COMBUSTION BYPRODUCTS RECYCLING CONSORTIUM
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MANUFACTURING FIRED BRICKS WITH CLASS F FLY ASH FROM ILLINOIS BASIN COALS

Final Report
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By

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DISCLAIMER

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ABSTRACT

The purpose of this project was to determine if Class F fly ash produced by one of the power generation stations of the Cinergy PSI is a viable raw material for brick production at a nearby brick plant. This power generation station is located in Indiana near the Illinois border, and burns Illinois Basin coals from both Illinois and Indiana.

A technical feasibility assessment was conducted for this process, which uses fly ash as a substitute for part of the clay and shale used in making conventional bricks. Commercial-scale production demonstrations, which included extrusion and firing evaluations, have produced a total of about 4,000 commercial-size paving bricks and 8,000 commercial-size three-hole building bricks for evaluation. The paving bricks contained 20% by volume of fly ash, and the building bricks contained 20%, 30%, or 40% by volume (about 37% by weight) of fly ash. These final products have met or exceeded ASTM standard specifications for pedestrian and lightweight traffic paving bricks and for building bricks of a severe weather grade. An economic evaluation indicated that it would be economically feasible for the brick plant to use the fly ash as a raw material in commercial brick production. Also, the environmental feasibility study showed that, similar to the regular commercial brick, the fly ash containing bricks are environmentally safe construction products.

This project was successfully completed, and the results indicated that the fly ash tested is a viable raw material for brick production at the nearby brick plant. The amount of fly ash that can be consumed will depend on the brick plant’s production rate and the amount of ash that can be successfully incorporated into the brick body. If bricks with 40 wt% of ash can be produced, and if a brick plant produces sixteen million bricks per year at five pounds per brick, about 14,000 tons of fly ash could be consumed by that plant each year.

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INTRODUCTION AND BACKGROUND

For the past five years, researchers at the Illinois State Geological Survey (ISGS)/University of Illinois (UIUC) have been working with brick manufacturers to develop high quality, marketable brick products that use high-volumes of Class F fly ash generated from burning Illinois coals (Chou et al. 2000, 2001, & 2002). In this fired brick-making process fly ash is substituted for part of the clay and shale, the two main ingredients of conventional bricks. Test bricks produced in previous project years using Illinois fly ash have met or exceeded commercial specifications. The process developed has now been commercially accepted and a joint venture by a major Illinois brick company and an utility company has been established to build a new brick plant in Illinois which will produce fly ash containing bricks.

The Illinois Basin covers most of Illinois and a part of southern Indiana and western Kentucky. Current coal production is about 33.8, 37.1, and 25.4 million tons in Illinois, Indiana, and western Kentucky respectively (U.S. DOE, 2001). From burning these bituminous coals, it is estimated that more than six million tons of fly ash (Class F) are produced each year, and it is currently either being ponded or landfilled (Personal communication between the PI of this investigation and Mr. H. Lewis, Cinergy PSI, 2003 and 2006). This Class F fly ash could be used for fired brick production rather than further contributing to a solid waste disposal issue. However, until the brick industry gains more confidence in using fly ash as a raw material in brick production, evaluation and testing will be needed on a case-by-case basis. The purpose of this project was to determine if Class F fly ash produced by Cinergy PSI's Cayuga Power Generation Station (CPSIC) is a viable raw material for brick production at Colonial Brick Company (CBC), a brick plant in Indiana near the Illinois border. CBC is located less than five miles from CPSIC, which burns Illinois Basin coal from both Illinois and Indiana.

EXECUTIVE SUMMARY

More than six million tons of Class F fly ash is generated each year from the combustion of the Illinois Basin coal at a rate of roughly one hundred million tons annually. Currently, there are no high volume users of this fly ash for cement related construction products. Most of the fly ash that has been produced was ponded or landfilled, and is readily available for the testing in fired brick applications. Nevertheless, until the brick industry gains more confidence in using fly ash as a raw material for their brick production, evaluation and testing will be needed on a case-by-case basis.

This project was supported in part by the United States Department of Energy, National Energy Technology Laboratory, and the West Virginia University Research Corporation, Combustion Byproducts Recycling Consortium, as well as the utility and brick industries. The purpose of this project was to determine if Class F fly ash produced by one of the power generation stations of the Cinergy PSI, which burns Illinois Basin coals from both Illinois and Indiana, is a viable raw material for brick production at a brick plant located less than five miles from the power station. The objectives of this project were to conduct the technical, economic, and environmental feasibility assessments of using the fly ash in commercial brick production. The project also facilitated communication between brick producers and utilities, which focused on the use of fly ash in commercial brick production. It also facilitated continued public outreach promoting the benefits of producing brick products containing fly ash.

Eight Tasks have been conducted to meet the project objectives.

Task 1: Acquire fly ash, clay, and shale samples

Task 2: Conduct chemical, physical, and engineering properties characterizations

Task 3: Conduct bench-scale production and produce commercial-size green bricks for preliminary in-plant firing evaluations

Task 4: Conduct up to four commercial-scale production test runs and optimize process parameters, as needed

Task 5: Conduct economic assessment and evaluate the critical economic factors in using fly ash as a raw material for brick making

Task 6: Conduct environmental feasibility study

Task 7: Conduct public outreach

Task 8: Prepare quarterly and final reports

More than 80 commercial-size green bricks were produced by a bench-scale mold pressed method. These bricks were produced with formulations containing various amounts of fly ash, shale and clay materials for preliminary firing evaluation. Firing was conducted using either the ISGS bench-scale kiln or as part of a commercial firing at CBC. From these preliminary in-plant firing evaluations, it was determined which formulations would be best suited for commercial-scale production test runs. Six commercial-scale production test runs have been conducted; two for making paving bricks and four for making building bricks. Each run produced 2,000 bricks for commercial evaluation. Paving bricks containing 20 vol% of fly ash and building bricks containing 20%, 30%, or 40 vol% (about 37 wt%) of fly ash were successfully produced with a production yield of greater than 95%, an acceptable yield for commercialization. The final products met the brick plant's in-house specifications for marketability and have met or exceeded ASTM standard specifications for pedestrian and lightweight traffic paving bricks and for building bricks of a severe weather grade.

An economic evaluation of utilizing fly ash in fired brick production at the participating brick plant was conducted and the results were optimistic. Fly ash has similar chemical and physical properties to clay and shale and can therefore be integrated into the brick plant's production process without capital costs for new equipment. Thus, the major factors considered during economic evaluation were the cost of obtaining raw materials and the production costs. When taking into account the utility company's contribution of half the cost of shipping due to their own savings as a result of not needing new holding ponds for their fly ash, and the cost savings from mining and processing the conventional raw materials, the total annual savings for the brick plant producing 12 million bricks containing 40 wt% of fly ash could be as much as $58,280.

Although fly ash and other brick-making raw materials are not currently regulated by the U.S. EPA, there were preliminary concerns that utilizing fly ash, a product of coal combustion, in fired brick production may present environmental problems due to leaching of trace metals such as mercury. Therefore, a leaching study on fired bricks from commercial-scale production with and without fly ash was conducted according to US EPA Method 1320, and the concentrations of twenty elements in the simulated acid-rain extracts of these samples were examined, including As, Ba, Cd, Cr, Ni, Pb, Ca, B, and Hg. The amounts of these elements in the extracts from both the fly ash containing brick samples and the commercial brick samples without fly ash have values well below the EPA's regulatory thresholds set for other solid waste materials. The results indicated that, similar to the regular commercial bricks, the fly ash containing bricks are environmentally safe construction products

This project was completed successfully, and the results indicated that the fly ash tested is a viable raw material for brick production at the nearby brick plant. The amount of fly ash that can be consumed will depend on the brick plant's production rate and the amount of ash that can be successfully incorporated into the brick body. At a brick plant's current production rate of sixteen million bricks per year (five pounds per brick), utilizing 40 wt% of fly ash per brick would result in an annual consumption of approximately 14,000 tons of fly ash.

The number of bricks produced in the U.S. has steadily increased each year. In 2001, nationwide production was estimated at 8.3 billion SBE (standard brick equivalents). By the year 2003, it had increased to 8.6 billion. In 2004, the production reached 9.3 billion, which would weigh 23.25 million tons at five pounds per brick. When looking at these statistics, it is evident that the brick market and demand for bricks are strong. Successful commercial use of bricks containing fly ash could provide an example for a growing and profitable market for Illinois Basin coal ashes, encourage electric companies to continue to use Illinois Basin coals, and develop new sources of raw materials for fired brick manufacturing.

EXPERIMENTAL

Sample Acquisition (Task 1)

Fly ash was used as a substitute for part of CBC's clay and shale, which are the main ingredients used in making regular bricks. Two shipments of ponded fly ash from the CPSIC were made. Fly ash sample from the first 20-ton lot (Ash II) shipment was used for bench-scale and commercial-scale production tests for making paving bricks as outlined in Task 4. Once this was completed, a 40-ton lot of ponded fly ash sample (Ash III) was acquired and used in four commercial-scale test runs in which three-hole building bricks were made, as outlined in Task 4. The shale-clay mix used in these tests is a standard formulation that CBC uses in mix design. Bucket-size samples of fly ash from the CPSIC, and clay and shale samples from CBC were acquired for characterization in Task 2. These samples were also used in the bench-scale production of commercial-size test bricks, as outlined in Task 3.

Characterization of Raw Materials, Intermediates, and Final Products (Task 2)

The raw material analyses included, but were not limited to, particle shape and size characterizations, thermo-evolution properties, and chemical compositions. The chemical analyses included major, minor, and trace elements (including mercury), and loss on ignition (LOI). In addition, fired bricks from the commercial-scale production were pulverized for use in simulated acid rain extraction. The extracts from this experiment were chemically analyzed for an environmental feasibility study in Task 6.

The analyses were conducted at the ISGS analytical laboratory, the UIUC laboratory, the Waste Management Research Center laboratory, and the ALS Chemex commercial laboratory. These laboratories are equipped with inductively coupled plasma (ICP), an atomic emission spectrometer (AES) for analyzing 30 elements, an X-ray fluorescence spectrometer (XRF) for analysis of metal oxides, a thermogravimetric analyzer (TGA), a scanning electronic microscope (SEM) for particle image analysis, and a cold vapor atomic absorption spectrometer (AA) for mercury analysis.

The bench-scale and commercial scale-up test bricks were analyzed for their color, physical appearance, and marketability based on the participating brick company's own specifications. In addition, the engineering properties (including water absorption and compressive strength) of these test bricks were also determined based on the ASTM standard test methods for the purpose of making comparisons to the brick company's standard bricks (made without fly ash). The commercial specifications utilized for the bench-scale and commercial scale-up test brick evaluations were ASTM C 902 for paving bricks and ASTM C 62 for building bricks.

Producing Bench-scale Commercial-size Green Bricks and Conducting Preliminary In-plant Firing Evaluations (Task 3)

In order to prepare for the commercial-scale production demonstration, the ash samples collected in Task 1 were blended with the clay/shale from CBC to produce small batches of commercial-size green bricks at the ISGS bench-scale facility. These mold-pressed commercial-size green bricks were either fired at the ISGS bench-scale facility or as part of a commercial firing at CBC for physical and engineering properties evaluations.

To determine the maximum amount of fly ash that could successfully be incorporated into the brick body while maintaining the engineering properties of the brick company's standard bricks without fly ash, a total of forty commercial-size green paving bricks containing CPSIC fly ash at 10, 20, 30, 40, and 50 vol% were made. The first set of paving bricks made with fly ash was blended with shale only, and another set of bricks made with fly ash inputs at the same level was blended with a mix of clay and shale. Firing of these two sets of paving bricks was conducted first at the ISGS bench scale facility and then as a part of commercial firing at CBC. The commercial firing facility was used in order to best simulate the firing conditions of the future scale-up runs.

Similarly, a total of more than 40 commercial-size three-hole green building bricks with various combinations of fly ash, shale, and clay were produced by a mold pressed method at the ISGS bench scale facility. These green building bricks with fly ash at levels of up to 60 % by volume (or about 56% by weight) were fired first at the ISGS bench scale facility and then as a part of commercial firing at CBC. The results were evaluated to determine the best candidates for scale-up production test runs. The formulations selected for the scale-up run were those that could maximize the amount of fly ash substitution while maintaining a level of quality similar to CBC's standard bricks.

Commercial-scale Production (Task 4)

The existing in-plant extrusion parameters were used and standardized to extrude bricks containing the maximum possible content of CPSIC's ponded fly ash. The formulations that were best for commercial-scale test runs using the existing in-plant parameters for making both the paving and building brick were determined based on the results of these bench-scale runs. There were two paving brick and four building brick commercial-scale production test runs conducted, each producing 2,000 bricks. The final products from each test run were analyzed according to ASTM commercial specifications. In addition, the production yield from each run was determined to ensure that the process could be established at the commercial facility.

Economic Assessment (Task 5)

An economic evaluation of fly ash brick production was conducted to include current plant parameters and the current transportation costs associated with shipping fly ash. Since fly ash is a byproduct generated from coal combustion, and most of it is ponded or disposed of in landfills, the major cost for obtaining the fly ash raw material is the transportation cost. Shipping and production cost incentives also must be evaluated on a case-by-case basis. However, no new major equipment is needed to retrofit existing machinery. The brick company has its own existing market and market penetration strategy, and the ash containing brick products will not compete with the current market for regular bricks. Furthermore, a survey was conducted on the nationwide brick production rate as well as the sales figures in the East North Central America (Illinois, Indiana, Michigan, and Wisconsin) region.

Environmental Feasibility Study (Task 6)

The environmental impacts of using Illinois Basin coal fly ash for producing fired bricks were assessed with methods previously developed. A leaching study was conducted on the final products using U.S. EPA Method 1320 (1986). The concentrations of twenty elements in the extracts of these samples were examined, including concentrations of As, Ba, Cd, Cr, Ni, Pb, Ca, B, and Hg. Analysis of the elemental composition of the leachates generated from the simulated acid-rain extractions was performed using an inductively coupled plasma (ICP), an atomic emission spectrometer (AES), and/or an atomic absorption spectrometer (AA). A cold vapor atomic absorption spectrometer was used for mercury analysis.

Public Outreach (Task 7)

The PI has entertained questions and initiated group discussions on the benefits of using fly ash in fired brick formulations, and has attended and presented project results to various interested organizations, such as the World of Coal Ash Conference held April 11-15, 2005, in Lexington, Kentucky (Chou et al 2005a) and the International Congress on Ash Utilization Conference held December 4-7, 2005 in New Delhi, India (Chou et al 2005b).

Quarterly and Final Reports (Task 8)

Quarterly progress reports were prepared and submitted to the funding agency on time. Conclusions drawn from interpreting the data developed during the project were presented in those progress and final reports.

RESULTS AND DISCUSSION

Raw Material and Characterization

The fly ash samples, as well as the clay, shale, and clay/shale mix raw materials acquired were analyzed for their chemical and physical properties. The clay/shale mix used is a standard formulation that the brick company uses. The resulting data, such as volatility (LOI content), soluble salt content (mainly CaO value), particle size, microstructure, and thermo-evolution characteristics, are useful for pre-screening the raw materials to help eliminate potential problems inherent in fired-brick making such as bloating, scum formation, and poor production yield.

The chemical composition of the raw materials was determined and presented as metal oxide composition and the amount of unburned carbon was measured as the loss on ignition (LOI) value. The chemical data (Table 1) indicated that the fly ash samples contain three major oxides (SiO_2, Al_2O_3, and Fe_2O_3) in an amount similar to that of the conventional clay, shale and clay/shale mix materials. From our previous fly ash brick studies, the CaO content provides a general guide for selecting samples to avoid salt scum deposition on the surface of the bricks after firing. In general, CaO values of up to 6% are manageable in brick making to avoid scum deposition. As indicated in Table 1, the CaO values for the shale and clay samples (less than 1%) are relatively lower than those of the ash samples (between 1.2% to 3%); however, the relatively higher values for the CaO content of these ash samples was not a concern for scum formation.

Table 1: Metal oxide compositions (wt%) in fly ash, shale and clay samples.

Sample ID	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	LOI
Ash II	59.13	26.32	5.04	0.85	0.05	1.38	1.06	0.60	3.52	0.09	1.16
Ash II (duplicate*)	54.78	24.36	5.48	1.22	0.06	1.04	3.00	1.11	2.75	0.23	4.95
Ash III	54.27	23.90	11.62	1.27	0.02	1.10	1.23	0.78	2.8	0.18	1.70
Ash III (duplicate*)	54.47	23.52	12.35	1.26	0.03	1.09	1.20	0.73	2.88	0.20	1.8
Shale/Clay Mix	59.64	18.29	6.49	1.10	0.12	1.91	0.61	0.85	3.08	0.16	7.46
Shale	60.15	17.88	6.67	1.07	0.10	1.96	0.70	0.94	3.09	0.16	6.93
Shale (duplicate*)	59.58	18.07	6.81	1.07	0.10	1.68	0.71	0.94	2.84	0.18	7.62
Clay	58.21	20.85	5.48	1.17	0.08	1.31	0.7	0.46	2.36	0.12	9.06

Ash II = the 20-ton lot CPSIC pond fly ash sample; duplicate* = duplicated sampling of the sample indicated; Ash III = the 40-ton lot CPSIC pond fly ash sample.

The LOI value indicates that the amount of volatile matter that would be released during firing. Table 1 shows that the LOI values for the fly ash samples were much lower (up to 4.95%) than that for the clay and shale samples (9.06 and 7.62 wt% respectively) used by the brick manufacturer. This is due in part to the fact that fly ash is a byproduct from coal combustion, so the material had already been through a high temperature heating process where most weakly bonded and highly volatile organic materials had either been burned off or were converted to tightly bonded organic materials. Overall, the CaO and LOI content of the ash material were acceptable for making fired bricks.

Thermogravimetric analysis (TGA) was conducted on the raw materials to determine the amount of weight loss from each sample at various temperatures. The samples were heated from 25°C to 1030°C at 30°C per minute under a nitrogen atmosphere. A typical TGA-first derivative curve for shale (A) fly ash (B) and clay (C) is shown in Figure 1. The results indicated that the temperature for maximum weight loss of the CBC shale sample occurred around 585 °C, whereas, the temperature for the maximum weight loss of the CBC clay sample was around 627°C, and the maximum weight loss for the CPSIC pond fly ash sample occurred around 778°C. It was expected that the maximum weight loss for the ash samples occurred at a relatively higher temperature than that of the shale and clay samples. As mentioned earlier, this is because that fly ash material had already been through the coal combustion process where most weakly bonded, highly volatile organic materials have either been burned off or were converted to tightly bonded organic materials. These organics were retained in the ash particles and were then released at a higher temperature during heating.

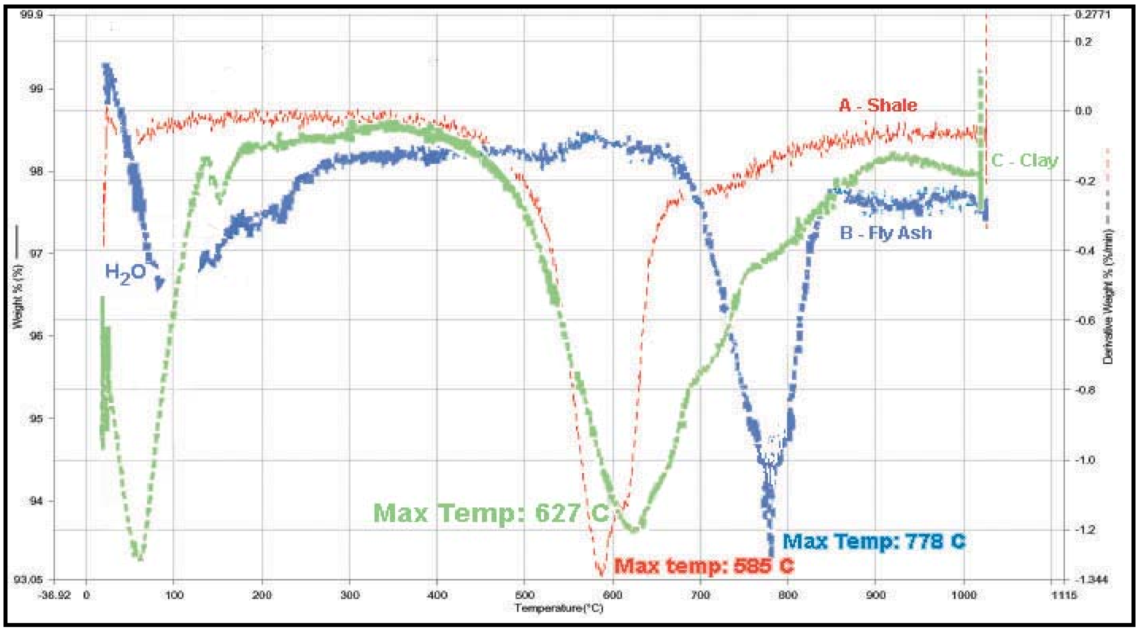

Figure 1: (A) The typical profile (TGA-first derivative curve) for CBC shale; (B) CPSIC pond fly ash; (C) and CBC clay samples while heated under nitrogen atmosphere

The typical SEM images for the samples of CPSIC pond fly ash and CBC shale are shown in Figure 2. The SEM analysis indicated that the fly ash sample consisted of significant amount of spherical particles, whereas the shale consisted of flat stacked particles. The spherical particles make fly ash a good filler material because they can fit into the gaps between particles of shale and clay. The addition of fly ash material may contribute to many of the unique characteristics observed for fly ash containing brick products. Our previous work has shown that the compressive strength of brick products increased as the amount of fly ash in the formulation increased. In this study, the fly ash bricks showed compressive strengths that were either similar or slightly higher than traditional fired bricks. In addition, in a separate study, bricks made with greater amounts of fly ash had a lower thermal conductivity, which is indicative of better heat insulation.

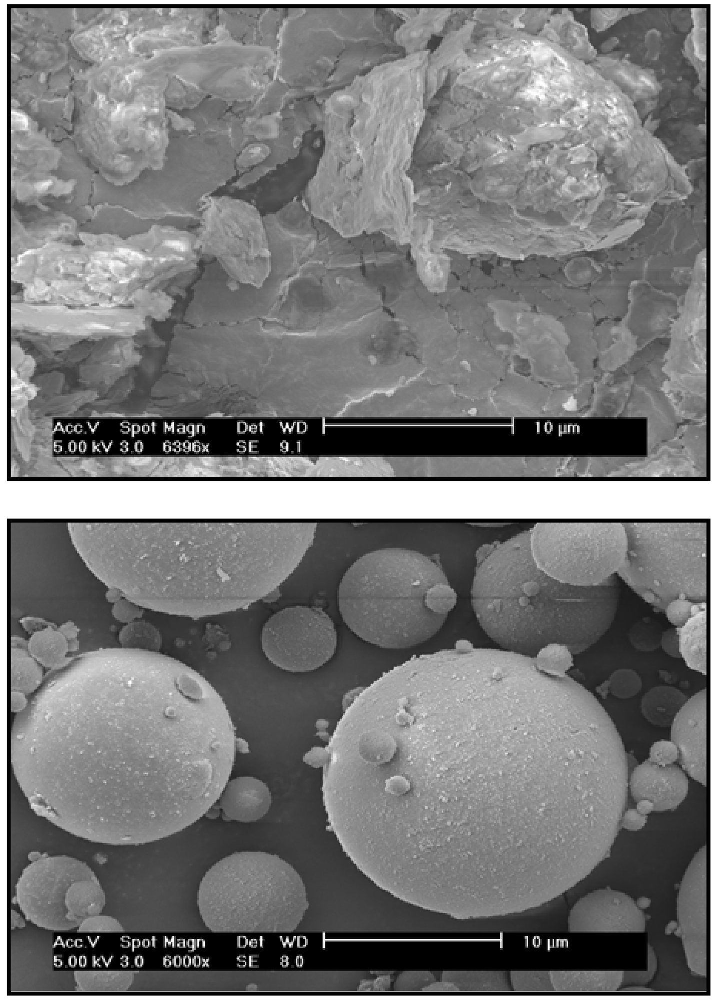

Figure 2: SEM images of CBC shale (upper) and CPSIC ponded fly ash (lower) samples at 6000x

The particle size distribution patterns of the CPSIC pond fly ash sample and CBC standard feed material (shale/clay mix sample) are shown in Figure 3 and Figure 4 respectively. The fly ash sample (Figure 3) shows ranges in size from 1 to 200 microns, with a majority smaller than 30 microns. A similar size distribution pattern was observed for the shale/clay mix after being ground at the brick plant (Figure 4). The fly ash sample is fine enough to be used in fired brick making without undergoing additional processing which represents a distinct economic advantage of utilizing fly ash in the brick formulation.

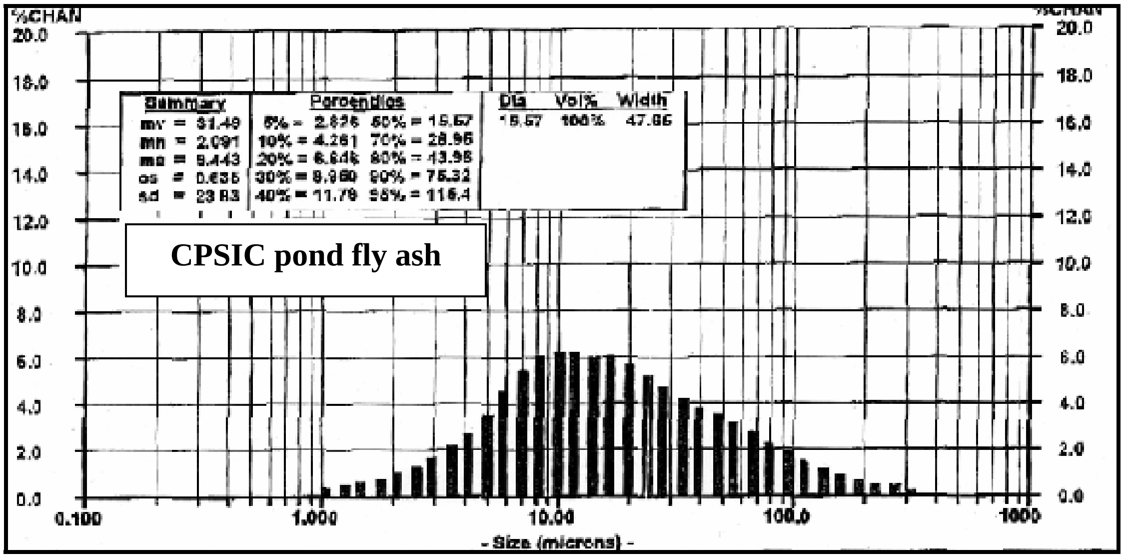

Figure 3: Particle size distribution of CPSIC fly ash

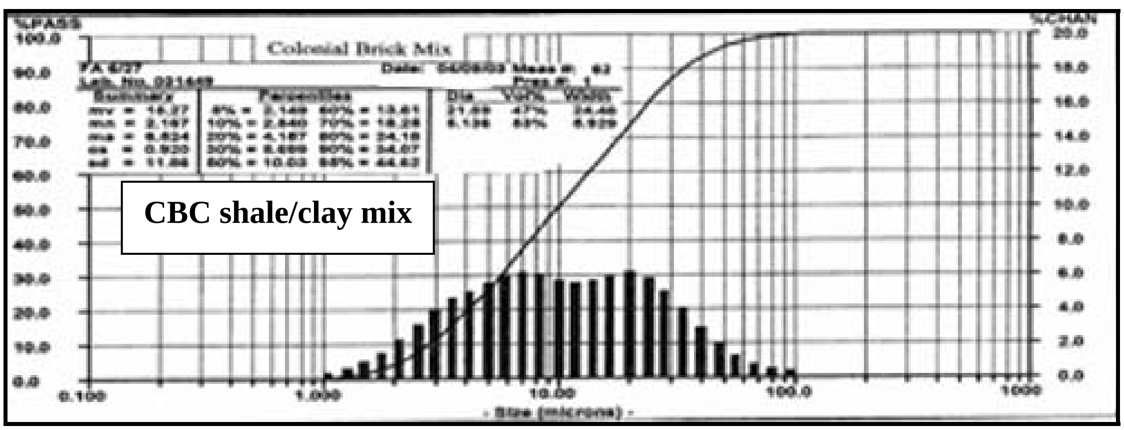

Figure 4: Particle size distribution of the standard shale/clay mix used by the brick plant

The X-ray diffraction (XRD) analysis determined the mineralogical properties of the fly ash, shale and clay samples. The ashes, as expected, are a mixture of crystalline and amorphous materials. The crystalline components include quartz that escaped melting and minerals such as mullite and hematite/magnetite that formed at high temperature during coal combustion. The shale sample contained refractory and generally larger particles (kaolinite and quartz) that maintain the shape of the body during firing, and the shale and clay samples also contained enough lower melting point minerals (feldspars, chlorite, and Fe-rich illite) to melt and form a steel-hard body, which has a very low water absorption.

Brick Production and Products Characterization – Paving Brick

Commercial specification for paving brick

The CBC plant is currently producing paving bricks containing no fly ash. In addition to the ASTM C902 specification, the CBC plant has its own in-plant method to monitor the quality of their commercial paving bricks.

As shown in Table 2, ASTM C902 specifies that paving bricks used for pedestrian and light traffic should have a minimum compressive strength of 7,000 psi for Grade SX (severe weather) for an individual brick or 8,000 psi for an average of five bricks. The maximum cold water absorption allowed is 11 wt% for an individual brick or 8 wt% for an average of five bricks. The maximum saturation coefficient (ratio of cold to boiling water absorption) must be equal to or less than 0.80 for an individual brick, or 0.78 for an average of five bricks. The abrasion resistance index is defined as the ratio of the cold water absorption to the compressive strength in percent. The maximum abrasion index allowed is 0.11 for Type I brick that is exposed to extensive abrasion, such as on driveways or at the entrance to a public building. The maximum abrasion allowed for Type II brick is 0.25, for brick exposed to intermediate abrasion, such as residential walkways. The maximum abrasion index allowed for Type III is 0.50. This type of brick is subject to low abrasion and is used in floors in single-family homes.

Table 2: ASTM C 902 specifications for pedestrian and light traffic paving brick

ASTM C902 Class Designation	Minimum Compressive Strength, psi		Maximum 24-h Cold Water Absorption, %		Maximum Saturation Coefficient*	
	5 Brick Average	Individual Brick	5 Brick Average	Individual Brick	5 Brick Average	Individual Brick
Class SX	8,000	7,000	8	11	0.78	0.80
Class MX	3,000	2,500	14	17	no limit	no limit
Class NX	3,000	2,500	no limit	no limit	no limit	no limit
Maximum Abrasion Resistance Index**						
0.11 (Type I)		0.25 (Type II)		0.50 (Type III)		

*The saturation coefficient is the ratio of absorption after 24 hour submersion in cold water to absorption after 5 hour submersion in boiling water; **The abrasion resistance index is the ratio of the cold water absorption to the compressive strength in percent.

Bench-scale production and product characterization

The firing of the two sets of green paving bricks conducted at the ISGS bench scale kiln was successful. Another set of the same green paving bricks, which was fired as a part of commercial firing at CBC commercial kiln, was also successful. These preliminary in-plant firing tests produced high-quality, attractive, and strong paving bricks, as shown in Figures 5 and 6.

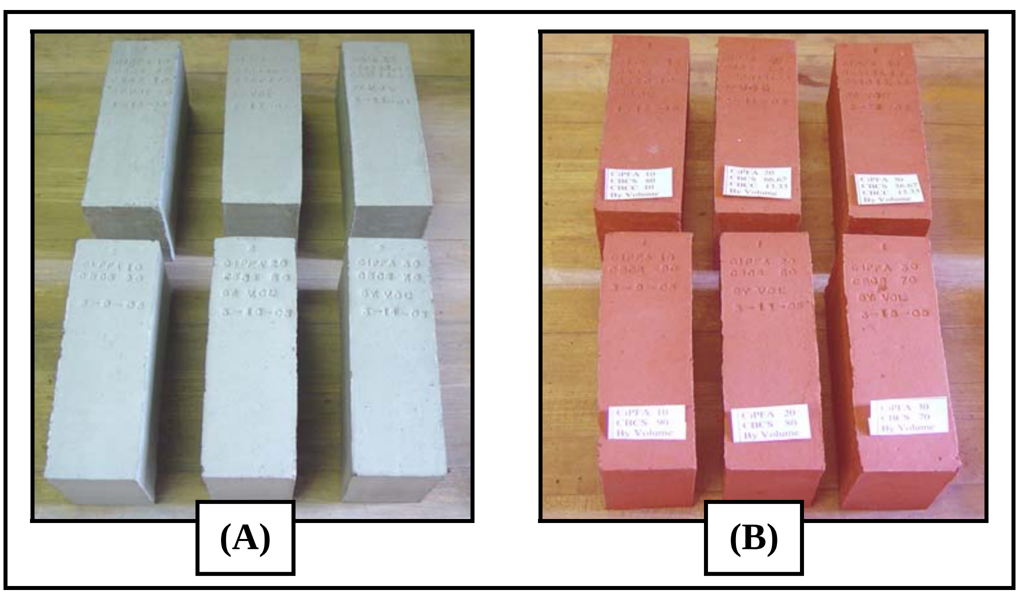

Figure 5: Mold-pressed paving bricks containing 10, 20, and 30 vol% fly ash, balanced with shale and clay, before firing (A) and after firing (B)

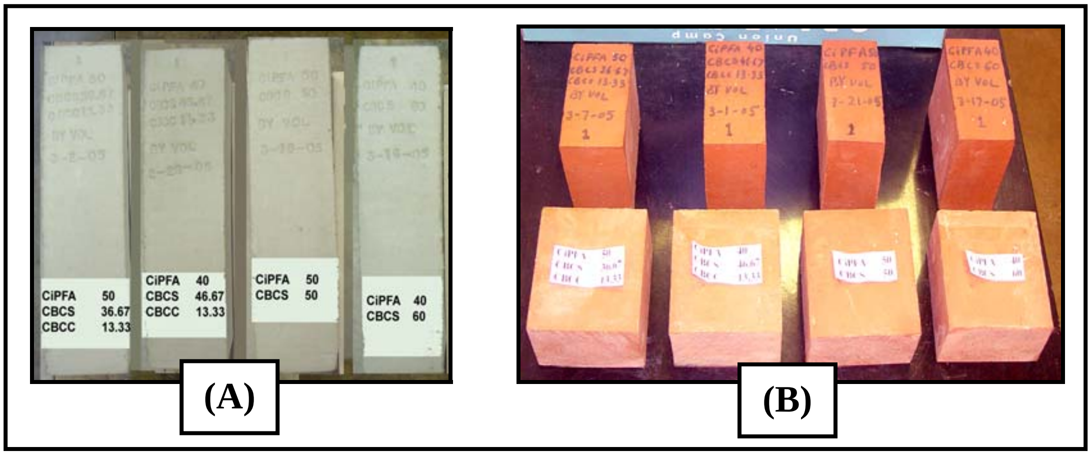

Figure 6: Mold-pressed paving bricks containing 40 and 50 vol% fly ash, balanced with shale and clay, before firing (A) and after firing and then splitting in half (B)

Water absorption tests were conducted on these mold-pressed fired bricks including cold and boiling water absorption measurements. A saturation coefficient was calculated in order to track batch to batch consistency. The results for the first set of paving bricks with fly ash inputs of 10 to 50 vol% blended with shale only are shown in Table 3. The results for another set of paving bricks made with fly ash inputs at the same level but blended with a mix of clay and shale are shown in Table 4.

Table 3: Engineering properties of mold-pressed paving bricks without clay

Brick composition, vol%	CPSIC 10 CBCS 90		CPSIC 20 CBCS 80		CPSIC 30 CBCS 70		CPSIC 40 CBCS 60		CPSIC 50 CBCS 50	
Firing facility	ISGS	CBC	ISGS	CBC	ISGS	CBC	ISGS	CBC	ISGS	CBC
Cold water 24 hr soak, %	8.84	4.66	8.47	6.61	9.37	8.36	9.85	8.20	10.05	8.84
Boiling water 5 hr soak, %	11.38	6.72	11.20	9.44	12.44	11.57	13.35	11.86	13.70	12.64
Saturation coefficient	**0.78**	**0.69**	**0.76**	**0.70**	**0.75**	**0.72**	**0.74**	**0.69**	**0.73**	**0.70**

CPSIC = Cinergy Ponded Fly Ash; CBCS = CBC Shale; CBCC = CBC Clay

A general trend was observed for the water absorption capacity of these mold-pressed bricks in which those with a greater fly ash input tended to absorb more water. However, the cold water and boiling water absorption capacities increased proportionally so the saturation coefficient remained nearly constant for each case. The maximum firing temperature for the ISGS kiln and the commercial kin at the CBC was similar, ranging between 1922°F and 1950°F. All of the mold-pressed test bricks met the ASTM commercial specification for water absorption. The compressive strength of the mold-pressed paving bricks was also measured, and the results ranged from 7230 psi to 16030 psi.

Table 4: Engineering properties of mold-pressed paving bricks with clay

Brick composition, vol%	CPSIC 10 CBCS 76.67 CBCC 13.33	CPSIC 20 CBCS 66.67 CBC 13.33		CPSIC 30 CBCS 56.67 CBC 13.33		CPSIC 40 CBCS 46.67 CBC 13.33		CPSIC 50 CBCS 36.67 CBC 13.33	
Firing facility	CBC	ISGS	CBC	ISGS	CBC	ISGS	CBC	ISGS	CBC
Cold water 24 hr soak, %	5.67	6.80	5.33	7.25	7.04	8.15	6.59	8.77	8.15
Boiling water 5 hr soak, %	8.21	9.33	7.72	10.15	9.96	11.51	10.10	12.62	12.04
Saturation coefficient	**0.69**	**0.73**	**0.69**	**0.71**	**0.71**	**0.71**	**0.65**	**0.69**	**0.68**

CPSIC = Cinergy Ponded Fly Ash; CBCS = CBC Shale; CBCC = CBC Clay

Commercial-scale production and product characterization

Based on the results of the bench-scale paving brick evaluation, two commercial-scale production test runs, including extrusion and firing of 2,000 bricks per run, were conducted at CBC's commercial facility. Run I produced paving bricks with raw materials containing 20 vol% (about 14 wt%) of the CPSIC fly ash balanced with 80 vol% of CBC shale. The extrusion and firing processes produced bricks with a 75% yield. Run II was then conducted with 20 vol% of the CPSIC fly ash balanced with a 3:1 mix of CBC's shale and clay.

Run I: 20 vol% CiPFA; 80 vol% CBCS

Run II: 20 vol% CiPFA; 60 vol% CBCS; 20 vol% CBCC

The engineering properties of the final products from the two commercial-scale production test runs (Run I and Run II) are compared in Table 5. Although the water absorption data and the compressive strength of the paving bricks from Run I have met or exceeded ASTM C 902 specifications, the extremely low water absorption capacity of the Run I bricks indicated that these bricks (Run I firing) had experienced an over heated heating cycle. Also, the production yield of Run I would be too low to be accepted for commercialization. The results from Run II indicated that an inclusion of a low level of clay material (20 vol%) in the raw mix containing fly ash improved the extruding ability of the mixed raw materials and reduced cracking and chipping of the bricks, thereby significantly increasing the production yield, from 75% to 100%. A photo of the high-quality, attractive, and strong paving bricks from the second commercial-scale production, Run II, is shown in Figure 7.

Table 5: Engineering properties of paving bricks with 20 vol% of fly ash from two commercial-scale production runs

		Run-I without clay added	Run-II with clay added
Max. water absorption	Cold water, wt% (Class SX < 8 wt%)	1.75	6.81
	Boiling water, wt%	2.55	9.65
	Saturation coefficient* (Class SX < 0.78)	**0.69**	**0.71**
Fired compressive strength, psi (Class SX >8,000 psi)		**29,910**	**23,540**
Suction rate, g (wt. gain/ minute)		2.50	20.8
Scum		No	No
Modulus of Rupture, psi (>1,000 psi)		1737	1959
Abrasion Resistance Index (Type I < 0.11)		0.006	0.029
ASTM C902 Classification		Class SX, Type I	Class SX, Type I
Production Yield		75%	100%

ASTM C902 - Standard specifications for Pedestrian and Light Traffic Paving Brick; Run I: 20 vol% fly ash and 80 vol% shale; Run II: 20 vol% fly ash, 60 vol% shale, and 20 vol% clay

Figure 7: Run II: 2000 paving bricks containing 20 vol% CPSIC fly ash

Brick Production and Product Characterization – Building Brick

Commercial specification for building brick

The CBC plant is currently producing building bricks containing no fly ash. In addition to the ASTM C62 specification, the CBC plant has its own in-plant method to monitor the quality of their commercial building bricks. ASTM C62 (Table 6) specifies that building bricks must have a minimum compressive strength of 2,500 psi for Grade SW (severe weather) for an individual brick or an average of 3,000 psi for five bricks measured. If the cold water absorption less than 8 wt%, then the boiling water absorption test and saturation coefficient specifications are waived. Otherwise, the maximum boiling water absorption allowed is 20% for an individual brick or an average of 17% for five bricks. The maximum saturation coefficient must be equal to or less than 0.80 for an individual brick, or an average of 0.78 for an average of five bricks.

Table 6: ASTM C 62 specifications for building brick

ASTM C 62 Class Designation	Minimum Compressive Strength, psi		Maximum 24-h Cold Water Absorption, 8 %*			
			Maximum 5-h Boiling Water Absorption, %		Maximum Saturation Coefficient**	
	5 Bricks Average	Individual Brick	5 Bricks Average	Individual Brick	5 Bricks Average	Individual Brick
Class SW	3,000	2,500	17	20	0.78	0.80
Class MW	2,500	2,200	22	25	0.88	0.90
Class NW	1,500	1,250	no limit	no limit	no limit	no limit

*If the cold water absorption does not exceed 8 wt%, then the boiling water absorption, and saturation coefficient specifications are waived; ** the saturation coefficient is the ratio of absorption by 24 hour submersion in cold water to the absorption after 5 hour submersion in boiling water.

Bench/Commercial-scale production

During bench-scale tests, the mold-pressed three-hole building bricks with fly ash at levels of up to 60 % by volume (or about 56% by weight) were fired as part of the commercial firing at CBC, and these preliminary in-plant firings were successful.

Based on the results of the bench-scale building brick evaluation and to determine which formulations could be the most readily adaptable to commercial production while still using a significant amount of fly ash, many discussions between the ISGS and the industry partners were conducted. It was concluded that four runs would be conducted with fly ash levels of 0, 20, 30, and 40 vol%. The run with 0 vol% fly ash was used as a control run to mimic the standard production formulations for the brick plant. Each of the runs with fly ash included a constant level of 10 vol% clay which helped to improve the yield of the final products. An increased fly ash inputs from 20, 30, and 40 vol% were chosen for the building brick test runs because the amount of fly ash used in the paving brick test runs was deemed the minimum workable level. The building brick test runs would determine whether additional fly ash inputs would be suitable for producing high quality final products.

Each scale-up extrusion run (one such run shown in Figure 8) produced about 2000 building bricks, and a total of about 8000 three-hole building bricks were produced for engineering evaluations. The strong and attractive bricks were produced with a commercially acceptable yield of greater than 95% (Figure 9). Formulations for each of the four runs are as follows (where CiPFA, CBCS, and CBCC refer to Ponded Fly Ash, Colonial Brick Company Shale, and Colonial Brick Company Clay, respectively).

Run E1: 0 vol% CiPFA; 85.71 vol% CBCS; 14.29 vol% CBCC

Run E2: 20 vol% CiPFA; 70 vol% CBCS; 10 vol% CBCC

Run E3: 30 vol% CiPFA; 60 vol% CBCS; 10 vol% CBCC

Run E4: 40 vol% CiPFA; 50 vol% CBCS; 10 vol% CBCC

Figure 8: Scale-up extrusion at the brick plant produced three-hole green building bricks (700 bricks per car)

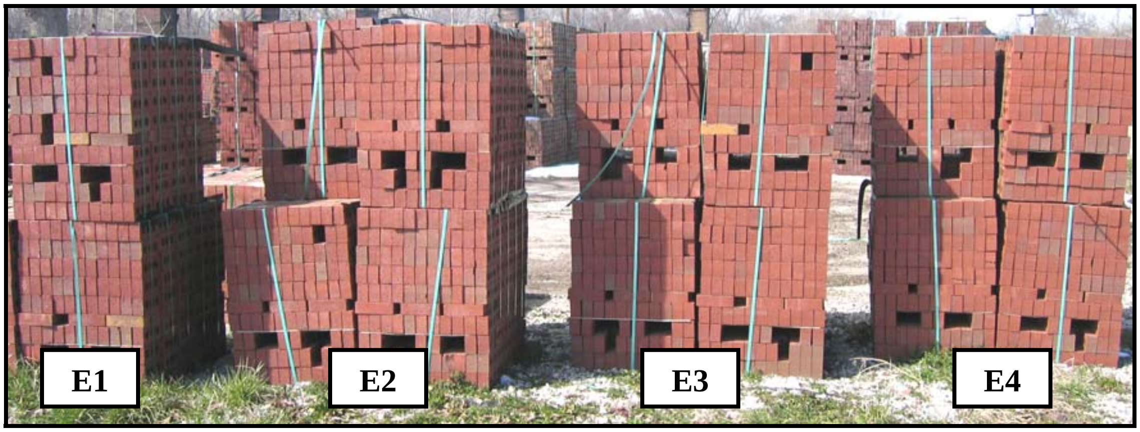

Figure 9: Four batches of fired building bricks produced from scale-up production test runs with fly ash inputs at 0% (E1), 20% (E2), 30% (E3), and 40% (E4) by volume

Table 7 shows the results of the engineering property tests which include water absorption, compressive strength, and suction rate. Since the cold water absorption for all four batch samples did not exceed 8 wt%, the boiling water absorption, and saturation coefficient specifications were not necessary. The results show that these building bricks far exceed ASTM building brick specifications and are marketable for the severe weather grade.

Table 7: Engineering properties of building bricks from commercial-scale test runs

Brick Sample ID		E1	E2	E3	E4
Max. water absorption	Cold water 24 hr soak, % (< 8 wt%)	3.75	4.00	3.93	4.05
	Boiling water 5 hr, %	(5.30)	(6.06)	(5.89)	(4.30)
	Saturation coefficient	(0.71)	(0.66)	(0.67)	(0.94)
Fired compressive strength, psi (Severe weather grade > 3000 psi)		16905	16410	16476	20980
Suction, gm wt gain/minute		5.02	5.62	4.91	2.92
Scum		No	No	No	No

E1, E2, E3, and E4 refer to the brick samples from Run E1, Run E2, Run E3, and Run E4 respectively. The data indicated in the parentheses are not needed because all the cold water absorption data were less than 8%.

The building bricks produced with 20 and 30 vol% of fly ash are comparable to the standard bricks with respect to their compressive strength data. The results from our previous laboratory studies with extruded bar-size test bricks indicated that the test bricks with a greater amount of fly ash have a greater fired compressive strength. The commercial-scale extruded test bricks appeared to have a similar trend as shown by the bricks with 40 vol% of fly ash having the greatest compressive strength. The bricks were also produced with a commercially acceptable yield of greater than 95% which means that building bricks with up to 40 vol% of fly ash would be acceptable for future commercial production. Once a supply of fly ash is secured, CBC will consider beginning the producing of fly ash containing bricks thereby extending the life of their clay and shale reserves.

Economic Assessment

The economic feasibility of producing fired bricks with fly ash at CBC is an important factor to consider in the commercialization. The ISGS/UIUC process developed for making fired bricks with coal fly ash uses fly ash as a substitute for part of conventional raw materials, clay and shale. Since the process can be adopted by using conventional machinery at the CBC facility, the additional capital cost investment will not be necessary. Therefore, the major factors to be considered during economic assessment are the cost of obtaining raw materials and the production costs. The CBC plant has a production capacity of sixteen million bricks per year. This cost analysis was conducted, for a conservative measure, using a production rate of twelve million bricks per year. Based on producing bricks with 40 wt% of fly ash and at 4.25 pounds for each brick, the production rate of twelve million bricks per year would translate to an annual fly ash consumption rate of 10,200 tons for the brick plant.

Fly ash is a byproduct of coal combustion, and it is readily available throughout the year. Also, the producer is eager to give it away at little to no cost. The main cost in obtaining the fly ash would be in transporting the fly ash from the power station to the brick plant.

Transportation cost – A trucking company was contacted to provide a quotation with a higher rate for shipping fly ash from the CPSIC to CBC. Since the distance between the two locations is less than 5 miles, the trucking company would charge a rate of $65 per hour rather than charging by the mile. If the dump truck can carry 25 tons of fly ash and requires two hours of handling time, the overall transportation cost would be $5.20/ton (Note that a lower rate of $3.50/ton was provided in an estimate by another company). The annual cost for transporting 10,200 tons of fly ash, at $5.20/ton, from the CPSIC to CBC would be $53,040.

Mining cost – If the brick plant were to produce 12 million regular bricks per year, the annual mining cost would be $143,000. Substituting the conventional raw material by using 40 wt% of fly ash can reduce the annual consumption of clay and shale material, thus reducing their mining cost to $85,000 per year, which is a saving of $57,000 per year.

Therefore, the total estimated annual saving in obtaining the raw material without any contribution from the utility company would be $4160. However, since the power company would be saving money because their cost in placing their fly ash in landfills and holding ponds would be reduced or minimized, they may be willing to help with the cost of shipping. If the utility company were to contribute half of the shipping cost ($26,520/year), the brick plant would have their saving increased from $4160 to $30,680 per year in obtaining their raw material.

Processing raw material – Fly ash is a fine material which does not require additional processing, unlike shale and clay which need crushing and extensive grinding. Thus, using fly ash as a substitute raw material has an additional benefit of reducing processing costs. Based on the brick plant’s yearly processing cost to process their clay and shale for brick making, and if fly ash could be used at a rate of 40 wt%, savings from the raw material processing would be $27,600 per year.

In summary, the overall estimated annual cost saving for the brick plant producing 12 million bricks containing 40 wt% of fly ash could be as much as $58,280.

Commercial Market for Brick

According to the Brick Industry Association, the number of bricks produced in the U.S., measured as standard brick equivalents (SBE) has steadily increased each year. In 2001, nationwide production was estimated at 8.3 billion SBE. By the year 2003, it had increased to 8.6 billion. In 2004, it reached 9.3 billion, which translates into 23.25 million tons (a standard brick weighs about five pounds). The production in the East North Central America region (Illinois, Indiana, Michigan, and Wisconsin) was estimated at 290.6 million SBE in 2003, and reached 342.6 million SBE in 2004 (U.S. Census Bureau, Economic and Statistics Administration, U.S. Department of Commerce).

Environmental Feasibility Study

Although fly ash and other brick-making raw materials are not currently regulated by the U.S. EPA, the leaching characteristics of fired bricks with and without fly ash were examined according to US EPA Method 1320. The concentrations of twenty elements found in the extracts of the samples, including As, Ba, Cd, Cr, Hg, Ni, Pb, Ca, and B, are shown in Table 8. The regulatory thresholds for the elements set by the US EPA for acid extractions from other solid wastes are listed in Table 8 as well. The data indicated that the amounts of these elements in the simulated acid-rain extracts from both the fly ash containing brick samples (E2, E3, E4) and the commercial brick samples (E1) have values well below the EPA's regulatory thresholds set for other solid waste materials. The results of this study indicate that similar to the regular commercial bricks, the fly ash containing bricks are environmentally safe construction products.

Table 8: Elemental concentrations in simulated acid rain extracts of fired bricks agitated with acidified water for 24 hours

Samples	Elemental concentrations in extracts (solid : liquid = 1 : 20) (mg/L)									
	Al	**As**	B	**Ba**	Ca	**Cd**	Co	**Cr**	Cu	Fe
Blank 1	0.05	**<0.004**	<0.01	**0.03**	0.11	**<0.004**	<0.002	**<0.001**	0.0044	<0.04
Blank 2	0.03	**<0.004**	<0.01	**<0.02**	<0.10	**<0.004**	<0.002	**<0.001**	0.0044	<0.04
E1	0.05	**<0.004**	0.05	**0.15**	10.20	**<0.004**	<0.002	**<0.001**	<0.004	<0.04
E2	0.52	**0.011**	0.05	**0.10**	16.00	**<0.004**	<0.002	**<0.001**	<0.004	<0.04
E3	0.16	**0.004**	0.07	**0.13**	14.20	**<0.004**	<0.002	**<0.001**	<0.004	<0.04
E4	0.21	**0.019**	0.10	**0.12**	10.70	**<0.004**	<0.002	**<0.001**	<0.004	<0.04
EPA limit	-	**5.00**	-	**100**	-	**1.00**	-	**5.00**	-	-

Table 8 (continued)

Samples	Elemental concentrations in extracts (solid : liquid = 1 : 20) (mg/L)										
	K	Li	Mg	Mn	Na	**Ni**	**Pb**	S	**Se**	Sr	Zn	**Hg**
Blank 1	<0.20	0.092	0.02	0.003	0.19	**<0.003**	**<0.01**	8.7	**<0.002**	<0.04	0.021	**0.000009**
Blank 2	<0.20	0.101	<0.02	<0.002	<0.10	**<0.003**	**<0.01**	8.9	**<0.002**	<0.04	0.015	**0.000005**
E1	6.90	<0.04	2.50	0.129	3.21	**0.005**	**<0.01**	9.9	**<0.002**	0.13	0.012	**<0.000002**
E2	6.30	<0.04	1.70	0.030	2.10	**0.004**	**<0.01**	19.8	**<0.002**	<0.04	0.007	**<0.000002**
E3	6.70	<0.04	2.29	0.042	2.61	**0.0041**	**<0.01**	20.4	**0.002**	0.07	0.011	**<0.000002**
E4	6.60	<0.04	2.15	0.023	1.93	**0.006**	**<0.01**	11.1	**<0.002**	<0.04	0.013	**<0.000002**
EPA limit	-	-	-	-	-	**5.00**	**5.00**	-	**1.00**	-	-	**0.2**

E1, E2, E3, and E4 refer to the extracts from building bricks containing 0%, 20%, 30%, and 40% by volume of fly ash respectively; Blanks 1 and 2 are blank values for the acid rain water before extraction

CONCLUSION

Paving bricks with 20 vol% of fly ash and building bricks with up to 40 vol% (about 37 wt%) of fly ash were successfully produced in commercial-scale production test runs. All of the final products met the brick plant's in-house specifications for marketability and far exceeded the ASTM commercial specifications for the severe weather grade. The results showed that the participating brick company can incorporate the fly ash into their commercial production without acquiring additional machinery, while concurrently reducing plant operation costs. Also, similar to the regular commercial bricks, the fly ash containing bricks are environmentally safe construction products.

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