Utilization of Lightweight Materials Made From Coal Gasification Slags

Quarterly Report

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1.0 PROJECT OBJECTIVES, SCOPE AND DESCRIPTION OF TASKS

1.1 Introduction

Integrated-gasification combined-cycle (IGCC) technology is an emerging technology that utilizes coal for power generation and production of chemical feedstocks. However, the process generates large amounts of solid waste, consisting of vitrified ash (slag) and some unconverted carbon. In previous projects, Praxis investigated the utilization of "as-generated" slags for a wide variety of applications in road construction, cement and concrete production, agricultural applications, and as a landfill material. From these studies, we found that it would be extremely difficult for "as-generated" slag to find large-scale acceptance in the marketplace even at no cost because the materials it could replace were abundantly available at very low cost. It was further determined that the unconverted carbon, or char, in the slag is detrimental to its utilization as sand or fine aggregate. It became apparent that a more promising approach would be to develop a variety of value-added products from slag that meet specific industry requirements. This approach was made feasible by the discovery that slag undergoes expansion and forms a lightweight material when subjected to controlled heating in a kiln at temperatures between 1400 and 1700°F. These results confirmed the potential for using expanded slag as a substitute for conventional lightweight aggregates (LWA). The technology to produce lightweight and ultra-lightweight aggregates (ULWA) from slag was subsequently developed by Praxis with funding from the Electric Power Research Institute (EPRI), Illinois Clean Coal Institute (ICCI), and internal resources.

The major objectives of the subject project are to demonstrate the technical and economic viability of commercial production of LWA and ULWA from slag and to test the suitability of these aggregates for various applications. The project goals are to be accomplished in two phases: Phase I, comprising the production of LWA and ULWA from slag at the large pilot-scale, and Phase II, which involves commercial evaluation of these aggregates in a number of applications.

Primary funding for the project is provided by DOE's Morgantown Energy Technology center (METC) with significant cost sharing by Electric Power Research Institute (EPRI) and Illinois Clean Coal Institute (ICCI).

1.2 Scope of Work

The Phase I scope consisted of collecting a 20-ton sample of slag (primary slag), processing it for char removal, and pyroprocessing it to produce expanded slag aggregates of various size gradations and unit weights, ranging from 12 to 50 lb/ft³. In Phase II, the expanded slag aggregates will be tested for their suitability in manufacturing precast concrete products (e.g., masonry blocks and roof tiles) and insulating concrete, first at the laboratory scale and subsequently in commercial manufacturing plants. These products will be evaluated using ASTM and industry test methods. Technical data generated during production and testing of the products will be used to assess the overall technical viability of expanded slag production. Relevant cost data for physical and pyroprocessing of slag to produce expanded slag aggregates will be gathered for comparison with (i) the management and disposal costs for slag or similar wastes and (ii) production costs for conventional materials which the slag aggregates would replace. In addition, a market assessment will be made to evaluate the economic viability of these utilization technologies.

1.3 Phase I Task Description

A summary of the tasks performed in Phase I is given below:

- Task 1.1 Laboratory and Economic Analysis Plan Development:** Development of a detailed work plan for Phase I and an outline of the Phase II work.
- Task 1.2 Production of Lightweight Aggregates from Slag:** Selection and procurement of project slag samples, slag preparation including screening and char removal, and slag expansion in a direct-fired kiln and fluid bed expander. The char recovered from the slag preparation operation was evaluated for use as a kiln fuel and gasifier feed. Environmental data for SLA production was collected.
- Task 1.3 Data Analysis of Slag Preparation and Expansion:** Analysis and interpretation of project data, including development of material and energy balances for slag processing and product evaluation.
- Task 1.4 Economic Analysis of Expanded Slag Production:** Economic analysis of expanded slag utilization was conducted by determining production costs for slag-based LWAs and ULWAs. Expanded slag production costs, both with and without the avoided costs of disposal, were compared with the market value of similar products and costs of management of slag as a solid waste.
- Task 1.5 Topical and Other Reports:** Preparation of topical, financial status, and technical progress reports in accordance with the Statement of Work.

1.4 Phase II Task Description

A summary of the tasks to be performed in Phase II is given below.

- Task 2.1 Test Plan for Applications of Expanded Slags (Field Studies):** This task involves the development of selection criteria and a field test plan for expanded slag applications. The plan will serve as a guide in the selection and implementation of field demonstrations for the most promising expanded slag utilization applications. Field applications will be selected on the basis of laboratory test results, marketability of the products, and the suitability of the project slags for these applications. Tentatively, the following applications are under consideration for testing:
- ▶ Lightweight concrete blocks made from 50 lb/ft³ SLA
 - ▶ Lightweight roof tiles made from 40 lb/ft³ SLA
 - ▶ Loose fill insulation made from 16 lb/ft³ SLA
 - ▶ Lightweight insulating concrete made from 16 lb/ft³ SLA.
- Task 2.2 Field Studies to Test Expanded Slag Utilization:** Under this task, field testing of the applications identified in Phase II, Task 2.1 will begin with test work to optimize the concrete mixes using expanded slag. A field report will be prepared for each field application.

Task 2.3 Data Analysis of Commercial Utilization of Expanded Slags: The objective of this task is to assimilate the data and test results collected during Phase II, Task 2.2, to convert these findings to common engineering terms, and to correlate these results with comparable information for conventional lightweight aggregates as reported in the literature. The data analysis will provide specific answers to the following issues:

- ▶ Performance of expanded slag in comparison with conventional materials
- ▶ Technical viability of lightweight and ultra-lightweight slags as aggregates.

Task 2.4 Economic Analysis of Expanded Slag Utilization: The objective of this task is to expand upon the preliminary economic assessment of expanded slag utilization conducted during Phase I. The economics will be studied based on a comparison of SLA application production costs as determined from the field tests with the current market prices of these products using conventional materials. During the preliminary evaluation in Phase I, two production scenarios emerged:

- ▶ Production of SLA at the gasifier location (on-site production)
- ▶ Production of SLA at a lightweight aggregate facility (off-site production)

The impact of the avoided costs of slag disposal on the economics of SLA production will also be evaluated. Slag utilization data and product samples will be made available to lightweight aggregate users to obtain estimates of potential market prices, and the impact of these prices on the economics of SLA production will be determined.

Task 2.5 Final Report: The data generated and collected for this project will be compiled in a final report to be submitted at the end of the project that will be a comprehensive description of the results achieved, consistent with the Reporting Requirements. The report will include tabulations of data, figures, photographs, and bibliographic citations. Data from topical and field reports will be summarized. The report will include the original hypothesis of the project and present the investigative approaches used, complete with problems encountered or departures from the planned methodology, and an assessment of their impact on the project results.

1.5 Scope of this Document

This is the eighth quarterly report and summarizes the work undertaken during the performance period between 1 June 1996 and 30 August 1996. This is the first report for Phase II of the project. The major accomplishments from Phase I are summarized in Section 3.

2.0 SUMMARY OF WORK DONE DURING THIS REPORTING PERIOD

2.1 Summary of Major Accomplishments

The following was accomplished during the current reporting period:

1. Approval for continuation of the project to Phase II was received from METC.
2. The Phase I Final Report was prepared and submitted to METC. This was revised based on METC comments and resubmitted in final form.
3. Laboratory-scale applications-oriented testing of SLA as a substitute for LWA and ULWA was continued in the current reporting period. This work involved testing expanded slag samples in the following applications:
 - Structural concrete (testing started)
 - Lightweight concrete masonry unit (lightweight blocks, 2-3 blends)
 - Insulating concrete (laboratory testing completed)
 - Lightweight roof tile aggregate using three SLA products (laboratory testing completed)
 - Loose fill insulation (laboratory testing completed)
 - Horticultural application.
4. Work was initiated to prepare and submit all future reports in Adobe Acrobat Portable Document Format (PDF) as requested by METC.
5. Contacts were initiated with manufacturers of lightweight precast products to determine their interest in producing demonstration products using expanded slag.

2.2 Chronological Listing of Significant Events in This Quarter

The following significant events occurred during the current reporting period:

Date	Description
7/1/96	Phase I Topical Report (final version) submitted
7/15/96	Laboratory testing of SLA for roof tile and insulating concrete applications completed
7/14/96	Structural concrete laboratory tests started
7/28/96	Manufacturer for block production selected

3.0 TO DATE ACCOMPLISHMENTS

A summary of the work completed in Phase I is given below.

Date	Accomplishments
10/24/94	Draft Laboratory and Economic Analysis Plan (project work plan) submitted
11/18/94	Slag char removal completed on the advance sample and prepared slag laboratory expansion testing initiated
12/02/94	Final "Laboratory and Economic Analysis Plan" prepared and submitted
05/21/95	Primary slag sample (20 ton) received at Penn State for preparation
06/01/95	Pilot unit for char removal set up and processing work started
08/20/95	Primary slag sample processing for char removal completed
9/10/95	Laboratory expansion studies of slag and slag/clay blends started
10/15/95	1-ft and 3-ft diameter kilns commissioned for pilot testing
11/15/95	Pilot testing of Slag I and Slag II and pellets in 3-ft dia. direct-fired kiln completed
11/17/95	Pilot testing using fluidized bed expander completed
12/12/95	SLA product characterization initiated
1/20/96	Laboratories for testing of SLA products identified
2/16/96	Test plan for second batch of fluid bed expander testing at Fuller completed
4/30/96	Application for continuation of the project to Phase II submitted
5/31/96	Phase I Final Report (draft) submitted

A summary of the work completed in Phase II to date is given below.

Date	Description
7/1/96	Phase I Topical Report (final version) submitted
7/15/96	Laboratory testing of SLA for roof tile and insulating concrete applications completed
7/14/96	Structural concrete laboratory tests started
7/28/96	Manufacturer for block production selected

4.0 TECHNICAL PROGRESS REPORT

4.1 Test Plan for Expanded Slag Utilization

The objective of this task is to carry out field testing of the slag utilization applications identified under Task 2.1. The types of products that will be reviewed for manufacture at the commercial scale are described below.

Lightweight Nonstructural Concrete Mix Design Optimization

Mix designs for lightweight nonstructural concretes (moderate strength concrete, nonstructural block concrete, and insulating concrete) will be developed and optimized before selecting specific

commercial-scale demonstration applications. This work will be completed following exploratory test work using the expanded slag products produced at the pilot scale in Phase I.

Development of Lightweight Structural Concrete Using Expanded Slag

The two coarse lightweight aggregates (pelletized fines and +6 mesh slag) produced from slag will be tested for structural concrete applications. In keeping with current practices for new LWAs, sets of concrete specimens will be prepared using a 1-ft³ concrete mixer and tested in accordance with ASTM specifications that are routinely used to specify structural LWA.

Manufacture and Testing of Masonry Blocks Using Expanded Slag

The objective of this subtask is to use commercial-scale concrete block manufacturing equipment and techniques to produce blocks from expanded slag. This work will commence after the completion of tests to optimize the block mix design. All test data generated to date will be compiled and discussed with a commercial producer of lightweight blocks. The commercial producer will first prepare trial batches of concrete which will be used to make manually formed blocks. Following evaluation of these blocks, a full-scale run (approximately 700 8-inch blocks) will be produced using their commercial batching plant and continuous block machine.

The appropriate proportion of aggregates, cement, and water will be batched using conventional mixing methods. A standard three-mold continuous block machine will be operated at a nominal rate of 250 blocks/hour. Block production will be conducted as a series of consecutive runs, each series being used to generate a different type of block. Evaluation of the blocks will include characterization of compressive strength development over time. Sets of three blocks will be tested for strength at 1, 4, 7, and 14 days after removal from the curing kilns. A set of three blocks will be selected at random from each block type produced for complete evaluation, in accordance with ASTM C 140, "Sampling and Testing of Concrete Masonry Units."

Manufacture and Testing of Lightweight Roof Tiles Using Expanded Slag

This subtask involves commercial-scale production of lightweight concrete roof tiles using expanded slag aggregates. The work will be conducted at a production plant of a large roof tile manufacturing company. Initially, trial batches of concrete will be prepared. The optimal mix design determined from the trial tests will then be used for a large-scale production run using continuous commercial mixing and molding equipment. After steam curing, sets of three tiles will be tested for unit weight and flexural strength at 1, 4, 7, and 14 days of ambient air curing. The tiles will also be examined for texture, completeness of mold filling, and cement-to-aggregate bonding. Sets of tiles will be exposed to sunlight and periodically monitored for signs of thermally induced degradation. Three tiles will be sampled monthly for up to six months and their strength and dimensional changes will be noted.

Other Demonstration Projects

The feasibility of using expanded slag aggregates in additional demonstration tests such as the manufacture of insulating concretes and loose fill insulation will be investigated. The project data will be discussed with producers and suppliers to obtain recommendations for demonstration projects.

Insulating Concrete. The application for insulating concrete is not well defined at this time because of the limited data currently available for it. The specific application for testing will be selected in conjunction with a survey of potential applications after reviewing the exploratory and optimization test work. The most promising applications to date include:

- ▶ Insulating concrete overlays of walls or floorings
- ▶ Precast building panels
- ▶ Built-up roofing systems.

Loose Fill Insulation. Samples of expanded slag will be tested as substitutes for this application. The need for silicone treatment will be evaluated, and direct comparisons will be made with expanded perlite products using Perlite Institute tests and standards.

4.2 Laboratory Evaluation of SLA for Structural Concrete Application

The objective of this test program is to develop mix designs to produce sand and SLA-based cement concretes with compressive strengths of 2500-4000 psi and corresponding unit weights in the 115-105 lb/ft³ range. These variations are accomplished by changing the proportion of cement relative to the SLA. The SLA samples tested are identified in Table 1. In addition, a control sample of commercially available structural aggregates was also tested. As may be seen in Table 1, the 3/4" coarse aggregates were demonstrated using three different cement levels to produce products with varying strengths (complete matrix) whereas the other samples were tested at only one strength level. This test work is in progress.

Table 1. Cement Levels Used in Testing SLA as Structural Aggregate

SLA Products Tested	Cement Level, Sacks/Yard ³
(i) 3/4" SLA (50/50 slag-clay pellets) as 3/4" coarse LWA	5½, 6½, and 7½
(ii) 1/4" x 50M SLA crushed as 3/8" combined LWA	One level of cement
(iii) Expanded 3/4" clay pellets produced during the pilot program	One level of cement

4.3 Laboratory Evaluation of SLA for Roof Tile Application

Prior to conducting the final tests many experiments were conducted with varying amounts of accelerator, superplasticizer, and water/cement (w/c) ratios in order to obtain the highest 7-day compressive strength while minimizing the use of additives. Three 2" x 2" x 2" mortar cubes were cast and cured in a wet box (relative humidity of ~70%) for 2 hours and then steam-cured at ~60°C for 4 hours. The cubes were demolded and returned to the wet box for further curing to 7 days. A summary of the mix design formulations and 7-day compressive strengths is presented in Table 2. The highest 7-day compressive strength for the expanded slag specimens was 2806 psi, which is 83% of the highest compressive strength obtained for the expanded clay (control) samples. Visual inspection of the crushed slag-based cubes revealed that the cement/aggregate interface was sound and that failure was chiefly due to aggregate breakage. This was confirmed by the specimens containing 50/50 slag/clay. The unit weight of the 100% expanded slag specimens ranged between 91 and 98 lb/ft³, that of the 50/50 specimens was between 102 and 105 lb/ft³, and that of the 100% clay control specimens was between 91 and 101 lb/ft³. These test results helped identify the final batch of laboratory tests which are described further in this section.

Table 2. Formulations and 7-Day Compressive Strength of Roof Tile Samples

Aggregate Type	CaCl ₂ •H ₂ O*	Super-plasticizer*	Mortar Unit Wt (lb/ft ³)	Water/Cement	SSD, %	Strength psi
Expanded slag	2	5	92.3	0.29	18.0	934
Expanded slag	2	2	93.3	0.35	18.5	2806
Expanded slag	2	1.5	98.3	0.38	17.4	2650
Control**	2	2	105.2	0.50	17	3106
50/50 slag/clay	2	1.5	105.2	0.35	26	2303
50/50 slag/clay	2	1.5	101.9	0.38	26	1917
50/50 slag/clay	2	1.5	101.8	0.41	26	1736

* As wt% of cement

** Expanded clay aggregate produced during pilot plant run.

Another batch of tests was run to measure 28-day compressive strength. In these tests, a total of six different aggregates were used: an aggregate supplied by Monier, a lightweight roof tile manufacturer, expanded slag, 50/50 slag/clay, 80/20 slag/clay, expanded clay from the pilot test program, and an expanded clay aggregate sample from Big River Industries, Inc., a leading manufacturer of LWA. The commercial samples and the expanded clay produced during the pilot run were used as controls for purposes of comparison. The aggregates were first immersed in deionized water and allowed to soak for 4-6 hours. After soaking, the standing water was decanted and the aggregates were allowed to dry in ambient air until they were in a saturated surface dry condition, as defined by ASTM. The moisture content of the aggregates was measured by weighing a sample of the aggregate before and after drying in a 105°F oven overnight.

The basic mix design included the use of 1.5 ml of Mighty 150 superplasticizer per 100 gm of cement, 2wt% CaCl₂•2H₂O (relative to the amount of cement used), and just enough water to create a mix with a slump of 0-1. The aggregate/cement ratio was kept constant at 2.5 by weight. A common type I cement manufactured by Medusa Cement was used. The amounts of superplasticizer and accelerator were fixed while the water/cement ratio (w/c) was varied, depending on the aggregate used, until the desired slump was achieved. All mixing was done according to ASTM C 305 for mortars. Initial evaluation batches using different w/c ratios were prepared and their 7-day compressive strength was measured. Based on these results, two final mix designs for each aggregate were selected. Six 2" x 2" x 2" specimen cubes of each mix design were cast. During molding, care was taken to ensure that the mixtures were well compacted. After mixing, the molds were placed in a covered wet bucket at room temperature for four hours, after which the specimens had sufficient strength to be demolded. They were then placed in a stainless steel tray with holes in the bottom, which was in turn placed in an unsealed plastic bag. The whole assembly was placed in a steam bath with a steam temperature of 60°C. The plastic bag prevented any hot water from dripping onto the cubes and eroding the samples. Since the bag was not sealed, there was no possibility of hydrothermal reactions. The cubes were steamed for four hours, then removed from the steam bath and further cured at room temperature in a covered wet box. Three cubes of each mix design were tested at 7 days and 28 days for compressive strength to failure according to ASTM C 109. Prior to testing, each cube was weighed and the average weight was used to calculate the

unit weight. The mix design, average unit weights, and average compressive strengths are given in Table 3.

Table 3. 28-Day Compressive Strength Results for Roof Tile Application

Aggregate	W/C	SSD, %	28-Day Compressive Strength, psi	Unit Weight lb/ft ³
Monier sample (control)	0.45	16.8	4789	102.2
Expanded slag	0.35	24.6	2823	94.5
50/50 slag/clay	0.35	19.6	2808	97.4
80/20 slag/clay	0.38	19.6	2940	99.7
Expanded clay (control)	0.65	19.0	3066	87.1
Big River clay (control)	0.40	15.1	7292	115.6

Superplasticizer: 1.5 ml/100 g cement (Mighty 150)
 Accelerator: 2% by weight (CaCl₂·2H₂O)
 Aggregate-to-cement ratio (by weight): 2.5
 Water-to-cement ratio: to obtain 0-1 slump

These experiments showed that the mechanical behavior of the samples is greatly affected by the water/cement ratio but not by the type of accelerators used. Typically, in cement systems, lowering the water/cement ratio improves strength if care is taken to keep the mix workable. However, in the case of the expanded slags, the water/cement ratio had to be kept relatively high (>0.35) in order to have the cement paste coat all the particles and keep the structure together.

4.4 Laboratory Evaluation of SLA for Loose Fill Insulation Application

Expanded slag produced using the fluidized bed expanded was screened according to ASTM C 549 for use as loose fill insulation. The SLA sample had a unit weight of 29 lb/ft³ and a thermal resistance of 1.46 hr-ft²-°F/Btu. This is higher than the value of 2.4 hr-ft²-°F/Btu for the 11 lb/ft³ unit weight perlite, as shown in Table 4. However, expanded slag is much easier to work with due to its significantly lower degradation characteristics and may also be easier to apply.

Table 4. Thermal Conductivity and Thermal Resistance for Loose Fill Insulation

Material Type	Unit Weight lb/ft ³	Temperature	Thermal Conductivity		Thermal Resistance
		°C	W/m-K	Btu-in/hr-ft ² -°F	hr-ft ² -°F-Btu
Expanded slag	29	25	0.093	0.645	1.46
Perlite	7.4-11	24	-	-	2.6-2.4

4.5 Laboratory Evaluation for SLA Insulating Concrete Application

In order to evaluate expanded slag as an aggregate in insulating concrete, specimens were made for testing of compressive strength and thermal properties. Two-inch specimen cubes were prepared using 3/8" x 0 expanded slag with a unit weight of 26 lb/ft³ for compressive strength testing, and a 12" x 12" x 1" slab was prepared to test insulation properties. The following mix proportions for insulating concrete were used, as recommended by the Perlite Institute:

Type I cement:	800 g
3/8" x 0 expanded slag:	4 times cement by volume
Water:	640 g
Air-entraining agent:	8.3 g
10 mm polypropylene fibers:	8 g

These samples were mixed according to ASTM C 109 and cured in a 98% relative humidity chamber set at 25°C. After 7 days, the cubes were removed for compressive testing. The highest 7-day compressive strength achieved was 1750 psi at a unit weight of 51 lb/ft³. The typical thermal conductivity of perlite (Group I) is 0.45-1.5 Btu-in/hr-ft²-°F, and that of shale-based aggregates (Group II) is 1.5-3.0 Btu-in/hr-ft²-°F. As may be seen in Table 5, the thermal conductivity of the SLA concrete at 0.984 Btu-in/hr-ft²-°F is much lower (i.e., better) than that of Group II shale aggregates and falls within the Group I range.

Table 5. Apparent Thermal Conductivity and Thermal Resistance of SLA Test Specimens

Material	Concrete Unit Wt lb/ft ³	Thermal Conductivity*		Thermal Resistance
		W/m-K	Btu-in/hr-ft ² -°F	hr-ft ² -°F/Btu
SLA, 26 lb/ft ³	45.1	0.142	0.984	0.93
Perlite	15-50	0.065-0.22	0.45-1.5	-
Shale	50-90	0.22-0.43	1.5-3.0	-

The SLA tests were conducted at 25°C whereas the reference data are at 24°C.

4.6 Conclusions and Recommendations

The following preliminary conclusions are based on laboratory-scale tests conducted for various applications:

- ▶ The 7-day compressive strength of roof tile concrete made from SLA (2800 psi) was close to the value obtained for the control sample (3390 psi) especially when adjusted for the lower unit weight of the SLA vs. the control sample (93.3 lb/ft³ vs. 105 lb/ft³). However, both of these strengths are lower than expected values. Tests were repeated to obtain 28-day compressive strength values. Methods of improving product compressive strength are being investigated.
- ▶ The 7-day and 28-day compressive strengths for the insulating concrete specimens were 175 psi and 230 psi respectively at a unit weight of 51 lb/ft³. Testing of their insulating properties is in progress.

5.0 PLAN FOR THE NEXT QUARTER

The following activities are planned for the next quarter:

- ▶ Complete laboratory evaluation of expanded slag products for structural applications.
- ▶ Evaluate laboratory applications data to select mix designs for commercial testing.
- ▶ Prepare plan for applications testing at the commercial scale.