusion temperatures to allow better predictive selection of ash for ceramics.

Flexural strength compared to fly ash oxide contents are shown in Figure 6. Points of interest include:

- High-flexural-strength ceramic has a moderate amount of sodium (approximately 6%), lower sulfur (<2%), and moderately high silica (approximately 47%).
- The lowest-flexural-strength ceramic contains the highest sulfur, sodium, and calcium with the least amount of silica. This sample also showed considerable flaking on the surface; this material was identified as Na₂SO₄ by XRD.
- Sodium affiliation with silica, aluminum, and calcium is apparently a critical component to the formation of high-flexural-strength ceramics. The formation of sodium sulfate appears to have a detrimental effect on the strength of the ceramic bars. This reaction ties up the sodium as NaSO₄ so that it cannot form the more advantageous Na-Al-Si_xO_y.

Table 6 lists XRD results for three ceramic bars. The low-flexural-strength ceramic bar revealed Na₂SO₄ and sodalite, (Na,Ca)₄₋₈(Al₆Si₆O₂₄)(SO₄,S,Cl)₁₋₂, the two major sulfur components present. The phases were conspicuously absent from the ceramic bar having high flexural strength. The primary sodium-containing phases in the latter were orthoclase, (Na,K)(Si₃Al)O₈, and nepheline, NaAlSiO₄. The lower SO₃ content appears to leave the Na free to react to form

TABLE 5

Flexural Strength and Water Absorption Results				
CBUL No.	Plant Name Na ₂ O Content	Flexural Strength	Water Absorption (after 5 hours boiling, %)	Saturation Coefficient
Ash 1	Hoot Lake ¹ 10% Na ₂ O	2297	5.4	0.72
Ash 2	Brett Admixtures 8.33% Na ₂ O	2384	8.0	0.38
Ash 3	Ontario Hydro 6.1% Na ₂ O	3053	8.3	0.32
Ash 4	Battle River 4.3% Na ₂ O	2464	18.7	0.48
	Max. Allowable ²	—	20	0.80

- ¹ This ceramic bar had considerable flaking after air drying. This flaky material was analyzed by XRD and found to be predominantly Na₂SO₄, with minor SiO₂ and MgO.
- ² ASTM C62 – Standard specification for building brick (solid masonry units made from clay or shale) Type SW used in any region where the units are in contact with the ground, in horizontal surfaces, or in any position where they are likely to be permeated with water.

TABLE 6

X-ray Diffraction Results of Low-
and High-Flexural-Strength Ceramic Bars

	Bar no. 1 Flaky Material (low flexural strength)	Bar no. 2 (low flexural strength)	Bar no. 3 (high flexural strength)
Major	Thenardite Na_2SO_4	Sodalite $(\text{Na}, \text{Ca})_{4-8}(\text{Al}_6\text{Si}_6\text{O}_{24})$ $(\text{SO}_4, \text{S}, \text{Cl})_{1-2}$	Orthoclase $(\text{Na}, \text{K})(\text{Si}_3, \text{Al})\text{O}_8$
Minor	Quartz SiO_2 Periclase MgO Anhydrite CaSO_4	Clinopyroxene $\text{Ca}(\text{Fe}, \text{Mg}, \text{Al})\text{Si}_2\text{O}_6$ Orthoclase $(\text{Na}, \text{K})(\text{Si}_3, \text{Al})\text{O}_8$ Ferrite Spinel $(\text{Mg}, \text{Fe})(\text{Fe}, \text{Al})_2\text{O}_4$ Nepheline NaAlSiO_4	Clinopyroxene $\text{Ca}(\text{Fe}, \text{Mg}, \text{Al})\text{Si}_2\text{O}_6$ Ferrite Spinel $(\text{Mg}, \text{Fe})(\text{Fe}, \text{Al})_2\text{O}_4$ Nepheline NaAlSiO_4

lower-melting Na-Al-silicates, which enhance the flexural strength of the ceramics. It is not known at this time the role that clinopyroxene or ferrite spinel play.

The ceramic samples were submitted for scanning electron microscopy (SEM) morphology and point chemical analysis using a scanning electron microscope equipped with an energy dispersive x-ray microanalysis system (EDS). The morphological results show a large amount of porosity (Figure 7) in the highest-flexural-strength sample. This amount of porosity most likely leads to decreased flexural strength. A larger amount of material to work with under the vacuum extrusion procedure may have prevented some of this porosity and increased the strength.

The point analysis using the EDS on the SEM shows that in the high-sodium sample, a large number of particles were coated with Na_2SO_4 in a fractured surface. In the higher-strength sample, the Na was associated with Si and Al, most likely lowering the melting temperature of the materials, allowing them to fuse at lower temperatures than those with high Na_2SO_4 .

3.0 CONCLUSIONS

One of the proposed applications for high-flexural-strength ceramics is in the production of railroad ties. Generally, literature on non-wood railway ties focuses on the use of prestressed concrete rather than on ceramics. One such document, *Manual for Engineering* (1984), is a specification intended to provide necessary guidance in the design, manufacture, and use of concrete ties and their components for main line railway track systems. The specification covers materials, physical dimensions, and structural strength of prestressed mono block and prestressed and conventionally reinforced two-block concrete ties. This specification does not cover techniques

Figure 4. Flexural strength testing apparatus.

Figure 5. Flexural strength vs. ash fusion temperature

Figure 6. Flexural strength vs. fly ash oxide content.

Figure 7. Morphology of ceramic sample.

or equipment for the manufacture of concrete ties or fastening. The only performance specification mentioned is a minimum concrete compressive strength of 7000 psi after 28 days of curing.

In other articles (Welty, 1987, 1988; Buekett, et al., 1987), the logistics of placing concrete ties and their economic savings are assessed. It was pointed out that concrete ties have been in service by railroad companies for several years, and the practice is gaining acceptance. In examining the cost factors surrounding concrete tie practice, it is obvious the improved material component required may have a higher initial cost than more conventional track components. However, the overall cost of track materials is only a fraction of the total cost of maintenance. Thus there is the inherent potential for significant overall savings by using, at first, more expensive components that eventually will require less ongoing maintenance. These articles focus on the methods of anchoring the rails to the concrete ties. The anchoring mechanics would be similar for ceramic ties as those now used for concrete. If the manufacturing costs for ceramic ties can be comparable to concrete, then the potential for commercialization exists.

4.0 FUTURE WORK

Continued research on ash in ceramics should include the following components:

- Obtaining the chemistry of the glass and clay used in the ceramic bars and studying the effects of these constituents on the flexural strength.
- Working with a larger number of samples and doing statistical correlations between ash chemistry, mineralogy, flexural strength, and other selected parameters.
- Determining the effect of microporosity on strength as a function of the extruder and quantity of ash available.
- Evaluate curing temperatures relative to ash fusion properties.

APPENDIX A

ANNOTATED BIBLIOGRAPHY: FLY ASH IN CERAMICS

FLY ASH IN CERAMICS ANNOTATED BIBLIOGRAPHY:

American Railway Engineering Association. "Concrete Ties," In *Manual for Railway Engineering*; Chapter 10, Issued 1984.

This specification is intended to provide necessary guidance in the design, manufacture, and use of concrete ties and their components for main line, standard-gage railway track systems. The specification contains minimum performance requirements for components for concrete tie railway track based on a variety of permissible tie spacings and ballast depths. Track constructed of tie and fastener components meeting the specifications applicable to the anticipated usage should be expected to give satisfactory performance under current AAR-approved maximum axle loads.

The specification covers materials, physical dimensions, and structural strength of prestressed monoblock and prestressed and conventionally reinforced two-block concrete ties. In addition, longitudinal and lateral load restraint requirements, as well as the electrical performance requirements for rail fastener and tie combinations, are given. Laboratory tests for the determination of the suitability of new designs are specified, as are necessary quality control procedures during manufacture. The specification does not cover techniques or equipment for the manufacture of concrete ties or fastenings.

Anderson, G.R. "Potential Products from North Dakota Lignite Fly Ash," Energy Development Board, June 1980.

This report discusses conventional construction product concrete (fly ash blocks), ceramics, and unconventional products. Information delineated includes manufacturing procedure, firing, testing, results and conclusions, and recommendations. Of particular interest is the mixing and extrusion procedures used for the current work.

Anderson, M.; Jackson, G. "The Beneficiation of Power Station Coal Ash and Its Use in Heavy Clay Ceramics," *Trans. Jour. Brit. Ceram. Soc.* 1983, 82 (2).

This article discusses the origin and composition of power station ash, variability of the ash, and variations caused by power station loading schedule. Also discussed the effects of variability on properties of clay/ash bodies. Chemical and physical properties of different ceramic mixes and the impacts of beneficiation are discussed.

Buekett, T.; Derek, F.; Surtees, J. "Concrete Ties in Modern Track," *Concrete*, RT&S 1987, Aug.

This article provides an overview of practice and expectations of performance for concrete ties. Among topics discussed are long-term savings, engineered rail fasteners, glue-on pads, turnout ties, proper concrete tie insertion, and product quality.

CANMET. "High Volume Fly Ash Concrete Using Canadian Fly Ashes," April 1994.

Chemical analyses of several different Canadian fly ashes, including Belle River, are discussed. The article discusses Na_2SO_4 efflorescence on cements using Belle River fly ash, high Na_2O , high SO_3 .

Dockter, B.A.; Manz, O.E. "Economic Feasibility of Producing Mineral Wool Fibers at a Coal Generation Power Plant," *In Proceedings of the 10th International Ash Use Symposium*; Jan. 1993, Vol. 2.

Mineral wool is a fibrous product made from melted rock, glass, and slag for use as building, pipe, and sound insulation. Mineral wool is one of the most efficient of all insulating materials, in addition to being fireproof, extremely durable, and insect- and vermin-proof. At the present time, almost all of the mineral wool produced in the United States utilizes waste slag obtained from steel mills as a primary raw material. This material and other additives are appropriately combined and placed into a cupola furnace to be melted, using coke as a fuel source. Many power plants throughout the world utilize what is known as "wet-bottomed" boilers to produce steam to generate electric power. Two types of by-product material are created by this type of boiler. By design, fly ash makes up approximately 30% to 40% of the residual material produced by wet-bottomed boilers. In the North Dakota area, four power plants utilize wet bottom boilers. The Milton Young Station at Center, ND; The Coyote Station at Beulah, ND; the Leland Olds Station at Stanton, ND; and the Big Stone Station at Big Stone, SD. The Coyote and Big Stone Plants had sufficient room in the boiler area to add the equipment necessary to fiberize mineral wool.

Humphrey, K.K.; Lawrence, W.F. "Coal Ash Usage: Producing Mineral Wool from By-Products," *Minerals Processing* 1970, March.

This article discusses mineral wool produced from coal ash slag and "modified" fly ash samples. Results include chemical analysis of fibers, pouring temperature, and comments on physical appearance of fibers. Quality testing was done, including corrosion resistance, fire and flame resistance, odor emission, and shot content. A discussion of economic advantages and disadvantages is covered.

IEA. "Application for Coal Use Residues" *Coal Research*.

This book delineates information on international companies involved in coal use residue applications. Information on each company includes supplier information (company name, address, country, telephone and fax numbers, and a contact person); product information (type, name, application, scale of operation, production capacity, and patents); and process product details (residue type, other materials used, properties, process description, additional information, and literature reference). Process flowcharts are shown where applicable.

Manz, O.E. "Utilization of By-Products from Western Coal Combustion in the Manufacture of Mineral Wool and Other Ceramic Material," *Cement and Concrete Research* 1984, 14, 513-520.

The ash by-products from combustion or gasification of western U.S. coals have chemical and mineralogical characteristics that lend themselves to utilization in ceramic materials. Laboratory- and pilot-scale fabrication of four such materials has been studied. Cyclone slag from four lignite-fired power plants and a dry scrubber ash have been fabricated into mineral wool insulation in a pilot-scale cupola. Extruded and fired mixtures of fly ash, clay, and ground glass have produced ceramics with extraordinarily high flexural strength. Ceramic-glazed wall tiles that utilize fly ash in place of clay have been prepared and shown to meet most specifications for fired clay tile. Both fired and unfired dry-pressed brick containing 100% western fly ash have met ASTM specifications for fired clay brick.

Manz, O.E. "Utilization of By-Products from Western Coal Combustion in the Manufacture of Mineral Wool," National Ash Association Annual Symposium, Orlando, FL, March 1985.

In the United States, mineral wool insulation is mostly made by directing molten blast furnace slag onto spinning disks, similar to a cotton candy machine. In North and South Dakota, four lignite-fired power plants utilize cyclone boilers that convert most of the ash into molten slag that could be fabricated directly into mineral wool. A pilot-scale cupola using coke as fuel has been used to melt various cyclone boiler slags, as well as dry scrubber ash and gasifier ash. Mineral wool was made using a spinning disk and by directing compressed air through holes in a blow cap. A summary is presented showing the effects of variation in chemical composition as well as the method of fabricating the wool.

Manz, Oscar E. "Utilization of Lignite and Subbituminous Combustion Ashes, Slags and Scrubber Sludges, and Gasification Ashes in a Variety of Commercially Viable Products," *In Proceedings of the 8th International Ash Utilization Symposium; Washington, DC, 1987, Vol. 1.*

Traditionally, the widespread utilization of combustion ashes has concentrated on the partial replacement of cement with fly ash in portland cement concrete. However, for several years, the Coal By-Products Laboratory at the University of North Dakota, in addition to research involving "western" fly ash in concrete, has been investigating the use of combustion and gasifier ashes in products such as sulfur concrete, mineral wool, high-flexural-strength ceramics, blended cement, road base stabilization, and high-percent replacement of portland cement with certain fly ashes.

Where possible, ASTM fabrication and testing procedures were used. Mineral wool of similar physical character to commercial wool and at lower potential cost was produced using 100% western ashes. Sulfur concrete utilizing 80% ash and 20% modified sulfur developed flexural and compressive strengths in excess of 2250 and 5000 psi, respectively. An economically competitive vitrified ceramic product with flexural strength above 7800 psi was produced from a mixture of 50% ash, 45% sand, and 5% clay. By using a total ash mixture of 26% gasifier ash and 74% combustion ash, a very satisfactory, economical, and durable

roadbed material was developed. The replacement of up to 50% of the cement in concrete with western fly ash produces economical, high-strength concrete. Ceramic-glazed wall tiles that utilize fly ash in place of clay have been prepared and shown to meet most specifications for fired clay tile. Both fired and unfired dry-pressed brick containing 100% western fly ash have met ASTM specifications for fired clay brick.

Field demonstrations have successfully verified the use of fly ash for road base stabilization, as much as 75% replacement of cement in concrete, for forming mineral wool below a power plant cyclone boiler, and forming 40-foot power poles containing 50% fly ash.

Manz, O.E. "Utilization of Advanced SO₂ Control By-Products: Laboratory Test Results," *In Proceedings of the 8th International Ash Utilization Symposium; Washington, DC, Oct. 1987, Vol. 1.*

As part of the Electric Power Research Institute's (EPRI) Advanced SO₂ Control Waste Management Project, by-products from four advanced SO₂ control systems were analyzed for physical and chemical properties and tested in the laboratory for potential suitability in various by-product utilization applications. The by-products tested included fly ashes from atmospheric fluidized-bed combustion (AFBC), calcium spray dryer, limestone furnace injection, and dry sodium injection systems for SO₂ removal. Utilization applications investigated in the laboratory included road base, soil, and sludge stabilization; asphalt mineral filler; mineral wool, brick, ceramic, and aggregate production; and partial cement replacement in grout and concrete. Standard ASTM test procedures were used where applicable to evaluate the potential suitability of the ash for use in the particular application. Laboratory test results reported here will provide input for selection and evaluation of potential advanced SO₂ control ash utilization markets in the next phase of the utilization study.

Manz, O.E.; Mitchell, M.J. "Selection of Ash for Utilization and Economics of Ash Use in Various Products," Presented at the 13th Biennial Lignite Symposium, Bismarck, ND, May 1985.

A variety of options have been demonstrated or have been suggested for the utilization of coal-derived ash materials. These range from soil stabilization to the recovery of alumina or exotic metals.

This paper examines some of these options, includes economics for some of the utilization methodologies, and serves as a general tutorial for matching a fly ash or bottom ash with a proposed use. The requirements for the use of ash in road building are discussed. The specific products discussed include ready-mix concrete for general purpose applications utilizing lignite ash as a direct replacement for portland cement. Fly ash, waste glass, and clay can be used to produce a high-flexural-strength ceramic material. Blended cement can be produced by several methods, including slagging fly ash and limestone at over 1400°C, yielding a material that is quenched and pulverized.

Mineral wool insulation can also be produced from ash. Other applications such as concrete railroad ties, wall and floor tile, and dry-pressed ash brick indicate the economic savings and broad potential involved in the use of properly chosen ash.

Minnick, L.J. "New Opportunities for Fly Ash as a Usable Resource," *In Proceedings of the 7th International Ash Utilization Symposium and Exposition; Orlando, FL, March 1985. Vol. 1.*

Fly ash in combination with other inorganic by-products is providing markets for construction-type applications. The sources of these secondary residuals are generated from technologies such as LIMB (limestone injection multistage boiler), dry scrubbing, postflame injection, etc. Other residuals include portland cement and limekiln dust, and ash from fluidized bed combustion of coal. This paper describes activities of an ASTM resource recovery committee which deals with construction and other secondary applications of recovered process waste. Guidelines and standard practices have been prepared relating to fly ash. Experiences of commercial applications are presented, including methods of preconditioning, handling, and production of the blended products. A brief review of process costs is also presented.

Welty, G. "Is Concrete's Day Dawning?" *Railway Age 1987, June.*

This article discusses the logistics of placing concrete ties and their economic savings. The advantages of concrete ties are discussed, such as longer life and lower maintenance costs.

Historical data on the use of cement ties are also given, including foreign and domestic use.

Welty, G. "Track: A Material Difference," *Railway Age 1988, March.*

This article stresses that the new product opportunities are multiplying for engineering departments willing to experiment. Options discussed are concrete ties, reconstituted ties, super-hardwood ties, and new options in fasteners and rail.