

**DEVELOPMENT AND DEMONSTRATION OF A PILOT SCALE FACILITY FOR
FABRICATION AND MARKETING OF LIGHTWEIGHT-COAL COMBUSTION
BYPRODUCTS-BASED SUPPORTS AND MINE VENTILATION BLOCKS FOR
UNDERGROUND MINES**

FINAL REPORT

By

Yoginder P. Chugh

**Department of Mining and Mineral Resources Engineering
Southern Illinois University-Carbondale (SIUC)
Carbondale, Illinois 62901-6603**

Prepared for

**United States Department of energy
National Energy Technology Laboratory
626 Cochrans Mill Road, P.O. Box 10940
Pittsburgh, Pennsylvania 15236-0940**

**Project Manager: Mr. Robert Patton
Project Contract No.:DE-FC26-99FT40029**

October, 2002

TABLE OF CONTENTS

List of Graphical Materials	ii
Executive Summary	v
Background and Problem Statement.....	viii
Objectives	viii
Pilot Scale Facility Development.....	1
Characteristics of Proposed Facility	2
Quality Assurance/Quality Control Procedures.....	10
Ultra-Lightweight Ventilation Blocks	11
Crib Elements.....	19
Post Elements.....	30
Conclusions.....	34
Recommendations.....	34
References.....	35
Acknowledgements.....	36

List of Figures

Figure 1 Overall Pilot Scale Facility Layout	2
Figure 2 Plan View, Fly-Lite Inc., at Full Production	2
Figure 3 Silos for Storage of Fly Ash and Binders.....	3
Figure 4 Ribbon Mixer	4
Figure 5 Dry Mixer with Screw Conveyors at Fly-Lite, Inc.	4
Figure 6 Typical Pug Mill.....	5
Figure 7 Wet Mixer, Fly-Lite, Inc.	5
Figure 8 Wet Mixer Operation, Fly-Lite, Inc.	6
Figure 9 Welded Block Mold	6
Figure 10 Support Cast into Disposable Mold.....	7
Figure 11 Mold Rack.....	8
Figure 12 Fork-Lift Truck Operation Putting Molds in Curing Chamber.....	8
Figure 13 Curing Chambers at Fly-Lite, Inc.....	9
Figure 14 Packaging Wrapper and Turntable for Stretch Wrapping.....	9
Figure 15 Programmable Control Systems for Pilot Scale Facility.....	10
Figure 16 A Typical Stress-Strain Curve of a Block.....	14
Figure 17 One-Day Water Immersion	15
Figure 18 Four-Day Water Immersion	15
Figure 19 Eight-Day Water Immersion	16
Figure 20 Sixteen-Day Water Immersion.....	16
Figure 21 Sixty-Day Water Immersion.....	16
Figure 22 Sixty-Day Water Immersion, Block #2.....	17
Figure 23 Compressive Strength/Density Relationship.....	20
Figure 24 Elastic Modulus/Density Relationship	20
Figure 25 Large Size Hot Water Curing Tanks for Crib and Post Elements.....	20
Figure 26 Load-Deformation Characteristics of 2 x 2 Cribs (Chugh et al, 1997).....	21
Figure 27 Typical Crib and Post Installation in a Mine.....	22
Figure 28 Layout for Field Demonstration #1	22
Figure 29 Crib Performance.....	22
Figure 30 Layout of Field Demonstration #2	23

Figure 31 Crib Performance Data	23
Figure 32 Geometry of the Designed Crib Element	25
Figure 33 A Cured Crib Element	25
Figure 34 Stress-Strain Data for 2-Foot High Wooden and CCBs-Based Cribs	26
Figure 35 Minimum Principal Stress Distribution in a Prismatic Element Crib	27
Figure 36 Minimum Principal Stress Distribution when the crib was failed at maximum 93 tons load (Diagonal Cut View)	28
Figure 37 Prototype Second Generation Crib Element in the Test Frame	29
Figure 38 Typical Load-Deformation Curve for a CUB-Based Crib	29
Figure 39 Installed Cribs at Mine #1 and Mine #2	30
Figure 40 Load-Deformation Characteristics of Wood and CCBs-Based Posts	31
Figure 41 Performance of Full-Size CCBs-Based Post into Disposable Molds	32
Figure 42 Load-Deformation Data for Composite Post-With and Without Axial Reinforcement	33
Figure 43 Field Demonstration of Composite Posts in a Central Illinois Coal Mine	34

List of Tables

Table 1 Available Data on Oxides Composition of FBC Fly Ash from SIU Power Plant	11
Table 2 Proposed QA/QC Limits on Process Variables, LOI, and Calcium Oxide ..	11
Table 3 Flexural Strength Test Results	18
Table 4 Engineering Properties of Developed Mixes	26
Table 5 Engineering Properties of Crib Elements	27
Table 6 Summary Test Data for CCBs-Based Cribs	28
Table 7 Comparison of Wood and CCBs-Based Posts	32

ABSTRACT

The overall goal of this program was to develop a pilot scale facility, and design, fabricate, and market CCBs-based lightweight blocks for mine ventilation control devices, and engineered crib elements and posts for use as artificial supports in underground mines to replace similar wooden elements. This specific project was undertaken to 1) design a pilot scale facility to develop and demonstrate commercial production techniques, and 2) provide technical and marketing support to Fly Lite, Inc to operate the pilot scale facility. Fly Lite, Inc is a joint venture company of the three industrial cooperators who were involved in research into the development of CCBs-based structural materials. The Fly-Lite pilot scale facility is located in McLeansboro, Illinois.

Lightweight blocks for use in ventilation stoppings in underground mines have been successfully produced and marketed by the pilot-scale facility. To date, over 16,000 lightweight blocks (30-40 pcf) have been sold to the mining industry. Additionally, a smaller width (6-inch) full-density block was developed in August-September 2002 at the request of a mining company. An application has been submitted to Mine Safety and Health Administration for the developed block approval for use in mines.

Commercialization of cribs and posts has also been accomplished. Two generations of cribs have been developed and demonstrated in the field. MSHA designated them suitable for use in mines. To date, over 2,000 crib elements have been sold to mines in Illinois. Two generations of posts were also demonstrated in the field and designated as suitable for use in mines by MSHA. Negotiations are currently underway with a mine in Illinois to market about 1,000 posts per year based on a field demonstration in their mine.

It is estimated that 4-5 million tons CCBs (F-fly ash or FBC fly ash) may be utilized if the developed products can be commercially implemented in U.S. coal and non-coal mines.

EXECUTIVE SUMMARY

The overall goal of this program was to develop, design, fabricate, and market CCBs-based lightweight blocks for mine ventilation control devices, and engineered crib elements and posts for use as artificial supports in underground mines. This specific project was undertaken to 1) design a pilot scale facility to develop and demonstrate commercial production techniques, and 2) provide technical and marketing support to Fly Lite, Inc to operate the pilot scale facility. This report summarizes all the work completed to date since project inception on September 30, 1999, until its termination on September 30, 2002.

Three industrial cooperators involved in the development of CCBs-based structural materials, Webb Oil Co., Eagle Seal, Inc., and Woodruff Supply Co., formed a joint venture, Fly-Lite, Inc. The pilot scale facility is located in McLeansboro, Illinois, immediately adjacent to the Webb Oil/Eagle Seal complex. It is designed to produce CCBs-based post and crib elements as well as CCBs-based mine ventilation blocks, developed at SIUC. Construction of the facility began in December 1998, and limited production of mine ventilation blocks began in April 2000. The facility was to start with production capacity of about 20 tons per day (tpd) of dry material, increasing it to about 100 tpd peak capacity.

Experience accumulated over the three years (1996-1999) during the fabrication of laboratory and prototype supports in previously funded projects was utilized to design the 100-tons/day pilot-scale facility. The facility was designed to process CCBs in a continuous operation at the lowest possible cost. A highly automated manufacturing process was designed which requires a minimum of manpower. The only labor required, other than maintenance, is for mold preparation, curing operations and storage of the finished supports. Manufacturing processes necessary for pilot scale facility include: 1) dry bulk materials handling system, 2) dry-mixing facilities, 3) wet-mixing facilities, 4) mold filling/ handling system, 5) mold preparation and curing facilities, and 6) inventory and packaging facilities.

A spreadsheet program (Microsoft Excel) was used to evaluate the economic feasibility of manufacturing products. A minimum after-tax rate of return of 23% can be achieved for a debt to equity ratio of zero and that, for a debt to equity ratio of 70%, an after tax rate of return of over 40% should be possible. These rates of return are most sensitive to labor cost, production rate and energy cost.

Mine Ventilation Blocks Production

Ultra-lightweight blocks were the first to be developed and produced from the pilot scale facility. It was decided to produce 8 in. x 12 in. x 16 in. blocks with density of 30-40 pcf. These blocks were made from FBC fly ash from SIUC new power plant and contained over 85% fly ash. Each block weighed 35-40 lbs. The marketable blocks were tested for strength and fire resistance. The Mine Safety and Health Administration (MSHA) found the produced blocks suitable for use in mines. The first shipment of ventilation blocks

was made on April 7, 2000. Over 10,000 blocks were sold during the period April 2000 to November 2001. Customers asked to develop data on durability of Fly-Lite blocks in water up to 60 days. The blocks actually gained strength rather than losing strength. The maximum strength gain recorded was about 100%, from about 150 psi to about 300 psi.

Around November 2000, due to malfunctioning of the FBC fly ash collection system, the quality of the fly ash supplied became very poor. The developed mix designs for ventilation blocks did not provide good quality blocks. The fly ash contained significant amounts of coarser spent bed ash that was difficult to entrain air and had very poor cementitious characteristics. About 50 different alternate mixes, and about five alternate curing cycles were attempted to utilize the poorer quality fly ash in fabrication of blocks. The results of these studies provided two mix designs that could lead to good quality lightweight blocks. The mix designs utilized over 90% FBC ash with a slightly different curing cycle than was previously being practiced. These mix designs, however, provided slightly heavier blocks (40 pcf) than were being marketed earlier (30 pcf).

Larger size mixes (producing 5-6 blocks at one time) were made at McLeansboro, Illinois, using the alternate mix designs and slightly modified curing cycle. The results were positive. About 6,320 blocks of this type were sold. Since then blocks have not been marketed since there is another product in the market that is competing with our product. Autoclaved fly ash blocks 8 in. x 8 in. x 24 in. are currently marketed to Illinois coalmines. These blocks are manufactured in Atlanta, Georgia and contain 65 % F-fly ash. We believe these blocks are being marketed at or below the manufacturing cost.

Highly variable fly ash quality has been the most significant problem in getting quality product out to the customers. Loss on ignition values are highly variable, from about 8 % to about 18 %. Particle size distribution is also highly variable, which affects air entrainment and curing characteristics.

During the month of August 2002, a full density material (90-95 pcf) was developed since such blocks are being used in large numbers by a coal company. These blocks are 8 in. x 16 in. x 6 in., weigh about 50 pounds and utilize about 90% FBC fly ash by weight. The manufacturing process does not require much air-entrainment. The blocks have been tested for durability in water and performed very well. An application has been submitted to MSHA on September 19, 2002, for their evaluation for suitability in mines. We expect markets for such blocks after MSHA evaluation.

Commercialization of Crib and Post Elements

The CCBs-based materials of 75-105 pcf using F-fly ash were successfully developed for these products and first generation crib and post elements were successfully field demonstrated. However, commercialization of this part of the project was delayed by almost one year since cheap square cross-section, disposable plastic molds (5 in x 5 in for cribs and 6 in x 6 in for posts) proposed for the cribs and posts were not available commercially. Three entrepreneurial companies, one in Kentucky, one in Canada and one in Indiana, expressed interest in fabricating such molds from recycled plastics.

However, business arrangements could not be satisfactorily developed to supply square cross-section disposable molds because: 1) crib elements and post elements had yet not been found suitable for mines by MSHA since we had not fabricated them, and 2) the companies wanted an order of at least 20,000 molds before they would invest monies on dies and extruders, and 3) companies were operating at over 90% of their equipment capacity during 1999-2001.

During July-September 2001, the PI and Fly Lite, Inc. developed two alternate concepts for crib element development using FBC fly ash. These concepts fall in two categories:

- 1) Instead of disposable plastic mold to protect element from breakage, longitudinal steel reinforcement was incorporated within the element. The casting was, however, done in conventional molds, which require demolding.
- 2) Geometry of the crib element was changed to produce lightweight crib element without significant air-entrainment of the mix composition.

Multiple iterations of testing and modifications led to development of crib elements that are commercially viable. Cribs of such elements can carry 90-100 tons of load, are rigid, and allow deformations recommended by MSHA. The mix designs contain 40% fly ash. Based on testing of several cribs in the presence of MSHA, and a review of the data by them, these elements were designated as suitable for use in mines. An important characteristic of these crib elements is that they offer low resistance to air flow. The performance of these elements was demonstrated in two mines; one in Illinois and one in Western Kentucky. To date, over 2,000 crib elements have been sold to coal mines in Illinois and Western Kentucky.

For production of posts, the PI and Fly Lite decided to use a circular post rather than a square post, as envisioned earlier, and used PVC tubing as a disposable mold. North American Pipe Company (NAPCO) of Litchfield, IL agreed to collaborate on this portion of the project. Several 6-foot long and 6-inch diameter posts were cast during the period of November 2001 to March 2002 and tested in a 150-ton machine at the Illinois Coal Development Park facilities to finalize mix designs and curing cycles. These posts were designed to carry 50-ton load with good post-failure characteristics. The mix designs contain over 85% FBC fly ash. The final designs were tested in the presence of MSHA and the data review led to their being found suitable for use in mines. These posts have been demonstrated in two mines; one in Illinois and one in Western Kentucky. At the time of submission of this report, negotiations are underway to market 1,000 posts per year to a coalmine in Illinois.

In summary, the pilot scale facility is operating as designed and planned. Lightweight blocks have been produced and marketed. Crib and post elements have been produced and demonstrated in the field. They have been found suitable for use in mines upon review by MSHA. Crib elements have been marketed. Marketing of posts is currently being negotiated. Quality control and quality assurance procedures have been developed and provided to Fly Lite, Inc. All the goals and specific objectives of the project have been fulfilled.

BACKGROUND AND PROBLEM STATEMENT

The overall goal of this program was to develop, design, fabricate, and market CCBs-based lightweight posts and crib members for use in underground mines, which are manufactured primarily from local sources of F-Type and FBC fly ash. The FBC by-products from the new powering unit at SIUC and F-fly ash from Southern Illinois Power Cooperative (SIPC) were to be used in the manufacturing of ultra-lightweight blocks and artificial supports (cribs and posts). A pilot scale facility was to be designed and constructed, and manufacturing techniques were to be developed. In addition, the performance of the manufactured supports, and blocks were to be monitored in the field after installation to ensure the desired level of performance. Finally, assistance was to be given in the marketing of these products to mines in the tri-state area.

This project was funded to assist Fly-Lite, Inc. in designing and constructing a pilot scale facility, producing marketable products on a pilot scale, and marketing them to area coal mines. SIUC has been providing technical support in the construction of the facility, developing quality assurance and quality control measures, developing adjustments to manufacturing techniques (where required), performing field testing of manufactured products, and providing assistance in marketing the supports and lightweight blocks.

OBJECTIVES

The development of environmentally sound and economically viable technologies for the utilization of conventional coal combustion by-products (fly ash and bottom ash) and flue gas desulfurization by-products (scrubber sludge, FBC residues) is a well-recognized problem for the Illinois high sulfur coal industry. Recognizing the current complexities involved in a multifaceted problem such as this, near-term utilization technologies (1-10 years) should be either high volume-low value, or medium volume-medium value approaches. High volume-low value approaches include back-filling abandoned mines to control subsidence and/or acid mine drainage, surface mine reclamation, or surface management to control acid mine drainage. Medium volume-medium value methods strategies include flowable fills, structural applications, concrete industry uses, and embankment and road construction materials. Furthermore, these technologies should emphasize utilization of fly ash, FBC fly ash and wet scrubber sludge that constitute a majority of CCBs production in Illinois.

Over the past decade considerable research has been done on high volume-low value disposal/utilization technologies (disposal in surface mines, reclamation, and underground disposal). About five years ago, the principal investigator (PI) conceived the following two (2) medium-volume, medium-value utilization technologies:

- 1) Replacement of wooden supports (posts and cribs) in underground mines with similar supports made from CCBs; particularly F-fly ash, and FBC fly ash.
- 2) Development of ultra-lightweight blocks (ULB) for mine ventilation stoppings using high volume FBC fly ash and F-fly ash.

Two advantages of these applications are that CCBs and FGD byproducts can be effectively utilized and then left behind in mines where the materials originated, and CCBs are uniformly distributed over a large area thus minimizing potential for negative environmental impacts. Wood prices have been steadily increasing over the past few years and are expected to increase at an even greater rate in the future. Wood can be supplied only seasonally while CCB-based materials could be supplied throughout the year (Yu, 1987). Furthermore, since the artificial supports are spatially distributed over a large area, the potential for negative environmental impacts is virtually non-existent. Additionally, the depletion of forests (and its associated ecological impacts) to provide about $100 \times 10^6 \text{ ft}^3$ of wood required by U.S. coal mines can be avoided. One of the problems with this application concept is that inorganic cement-based products are typically heavier (140-150 pcf) than wood (40-50 pcf) and therefore will not be received favorably by industry without modification (Biron and Arioglu, 1983).

Ultra-lightweight blocks, currently available in the market, have low strength (<100 psi) and high deformability (<8000 psi elastic modulus). If these blocks can be made with high-volume fly ash, the potential exists to utilize additional fly ash in such an application.

Over the past 60 months or so, under contracts from the U.S. Department of Energy and Illinois Clean Coal Institute, the PI developed, characterized, and demonstrated in mines posts and crib members fabricated from lightweight CCBs-based structural materials (Chugh et al., 1996). These materials were initially developed using fly ash from the Gibson Power Plant of CINERGY located in Indiana across the Wabash River near Mt. Carmel, Illinois. The developed materials and artificial supports received positive responses from coal industries and commercial potential (Chugh et al., 1997). Later similar materials were developed using FBC fly ash from Southern Illinois University FBC power plant.

PILOT SCALE FACILITY DEVELOPMENT

Location

The Gibson Power Plant was initially selected for supplying fly ash since it was centrally located in relation to the Illinois Basin coal industry and because about 50% of the coal it was burning was supplied by Wabash mine, located just south of Mt. Carmel, Illinois. Although management at the Gibson plant was enthusiastic about siting the pilot scale facility at their location, the power plant had severely curtailed the use of coal from Wabash mine and received most of its coal from mines located in Indiana. The State, therefore, recommended that the PI consider siting the pilot scale commercial facility within the state of Illinois.

The Lake-of-Egypt Power Plant of Southern Illinois Power Cooperative (SIPC) was considered as a possible siting location in 1997. Initial laboratory results indicated the possibility of developing lightweight structural materials from SIPC fly ash. However, the high amount of unburned carbon ($> 10\%$), and high amount of iron oxides present in SIPC fly ash required large amounts of foam to reduce material densities to the target levels. Therefore, fly ash from AmerenCIPS Grand Tower Power Plant (GT) was tested and used in the development of mixes in the facilities at Carterville, Illinois. However, this power plant was closed in 1999.

During 1999, the PI also developed high quality ultra-lightweight blocks using about 80% fly ash from the SIUC circulating FBC plant. The developed blocks had superior characteristics than similar blocks currently available on the market and could be produced at a competitive price. Three industrial cooperators, Webb Oil, Woodruff Supply, and Eagle Seal formed a joint venture to create Fly Lite, Inc. The Fly Lite management decided to locate the pilot scale facility in McLeansboro, Illinois, since it will be central to the tri-state area mines.

Experience accumulated during the fabrication of laboratory and prototype supports in previous projects was utilized in designing the pilot-scale facility for production of CCBs-based products and mine supports. This facility was designed to process large volumes of fly ash in a continuous operation, producing products of high quality. Toward this end, a highly automated manufacturing process was designed which would require a minimum of manpower to operate. The only labor required for manufacturing the supports, other than maintenance, would be for mold preparation, curing operations and stockpiling of the finished supports. The overall facility layout is shown in Figures 1 and 2.

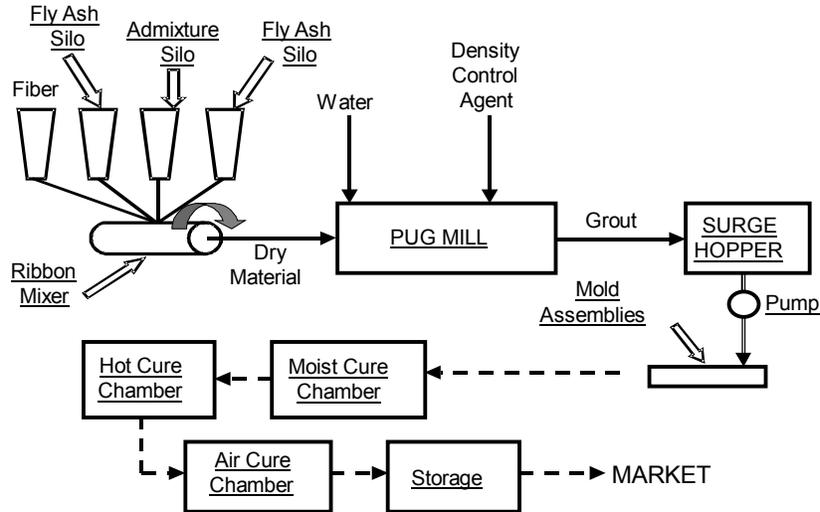


Figure 1: Overall Pilot Scale Facility Layout

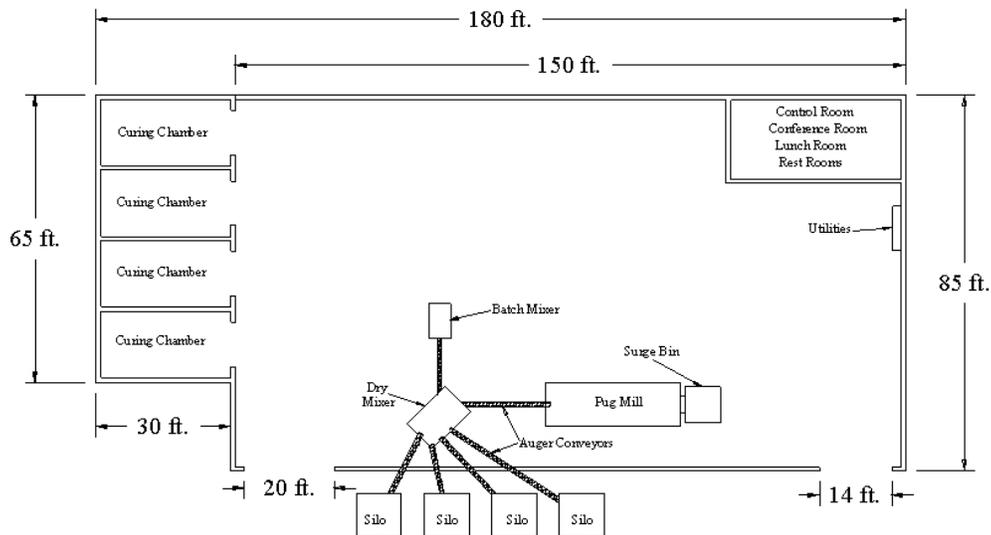


Figure 2: Plan View, Fly-Lite Inc., at Full Production

Facility and Components: Manufacturing processes necessary for producing CCBs-based artificial supports on a pilot scale include: 1) dry bulk materials handling system, 2) dry mixing facilities, 3) wet mixing facilities, 4) mold filling/handling system, 5) mold preparation and curing facilities, and 6) inventory and packaging facilities. A computerized system is utilized where programmable linear controllers (PLCs) are adjusted to establish the mix parameters for each product.

Dry Bulk Materials Handling

Fly ash is a very fine pozzolonic material with mean particle size of about 20 microns. When dry it flows well, but it also becomes airborne easily. These characteristics

indicated that the most practical option for bulk handling of this material should be an enclosed screw, or auger conveyor powered by an electric motor. A closed-conveyor system of this type can be readily programmed to produce dry mixes of differing percentages of fly ash and binders.

Steel silos designed for the storage and dispensing of fine dry bulk materials, shown in Figure 3, are the least-cost alternative for bulk storage of fly ash and binding agent(s). These silos are readily available, along with equipment designed for loading and unloading. In addition, pneumatic tanker trucks, as well as electric and pneumatic-flow vibrators for uninterrupted material flow are also available. The silos, installed at a height sufficient to provide a shallow conveyor angle (10-15°), discharge into a PLC-controlled conveyor leading to a dry bulk mixer. Capacity of the silos is around 100 tons each.

The design of the screw conveyors was determined from the Conveyor Equipment Manufacturers Association (CEMA) Screw Conveyors book. This manual provides for screw conveyor design parameters based on the type of material to be conveyed and takes into account material size, flowability, abrasiveness, and other miscellaneous properties. Designing the conveyors to deliver 17 tph of material should allow for capacity processing peak of 100 tons of dry material in 6 hours. This should allow sufficient time for cleanup of the facilities as well as any minor interruptions to production. Utilizing one screw conveyor size will simplify parts inventory and minimize conveyor downtime through parts interchangeability. A 12-inch diameter screw conveyor turning at 70 RPM was required for conveying fly ash at 17 tph. Five (5) HP variable speed motors were required for operating the conveyors.



Figure 3: Silos for Storage of Fly Ash and Binders

Dry Mixing Facilities

In general, most fly ashes blend easily and binders also seem to blend well with any fly ash. Laboratory experience indicated that premixing the dry constituents would greatly reduce the wet mixing time required to produce a homogeneous grout. For a high capacity system, a high-agitation continuous mixer, such as the ribbon mixer illustrated in Figure 4, was utilized to thoroughly blend all dry mix constituents before discharging it into another screw conveyor leading to the wet mixer. The capacity and mixing speed of

the dry mixer should be indexed to the throughput capacity of the final mixer at 17 tph. Figure 5 shows the dry mixer installed at the facility.

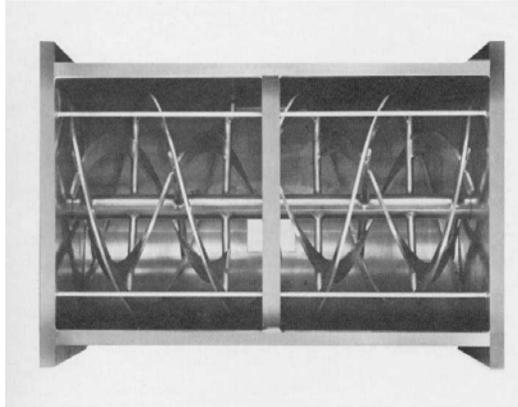


Figure 4: Ribbon Mixer



Figure 5: Dry Mixer with Screw Conveyors at Fly-Lite, Inc.

Wet Mixing Facilities

Having utilized different types of mixers in the fabrication of CCBs-based materials in the laboratory and consulting with contractors and manufacturers, it was determined that some type of high-capacity, in-line, high-shear mixer would be required to properly mix the large volumes of relatively dry mixes required in the manufacturing of CCBs-based supports. A pug mill, illustrated in Figure 6, is a high-volume, high-shear, continuous mixer, designed to thoroughly mix large volumes of low-moisture content materials and should be ideal for such an application.

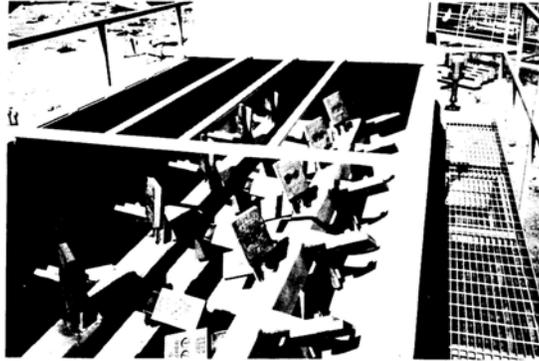


Figure 6: Typical Pug Mill

The shearing action in a pug mill is provided by the interaction of mixing paddles attached to parallel shafts. The pitch of the mixing paddles, shaft speed, and mixer volume all play a role in determining residence time and output rate of the grout mix. Adjustments to optimize the mixing process can be performed by changing the paddle angle and/or shaft speeds. The capacity and mixing speed of the pug mill should be matched to the throughput capacity of the dry mixer at 17 tons per hour. Figure 7 shows the wet mixer installed at Fly Lite. Figure 8 shows the wet-mixer in operation.

A precise flow of water is introduced uniformly, across the width of the mixer, onto the dry mix, shortly after it is introduced into the pug mill at a ratio of about 30% to 35% by weight for F-fly ash and about 50% by weight for the FBC fly ash. If utilizing foam as a density control agent, it will be introduced further down the length of the mixer, approximately $\frac{1}{2}$ to $\frac{3}{4}$ of the way upstream in the direction of the mix. The optimal time for foam introduction into the wet mixer was later determined to be after wet mixing had been completed. Several experiments were conducted to determine if preconditioning of FBC fly ash was needed to develop good quality products and it was deemed unnecessary.



Figure 7: Wet Mixer, Fly-Lite, Inc.



Figure 8: Wet Mixer Operation, Fly-Lite, Inc.

Mold Design

Producing large volumes of CCBs-based materials necessitates that provisions be made to handle large quantities of prefabricated molds (1050 post molds, 5400 crib molds, and 500 block molds per day). One of the goals in the design of the pilot scale facility was to try to produce a product utilizing a minimum of labor. Some amount of labor will be expended on mold preparation and loading and unloading the mold racks, and additional labor will be required to prepare the finished product for marketing. Three molding options were explored: permanent molds, disposable molds, and bulk casting.

Using permanent molds in the production of large numbers of CCBs-based supports would be very labor intensive. This is because permanent molds would require preparation and manual demolding of the cured supports. Additional manpower would then be required to prepare the loose support members for storage and shipping. In addition, a certain number of molds would require replacement yearly, adding to the cost of operations. Figure 9 shows a permanent welded block mold used for mine ventilation blocks.

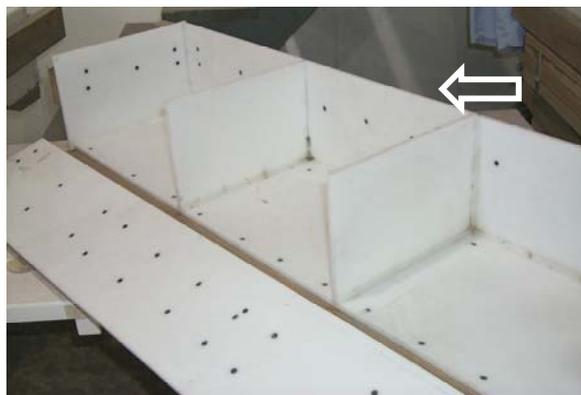


Figure 9: Welded Block Mold

Casting the grout into large slabs and cutting the cured material to the desired shape(s) was also investigated. This approach was eventually abandoned due to concerns about the amount of dust that would be generated by sawing operations, and the expense of

purchasing a saw mill, converting it to handling large, heavy slabs of CCBs-based materials and providing the labor to operate it.

Utilizing disposable molds (casting grout in a plastic pipe or mold), illustrated in Figure 10, in the manufacturing of structural supports was viewed as the least-cost method of production, minimizing the number of man-hours spent preparing the racks and molds. Additional benefits to utilizing disposable molds, illustrated in the manufacturing process are the elimination of the humidity chamber in the curing cycle as well as reinforcing fibers, and the superior performance characteristics of supports cast into disposable molds. Because the sheath surrounding the grout prevents the movement of water between the CCBs-based material and the surrounding air, all of the moisture present in the mix is available for the curing cycle. A sufficient number of temperature-controlled chambers are all that will be required for curing operations. Ventilation blocks will still require the use of permanent molds, however.

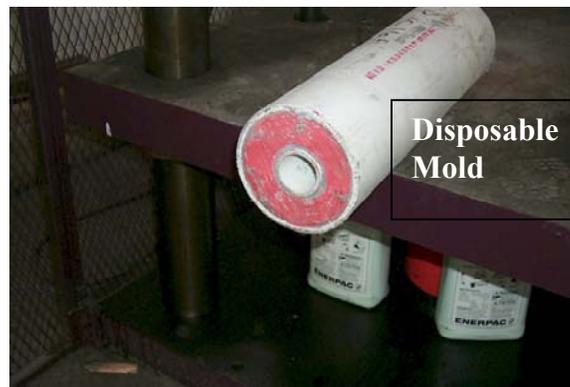


Figure 10: Support Cast into Disposable Mold

Mold Filling/Handling System

Molding operations consist of preparing the molds, filling them with grout, and transporting them to the required location within the plant for curing. The mixed grout exiting the pug mill will flow into a surge hopper equipped with a slow-speed paddle mixer and pumps. The pitch of the slow-speed mixer blades should be adjusted to push the grout mix to the bottom of the bin, where the grout pump inlets will be located. The wet grout will then be pumped into molds, located in large racks, by use of a piping system utilizing multiple nozzles. Designing and optimizing such a system will require substantial field engineering and the design of the rack and nozzle system will be unique to a particular product.

For reliable plant operation, a robust pump assembly must be utilized for molding operations in a manufacturing facility. An extrusion pump or concrete pump should be utilized for this task in the pilot scale facility to ensure reliability. Other less expensive options were also investigated for use in advanced plant designs to help minimize capital expenditures.

To provide maximum process flexibility, mold racks were designed (Figure 11) for transportation in multiples, utilizing a forklift. Such a system should result in a shorter product-changeover time and greater control over the mold handling process. This will require a piping and nozzle arrangement that can be set up for different products with a minimum of time and difficulty. A forklift operation of handling multiple molds is shown in Figure 12.



Figure 11: Mold Rack



Figure 12: Fork-Lift Truck Operation Putting Filled Molds in Curing Chamber

Mold Preparation and Curing Facilities

Preparation of the disposable molds would require trimming the tubing to the required length and capping one end. After the molds have been filled with grout, the open ends will be capped and the filled molds placed in the curing chambers. A 100% relative humidity environment will not be required because the wet grout will not be exposed to the air. Curing chambers at Fly Lite are shown in Figure 13.



Figure 13: Curing Chambers at Fly-Lite, Inc.

Inventory and Packaging Facilities

After removing the cured supports from the handling racks, they must be prepared for shipment before they are placed in inventory. The number of support members to be bundled for shipping should be limited to about 800 pounds per shipping unit. The bundled supports are believed to have an infinite shelf life; specimens cast in permanent molds remained outdoors, uncovered, for an entire winter before they were taken below for a field demonstration of the technology and for much of that time they were covered in ice and snow. Metal banding of the support members and plastic shrink-wrap for the ventilation blocks should prove sufficient for bundling the supports into pallets for shipping. The turntable being utilized for applying the shrink-wrap to the palletized ventilation blocks is shown in Figure 14.



Figure 14: Packaging Wrapper and Turntable for Stretch Wrapping

Figure 15 shows the computer-controlled auger conveying system from the bulk materials silos. This system serves as the input to the dry mixer, shown in Figure 5. After the dry mix constituents have been thoroughly blended, the “dry mix” is conveyed to one of two wet mixers, where precise amounts of water and foam are added to the mix to control product density and water/powder ratio. Figures 7 and 8 illustrate the wet mixers at Fly-Lite. The foam discharge nozzle can be seen in the upper left. Also shown in Figure 7 is the mold filling operation. Fly-Lite management has been pursuing suitable designs for more efficiently filling and handling the large number of molds necessary for large quantity production. A double-diaphragm pump (blue) of the type used for emptying the mixers into the molds currently in use is seen in Figure 7.

Propane-fueled fork-trucks, shown in Figure 12, are utilized for mold and product handling operations.



Figure 15: Programmable Control Systems for Pilot Scale Facility

After curing, the blocks are removed from the molds and placed on pallets for shipping. For ease of handling and product durability, the stacked blocks are packaged in commercial, plastic shrink-wrap. This method results in durable, easy to handle pallets that are ready for shipment. The wrapper and turntable used for packaging operations is shown in Figure 14.

QUALITY ASSURANCE/QUALITY CONTROL PROCEDURES

Before marketing the ventilation blocks, composite crib elements, and composite posts to the mining industry, the Mine Safety and Health Administration (MSHA) asked that quality assurance/quality control (QA/QC) procedures be developed for fabricating all three products at Fly-Lite. The following lists the mix constituents and manufacturing tolerances as well as the acceptable variance in the raw materials makeup of the product.

Quality Control of Ingredients

Ventilation Blocks:

There are three (3) main ingredients in the fabrication of the fly ash-based mine ventilation blocks, whose quality should be controlled: 1) fluidized bed combustion (FBC) fly ash, 2) cement, and 3) synthetic fibers. All three are important to get a good quality product.

The performance of the fabricated blocks depends primarily on the following process factors: 1) percentage of fly ash, fibers and cement by weight in the dry mix, 2) water to dry powder ratio, 3) thoroughness of mixing the dry ingredients with water, 4) casting density, and 5) curing cycle and curing times. Of these, items 2, 4, and 5 are the most critical.

The manufacturing process will utilize ordinary Portland (Type I) cement and lime and the supplier will provide a chemical composition data sheet for the material. The quality of the fly ash, with respect to the loss on ignition (LOI) or unburned carbon, is most variable during the boiler start-up and shutdown periods. Therefore, the FBC fly ash will be collected during periods of relatively constant, normal loads. The operator of the FBC unit, Southern Illinois University, Carbondale (SIUC), maintains logs of the start-up, shutdowns, and plant loads to help ensure that quality fly ash is being supplied to Fly-Lite. Table 1 shows oxides composition for SIUC FBC fly ash.

Relatively consistent quality blocks can be produced by adequately controlling the amount of loss on ignition and calcium oxide present in the fly ash (Wei, Naik, and Golden, 1994). Table 2 shows the limits proposed for these compounds in the fly ash as well as the maximum water/powder ratio and minimum as-cast density. The fly ash to cement ratio has a minor effect on overall density.

Table 1 – Available Data on Oxides Composition of FBC Fly Ash from SIUC Power Plant

	7/21/99	11/24/99	12/7/99	1998 (Date unknown)
SiO ₂	31.3%	35.8%	33.9%	36.1%
AlO ₃	10.6	13.3	12.2	13.9
Fe ₂ O ₃	8.3	11.8	10.9	11.1
Na ₂ O	0.4	0.6	0.4	0.6
MgO	0.4	0.4	0.4	0.4
SO ₃	12.8	6.8	7.8	8.2
K ₂ O	1.1	1.5	1.4	1.4
Mn ₂ O ₃	0.1	0.1	0.1	0.1
P ₂ O ₅	0.10	0.09	0.11	0.10
TiO ₂	.24	.43	.39	.40
CaO	20.9	19.1	16.3	18.0
Loss on Ignition	14.7	10.3	12.1	9.8

Table 2 – Proposed QA/QC Limits on Process Variables, LOI, and Calcium Oxide

Item	Limit
LOI	<15%
CaO	>15%
Water to Dry Powder Ratio	<38%
Cast Density	>35 lb/ft ³

Composite Crib Elements:

There are six (6) main ingredients in the fabrication of the fly ash-based mine composite crib elements, whose quality should be controlled: 1) Fluidized bed combustion (FBC) fly ash, 2) cement, 3) synthetic fibers, 4) sand, 5) gravel, and 6) geometry of placed reinforcement. All six are important to get a good quality product.

The performance of the composite crib elements depends primarily on the following process factors: 1) percentage of fly ash, sand, gravel, fibers and cement by weight in the dry mix, 2) water to dry powder ratio, 3) thorough mixing of the dry ingredients with water, 4) reinforcement geometry, 5) casting density, and 6) curing cycle and curing times. Of these, items 2, 4, and 6 are the most critical.

As is the case with the fabricated ventilation blocks, the manufacturing process will utilize ordinary Portland (Type I) cement and fly ash. Sand and gravel from a local supplier to a Ready-Mix plant will be utilized. Any change in supplies must be documented with testing of the product quality.

Composite Posts:

There are six (6) main ingredients in the fabrication of the fly ash-based mine composite posts, whose quality should be controlled: 1) fluidized bed combustion (FBC) fly ash, 2) cement, 3) 6 – inch diameter PVC Schedule 40 pipe, and 4) reinforcement, if desired. All four are important to get a good quality product. QA/QC controls for ventilation blocks and cribs also apply here.

The performance of the composite posts depends primarily on the following process factors: 1) percentage of fly ash, and cement by weight in the dry mix, 2) water to dry powder ratio, 3) thorough mixing of the dry ingredients with water, 4) reinforcement (if desired), 5) casting density, and 6) curing cycle and curing times. Of these, items 1, 3, and 5 are the most critical.

Quality Control of the Composite Element Fabrication Process

Almost all of the fabrication process has been computerized to minimize human error and ensure quality blocks. More specifically, the plant and fabrication process has the following controls.

- 1) All ingredient feeds into the dry mixer(s) are controlled through computer-controlled auger conveyors.
- 2) Dry ingredient mixing time is computer controlled.
- 3) Mixing water temperature and mixing water weight is controlled for batch or continuous mixing.
- 4) Wet mixing time is computer controlled.
- 5) The curing cycle and curing temperature are controlled through a computer.
- 6) Pre-fabricated mold and steel re-enforcement assures consistent size and shape.
- 7) Protective packaging of end product during shipping.

Quality Assurance of the Composite Fabricated Elements

The use of quality ingredients and quality control of the fabrication process should result in a quality product of the required specifications. However, to ensure that the consumer receives the best possible product, quality assurance procedures should be utilized. These include:

- 1) **Cement Quality:** For each batch of supplied cement (20 tons), about five (5) pounds of cement will be sampled. Three (3), two-inch cubes of full-density will be cast as per ASTM (1994) test requirements. The cubes will be cured according to specifications and tested for unconfined compressive strength. The average compressive strength for the three samples should be within 95% of the manufacturer specifications.
- 2) **Cement-Foaming Characteristics:** Three (3), two-inch cubes of cement only will be cast at the required density of the ventilation blocks and cured according to the curing requirements of the blocks. The cured samples will be tested for unconfined compressive strength and the average of the results should be within 10% of the previous batches. This should ensure the quality of the cement, foaming liquid, and the foaming characteristics of the cement.
- 3) **Lime:** Hydrated lime (industrial grade) will be utilized. For each batch of lime supplied, three (3), two-inch cubes of 90% fly ash and 10% lime will be cast. The cubes will be cured according to specifications and tested for unconfined compressive strength. The average compressive strength for the three samples should be within 95% of each other.
- 4) **Fly Ash:** For each batch of supplied fly ash (20 tons), two batches of five (5) pounds will be appropriately sampled. From each batch, three, full-density, 2-inch cubes of fly ash-cement, in the same proportions as specified for the manufactured block, will be cast and cured as indicated in (1) above in this section. The cubes will be tested for unconfined compressive strength and the average values of the batches must be within 90% of each other and previous samples.
- 5) Two samples from each batch will also be tested for LOI. The average LOI values for the two batches must be within two (2) percentage points of each other.
- 6) The tests in (3) above will also be performed at the specified composite element density. The average values for the two batches must be within 90% of each other.
- 7) One of every 200 composite elements produced will be tested for unconfined compressive strength. The compressive strength values for the samples must be within 25% of each other.

ULTRA-LIGHTWEIGHT VENTILATION BLOCKS

Ultra-lightweight blocks were the first to be commercialized. It was decided to produce 8 in. x 12 in. x 16 in. blocks with density of 30-40 pcf based on current products in the

market. The industry wanted blocks weighing no more than 35 lbs. The blocks must be approved for strength and fire resistance before they can be used in mines as ventilation control devices. Mine Safety and Health Administration approved the produced blocks for use in mines. The first shipment of ventilation blocks occurred on April 7, 2000. Over 10,000 blocks were sold during the period April 2000 to November 2001. The blocks had compressive strength of about 150 psi and elastic modulus of over 10,000 psi, which is considered good. A typical stress-strain curve for such block is shown in Figure 16.

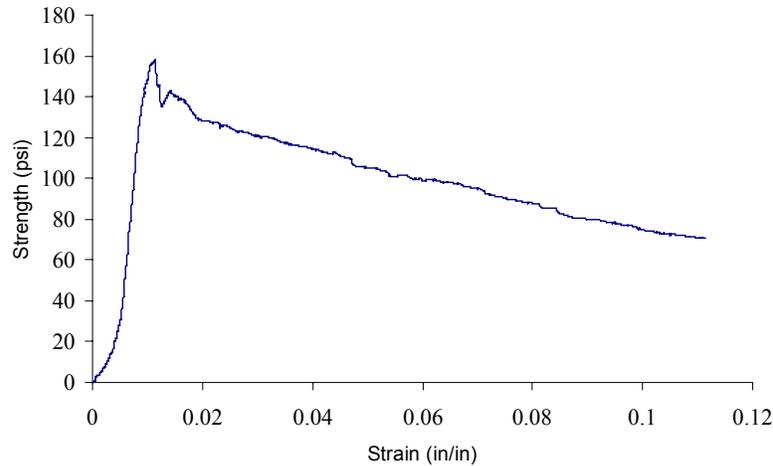


Figure 16: A Typical Stress-Strain Curve of a Block

Mold Modification

Feedback from a customer indicated a problem with the dimensional tolerances of the delivered blocks. A significant number of the blocks were not sufficiently square and were difficult to stack properly. This required additional time to erect the ventilation walls, increasing production costs.

To remedy the situation, the material being used for fabricating the block molds (ultra-high molecular density polyethylene) was welded as well as screwed together as shown in Figure 9. This not only enables more consistent block dimensions, but aids in the removal of the cured product from the mold due to the radius added to the inside corners of the mold. Blocks produced in these molds are more easily removed after curing, resulting in fewer damaged units.

Effects of Wetting on Ventilation Blocks

Before committing to the purchase of ventilation blocks from Fly-Lite, management at an Illinois mine requested that tests be performed on the ventilation blocks to determine their tolerance to immersion in water for a span of approximately two months. Toward this end, a total of six (6) different blocks were tested for water tolerance. Blocks were soaked in water for varying number of days up to 60 days maximum. The blocks actually

gained strength rather than losing strength. The maximum strength increase recorded was 100% from 150 psi to about 300 psi.

Testing consisted of first, obtaining regular production blocks in the 30-40 pcf range and cutting them in half. One-half of the block was subsequently immersed in water and the other stored in a cool, dry location. Matching halves were then tested for unconfined compressive strength after one, four, eight, sixteen, and sixty days of submersion. The results compare the compressive strengths of the saturated and dry blocks, shown in Figures 17, 18, 19, 20, 21 and 22, respectively.

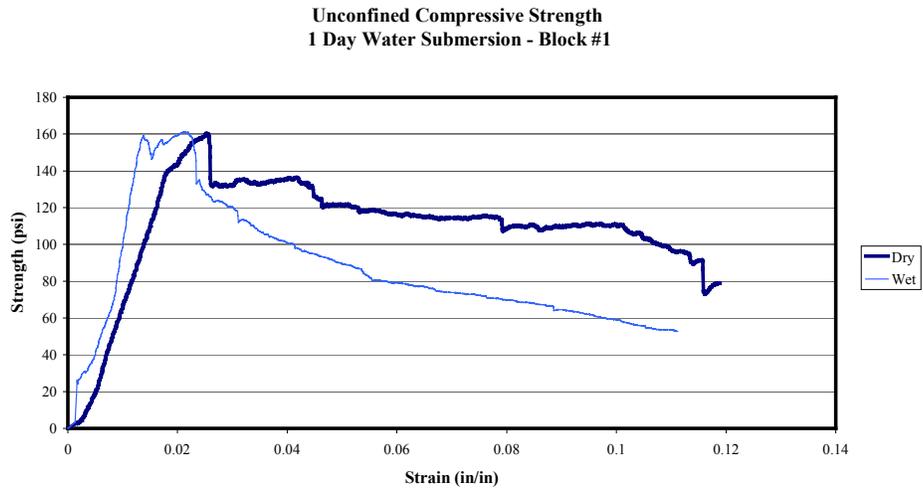


Figure 17: One-Day Water Immersion

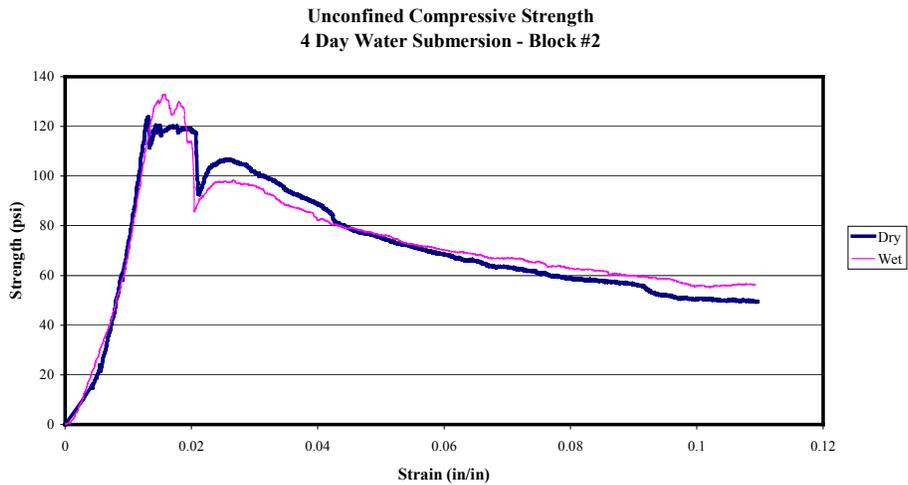


Figure 18: Four-Day Water Immersion

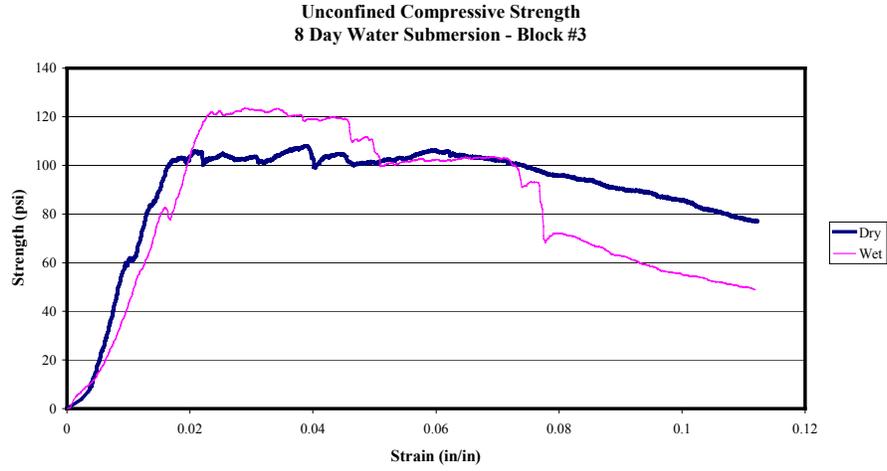


Figure 19: Eight-Day Water Immersion

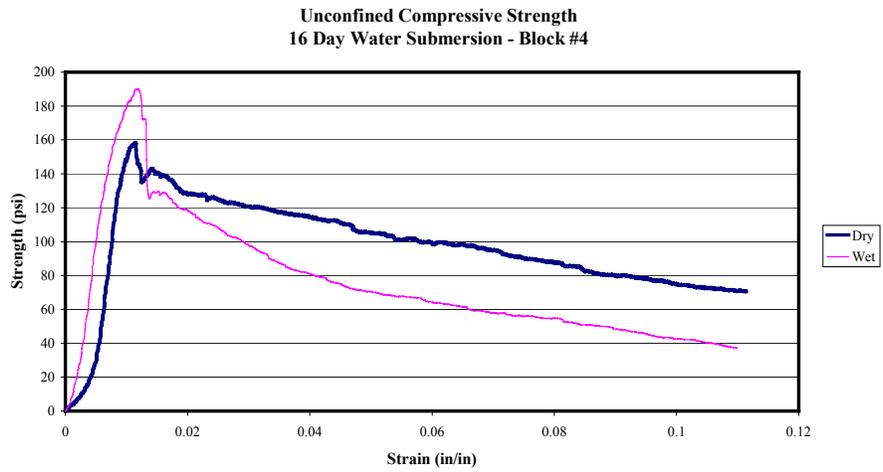


Figure 20: Sixteen-Day Water Immersion

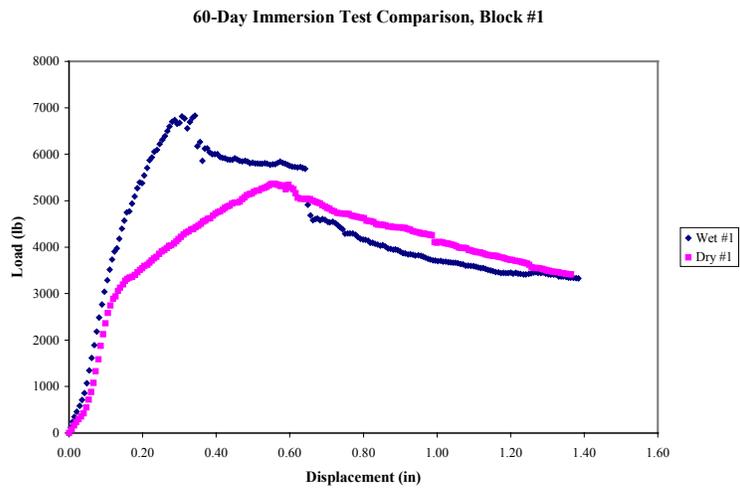


Figure 21: Sixty-Day Water Immersion, Block #1

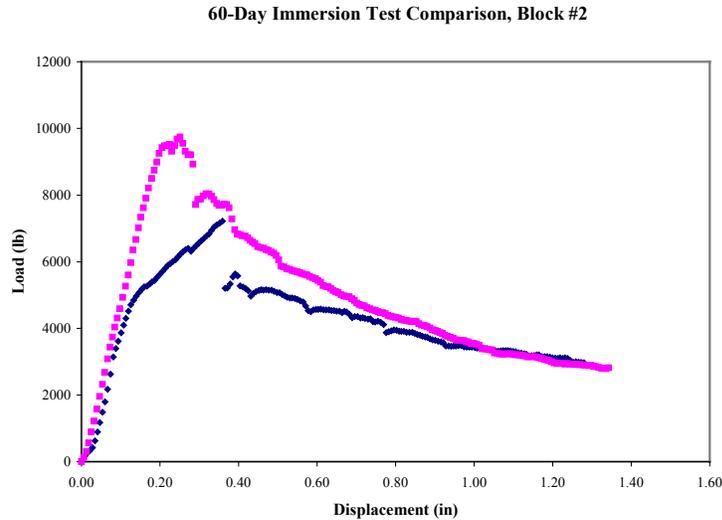


Figure 22: Sixty-Day Water Immersion, Block #2

The results of these ventilation block tests demonstrate that water-saturated Fly-Lite blocks showed no decrease in performance after submersion in water. In fact, the test results show that this material becomes stronger with exposure to water. This is more than likely due to the high percentage of FBC ash utilized in the grout mix, an additional amount of the FBC ash is reacting with the water as it penetrates into the interior of the block over time. The blocks were totally saturated after about eight days in water.

Flexural Strength Tests on Block Walls

Before a product may be marketed for use in underground mines, a product certification must be obtained from the Mine Safety and Health Administration. The certification is issued when the product meets the performance criteria prescribed in the Code of Federal Regulations (CFR), Part 30. Ventilation control devices, such as the ventilation blocks from Fly-Lite, must meet rigid standards concerning resistance to combustion and ventilation pressures.

For expediency, the Non-Destructive Testing (NDT) Group was chosen to conduct the pressure simulation, or flexural tests on the ventilation blocks. Three 4 ft × 8 ft walls were erected at NDT testing facilities on February 25, 1999. The blocks were dry-stacked and the joints sealed with Eagle Seal's "Air Float" sealant. The test walls were allowed to cure for 28 days and were tested on March 25, 1999. The tests consisted of applying an increasing load to the center front of the wall as per ASTM E72-80, "Conducting Strength Tests of Panels for Building Construction" (1994). The results of the tests are summarized in Table 3.

The average flexural strength obtained exceeded the minimum 39 lb/ft² required by MSHA by almost 20%.

Table 3 – Flexural Strength Test Results

Test No.	Load (lb)	Flexural Strength (lb/ft ²)
1	1810	61.1
2	1415	47.8
3	905	30.5
Average	1377	46.5

Fire Resistance Tests for MSHA Approval

Fire testing of the Fly-Lite ventilation blocks was conducted by MSHA in accordance with ASTM E119-88 “Fire Tests of Building Construction and Material” (1994). After conducting the test, MSHA concluded that the Fly-Lite blocks meet the incombustible requirements of 30 CFR Part 75.33. The blocks passed the test.

Manufacturing Process Modifications

Around November 2000, due to malfunctioning of the fly ash collection system at the SIUC FBC power plant, the quality of the fly ash supplied became very poor and previously developed mix designs for ventilation blocks did not provide good quality blocks. The fly ash contained significant amounts of coarser spend bed ash that was difficult to foam and had very poor cementitious characteristics. About 50 different alternate mixes, and about five alternate curing cycles were attempted to utilize the poorer quality fly ash in fabrication of blocks. The results of these studies provided two mix designs that could lead to good quality lightweight blocks. The mix designs utilize over 90% FBC ash with a slightly different curing cycle than was previously being practiced. These mix designs; however, provide slightly heavier blocks (40 pcf) than were being marketed earlier (30 pcf).

Larger size mixes, producing 5-6 blocks at one time, were made at McLeansboro, Illinois using the alternate mix designs and slightly modified curing cycle. The results were positive. About 6,320 blocks were sold. Since then, few blocks have been marketed since there is another product in the market that is competing with our product. Autoclaved fly ash blocks 8 in. x 8 in. x 24 in. are currently being dumped in the market place. These blocks, currently manufactured in Atlanta, Georgia, contain 65 % fly ash and are being marketed below the price of our block.

A perplexing phenomenon was encountered while producing the lightweight ventilation blocks when a storm front was approaching. The micro-bubbles, introduced into the mix in the form of micro-cellular foam, would suddenly rise to the top of the mold with an accompanying segregation of fly ash and cement in the remaining material as weather conditions changed. Apparently, the amount of foam in the mix to achieve the desired density is at or near the maximum the grout will accept and a rapid decrease in barometric pressure triggers the release of the air bubbles from the mix.

Fly-Lite personnel discovered that adding foam to the dry material before adding water would enable the mix to remain stable enough to mold and cure without incident. Strength tests have concluded that this method of production has no adverse effects on the performance of the blocks. However, more foam is required to manufacture the blocks with this method and it will be limited to those periods when atmospheric conditions require it.

To facilitate the handling of large numbers of molds, a prototype mold-rack, illustrated in Figure 11, was fabricated and utilized in the manufacturing process. This device is mobile and was designed to transport eighteen (18) mold assemblies (54 blocks) to and from the curing chambers. Mounted on dollies, the rack can be moved by hand or with the aid of a forklift.

Highly variable fly ash quality has been the most significant problem in getting quality product out to the customers. Loss on ignition values are highly variable from about 8 % to about 18 %. Particle size distribution is also highly variable.

During the month of August 2002, a full density material (90-95 pcf) was developed since such blocks are being used in large numbers by a coal company. These blocks are 8 in. x 16 in. x 6 in. and weigh about 50 pounds and utilize about 90% fly ash by weight. The manufacturing process does not require much air-entrainment. The blocks have been tested for durability in water and performed very well. An application has been submitted to MSHA on September 19, 2002 for their evaluation for suitability in mines. We expect markets for such blocks after MSHA evaluation.

CRIB ELEMENTS

The CCBs-based materials of 75-105 pcf were successfully developed for crib elements and contained 65–85% fly ash and had compressive strength of 1,500–2,500 psi. The first generation crib elements were successfully demonstrated in the field in two mines. However, commercialization of this part of the project was delayed by almost one year since cheap square cross-section; disposable plastic molds (5in. x 5in. for cribs and 6in. x 6 in. for posts) proposed for fabrication were not available commercially. Three entrepreneurial companies, one in Kentucky, one in Canada and one in Indiana, expressed interest in fabricating such molds from recycled plastics. However, after working with these companies for over 12-months (providing technical support to develop such molds, and identifying markets for them), business arrangements could not satisfactorily be developed to supply square cross-section disposable molds. There were three major reasons for that: 1) crib elements and post elements have not been approved by MSHA since we had not fabricated them and 2) the companies wanted an order of at least 20,000 molds before they would invest monies on dies and extruders, and 3) companies were operating at over 90% of their equipment capacity during 1999-2001, and wanted to make sure that they will make profit.

First Generation CCB-based Crib Element: Mix Development and Product Characterization Studies

Initial laboratory studies resulted in mix development for lightweight CCBs-based structural materials in the 75-105 pcf density range for use as crib or post elements. The mixes typically consisted of about 70% F-fly ash, binders, and appropriate fibers (Chugh, et. al, 1997). Laboratory characterization of specimens for crib elements was accomplished by determining the unconfined compressive strength and elastic modulus as a function of density. 5 in. x 5 in. x24 in. crib material samples were tested in a MTS stiff testing machine under a constant rate of loading, approximately 3000 lb./minute.

Figure 23 shows the relationship between the unconfined strength, C_o and the density, ρ where C_o (cribs) = $44.73e^{0.0433\rho}$, R^2 (cribs) = 0.73, N=203. Figure 24 shows the relationship between the elastic modulus, E , and the density, ρ , where E (cribs) = $0.1939e^{0.0339\rho}$, $R^2 = 0.3842$, N=102. A more detailed discussion of characterization studies is included elsewhere, Prichard, 2000.

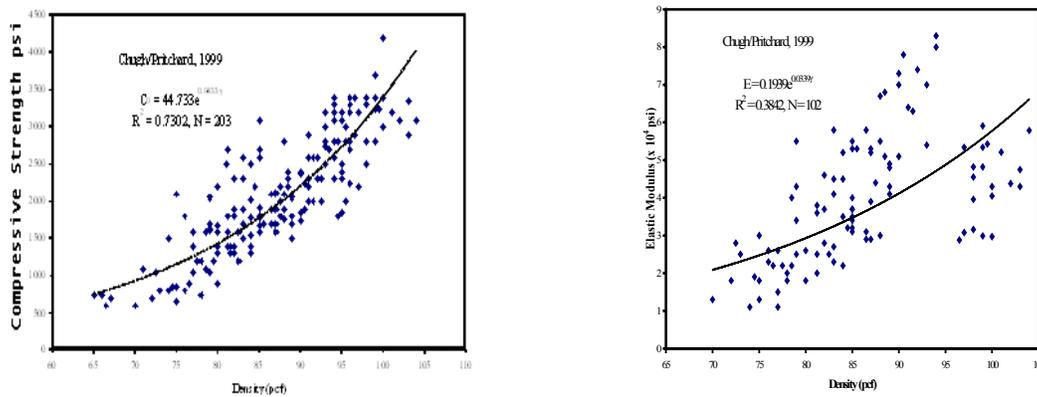


Figure 23: Compressive Strength/Density Relationship Figure 24: Elastic Modulus/Density Relationship



Figure 25: Large Size Hot Water Curing Tanks for Crib and Post Elements

Experience gained in the production of laboratory-sized specimens was used in assembling a facility for producing full-sized crib elements. The facility consisted of a large mixer, mold preparation/handling operations, curing equipment, and finished product storage. The first generation crib elements were designed to be prismatic (similar to wooden elements). Fabrication of the prototype, CCBs-based crib supports began during August 1996 and concluded in May of the following year. Approximately 230 crib members (5 inch \times 5 inch \times 30 inch) were produced for use in two in-mine field demonstrations and for characterization testing. Figure 25 shows the large hot water curing tanks for crib and post elements.

Crib Element Characterization: Engineering properties of the crib elements were obtained utilizing a large-scale testing machine located at the research facilities of the Illinois Clean Coal Institute at Carterville, IL. This machine has a capacity of 400,000 lb. and can test cribs 30" \times 30" and 6 feet in height.

Figure 26 illustrates the relative performance of 2-foot high wooden and CCBs-based cribs. The engineered cribs averaged 2,400 psi in compressive strength while the wooden crib yielded a compressive strength of around 900 psi. The elastic modulus of the CCBs-based cribs averaged about 300,000 psi while the wooden crib demonstrated an elastic modulus of only about 17,000 psi. This shows an improvement of about 167% in compressive strength and a 1,665% in the elastic modulus.

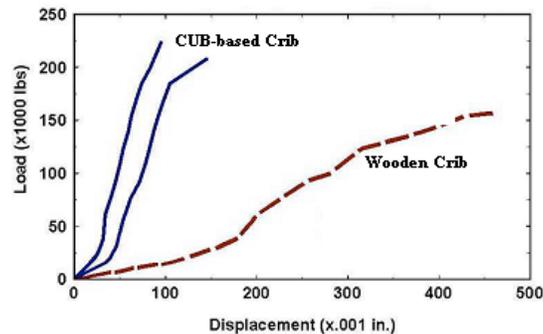


Figure 26: Load-Deformation Characteristics of 2x2 Cribs (Chugh et al, 1997)

Field Demonstration # 1: The first field demonstration of the CCBs-based prismatic crib elements (Figure 27) took place at a longwall mine in Illinois. (Chugh et al, 2000) The cribs were placed in the tailgate entry, illustrated in Figure 28, in a longwall panel. Two cribs were erected and equipped with load cells designed at SIUC. Two wooden cribs were equipped with load cells as controls.



Figure 27: Typical Crib and Post Installation in a Mine

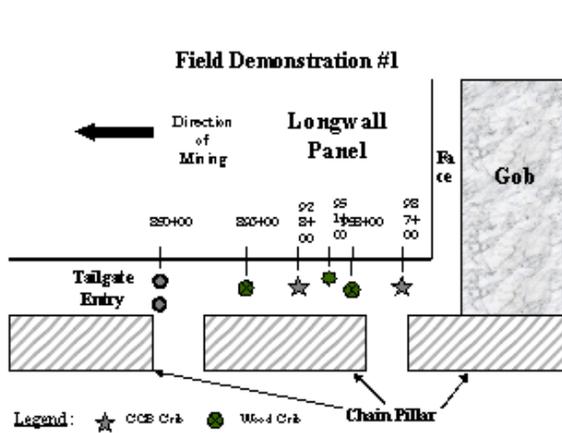


Figure 28: Layout for Field Demonstration #1

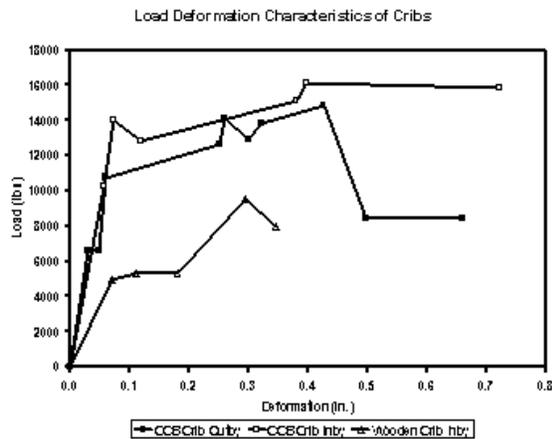


Figure 29: Crib Performance

For the cribs, one of these load cells was placed at each corner during assembly, approximately halfway between the roof and the floor. Convergence points, consisting of 1/2-inch x 18-inch diameter pins driven into the mine floor beneath a roof bolt, were installed adjacent to each installed crib. An extensometer was utilized for measuring the roof-to-floor convergence.

The results of the field demonstration are shown in Figure 29 that compares the performance of the wooden and CCBs-based cribs as load vs. deformation. Load values were obtained from measuring the compression of the polyurethane wafers of the load cells while the deformation values were obtained from the convergence stations. Clearly, CCBs-based cribs demonstrated higher stiffness and higher sustained load carrying capacity, than the wooden counterpart.

Worker reaction to the supports was very positive. The time and degree of difficulty in erection of the supports was no different than conventional wooden supports. This was

due to the fact that the supports were similar in size and shape to the supports the labors were accustomed to.

Field Demonstration # 2: The second field demonstration of the CCBs-based prismatic crib elements took place at a mine in Western Kentucky. For this demonstration, the crib supports were installed on the headgate of a new longwall panel. This mine is required to fully support all gate entries for ventilation requirements and a bleeder fan is used to provide ventilation to the longwall face; full support of the head and tailgate entries is mandatory for maintaining proper airflow.

The test area illustrated in Figure 30 was located one crosscut in from the longwall setup rooms in the middle entry of the three-entry headgate. This area was chosen because of the severe loading that normally occurs at this location as a new face begins production. Loading of the roof in this area typically occurs at a rapid rate until failure of the main roof, which consists of massive beds of Limestone and Dolomite. Subsidence of the surface area above the panel is an indication that main roof failure has occurred.

After bringing the crib elements inside, mine personnel installed the cribs at a single location instead of the three locations planned. The installation of additional conventional cribs out by the test area precluded the disassembly and re-erection of the CCBs-based supports to their preplanned locations. SIUC personnel installed the instrumentation on the supports before longwall operations began, utilizing the same procedures as at the previous field demonstration.

The results of this demonstration can be observed in Figure 31 that shows the loading of the cribs as a function of face location. In the figure, “0” face distance means that the longwall panel had not begun production. Subsequent, positive distances symbolize the distance that the face had retreated from the setup rooms, away from the cribs.

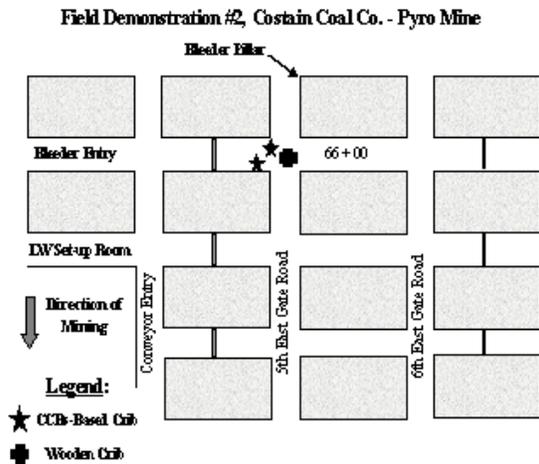


Figure 30: Layout of Field Demonstration #2

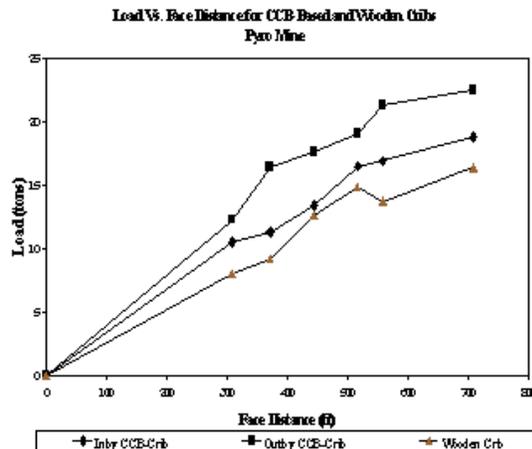


Figure 31: Crib Performance Data

Similar to field demonstration # 1, the CCBs-based crib elements carried higher load with higher rate of loading than their wooden counterparts.

Summary of Field Demonstrations: Field demonstrations of the CCBs-based artificial supports were successful and the superior performance characteristics and the potential for utilization as direct substitutes for wooden supports were clearly documented. At Mine 1, the CCBs-based cribs supported loads that were, on average, 62% higher than the wooden crib. At mine 2, the CCBs-based crib supported loads that were, on average 26% higher than the wooden crib.

The observed elastic modulus of the CCBs-based cribs was 2.0 to 2.5 times higher than the wooden cribs at the second mine. Mine personnel, both management and labor, were very receptive to use of the supports at both mines since the supports were engineered to be direct replacements for the wood supports currently in use. This enthusiasm was enhanced further when the relative performance of the supports was revealed. Equally important, as of January 1999, mine management at Mine 2 reported that the test cribs remain intact, despite the failure of most wooden cribs in the area immediately adjacent to the test area.

Second Generation Crib Development and Demonstration

The first generation crib development, discussed above, had the following disadvantages:

1. It obstructed air flow similar to a wooden crib
2. Due to short fiber length and their random distribution, the crib elements cracked near surface in a brittle manner during transport.
3. Since the primary constituent in the crib element was real fine size fly ash, the binder requirements were high (~30%), thus making the product expensive.

To overcome several of these disadvantages, a different approach was taken to develop second-generation crib element during the period 2001-2002. More specifically:

- A commercially available continuous steel reinforcement system was added to the crib element. Short-length random distribution of fibers was still maintained to enhance post-failure toughness.
- Coarser ingredients such as sand and pea gravel were added to the fly ash to decrease binder requirements.
- Density reduction through addition of foam was eliminated since it significantly increases cost and is sensitive to loss-on-ignition in fly ash. Furthermore, it reduces stiffness of the product.
- Weight reduction was achieved by redesigning the crib element so that material distribution was based on stress distribution, and resistance to airflow, and ease of material handling. The design was based on finite element analysis (FEA) of a prismatic crib element (conventional design) and alternate designs developed here. The results of these studies are described later.

- The redesigned element shown in Figures 32 and 33 is much easier to handle during crib installation. Furthermore, because of its geometry it is much easier to install in undulating roof and floor areas. Therefore, labor installation costs are expected to be lower.

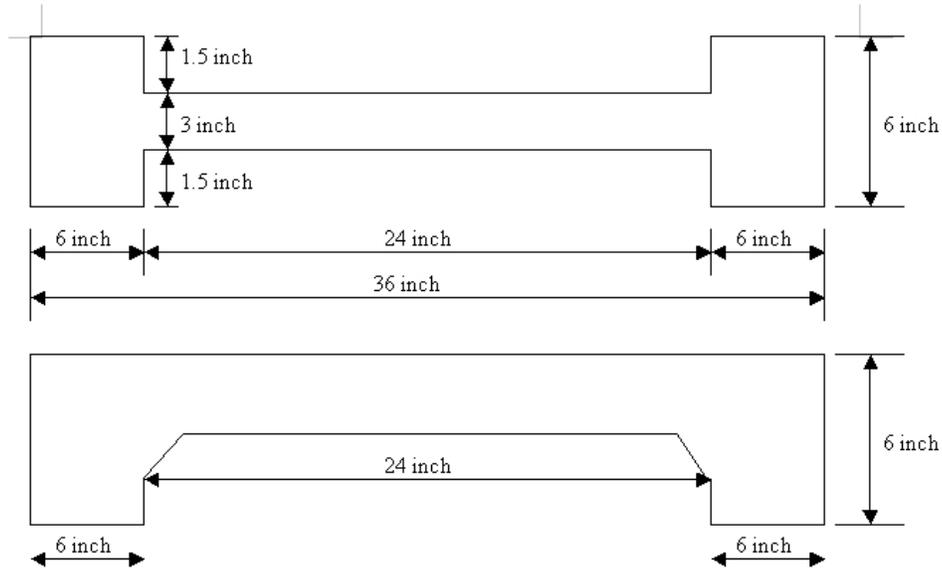


Figure 32: Geometry of the Designed Crib Element



Figure 33: A Cured Crib Element

Mix Development and Product Characteristics: Pea gravel and river sand were obtained from a commercial supplier. Several mix designs, involving sand, pea gravel, FBC fly ash (20-50% by weight) were developed. The following two mix designs were considered appropriate for crib development based on their compressive strength and elastic modulus values. These were:

1. Gravel – 24%, Sand-24%, Fly Ash – 40%, Inorganic binder- 12%
2. Gravel – 29%, Sand-29%, Fly Ash – 30%, Inorganic binder- 12%

The engineering properties of the mixes are summarized in Table 4. The first mix design provided slightly better strength and post-failure stiffness than the second mix. Therefore,

all further development was done with the first mix. The results for 2-foot high cribs using the two mixes above, along with the wooden cribs, are summarized in Figure 34. The designed crib elements provide significantly higher strength and stiffness as compared to a wooden crib.

Table 4 – Engineering Properties of Developed Mixes

Composition	Compressive Strength (psi)	Elastic Modulus (psi)	Density (pcf)	No of samples
1	1,276	185,692	110	10
2	1,064	109,500	117	2

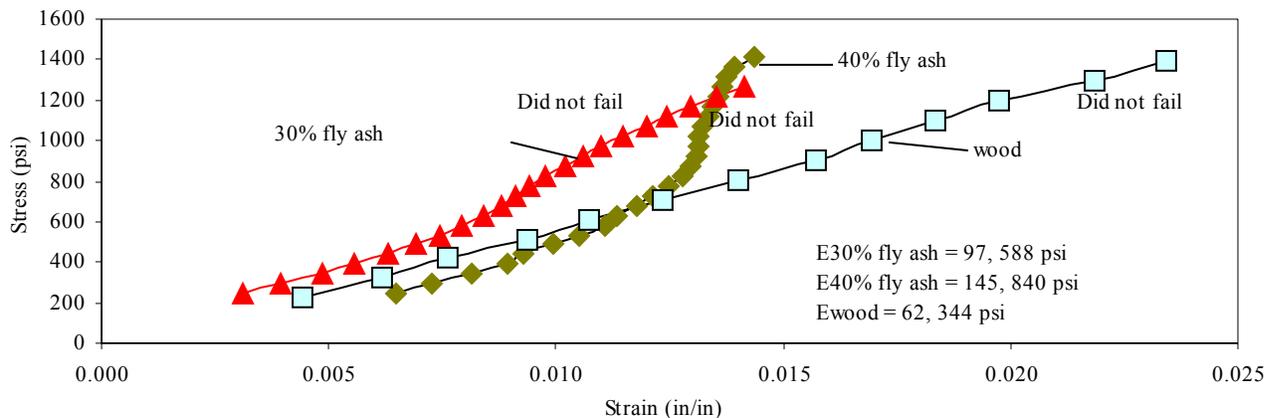


Figure 34: Stress-Strain Data for 2-Foot High Wooden and CCBs-based Cribs

Finite Element Analysis of a Crib Element

Two-dimensional linear FEA was performed on a conventional prismatic element as part of the crib to develop alternate crib element geometries (Figure 35). The results indicated that most of the load is transferred through contact areas and vertical stresses are compressive in the material. Most of the material away from the contact zone has very low horizontal stress and literally no vertical stress. In a mine environment, horizontal stress in the longitudinal member may, however, be much larger than indicated by FEA because of uneven roof and floor strata, and differential settlement. Adjacent to the contact areas are zones of high tensile stress that can cause cracking of the element. The analysis above led to the following thoughts in the redesign of the crib element.

- The crib element away from the contact areas can have much smaller cross-section areas designed to carry horizontal loads. This area must also be shaped and suitably reinforced to minimize tensile and torsional cracking of the element.
- The crib element geometry should provide largest area for airflow when installed as a crib.
- The contact areas must be as large as possible to maximize load carrying capacity

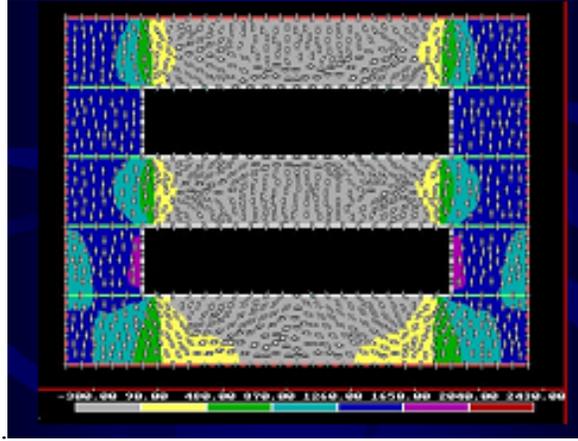


Figure 35: Minimum Principal Stress Distribution in a Prismatic Element Crib

The prismatic crib element was redesigned to satisfy above thoughts and with the additional requirement that the weight of the crib element should be similar to that of a prismatic wooden element. Through several iterations of experimental testing, the crib element geometry was optimized to provide the best load carrying capacity for minimum weight. Such an element has 90-100 tons of load carrying capacity, stiffness, about 2-3 times larger than a typical wooden element, and good post-failure characteristics.

Finite Element Analysis of A Prototype Crib

The designed crib element in a full-size crib was modeled using FEA to determine stress distribution. A comprehensive package of commercial finite element analysis software, ALGOR (version 12:00) for Windows, was utilized to perform FEA. This Mechanical Event Simulation (MES) software works with linear stress, nonlinear stress, and multi-physics analysis for comprehensive analysis.

Full-scale 3-D crib element and 3-D crib models were developed using three-dimensional 6-node or 8-node flexible brick element. Table 5 lists the engineering properties of the crib element used for simulation.

The Engineering properties of crib element are given below:

Table 5 - Engineering Properties of Crib Element

Specific weight*, pcf	Elastic modulus, psi	Poisson's ratio	Cohesion psi	ϕ o	Compressive Strength, psi	Shear modulus, psi
130 pcf	100,000	0.25	529.5	23	1,200	40,000

*This includes the weight of reinforcement

Nonlinear material properties described by Drucker-Prager failure criterion were utilized for all models. The crib was incrementally loaded vertically in 100 psi increments to study yielding and ultimate load carrying capacity. The results indicated that crib yielding was initiated at about 83-tons and the crib failed at about 93 tons. The results agree well

with actual values observed in laboratory testing. Three dimensional stress distribution in a simulated crib at failure is shown in Figure 36.

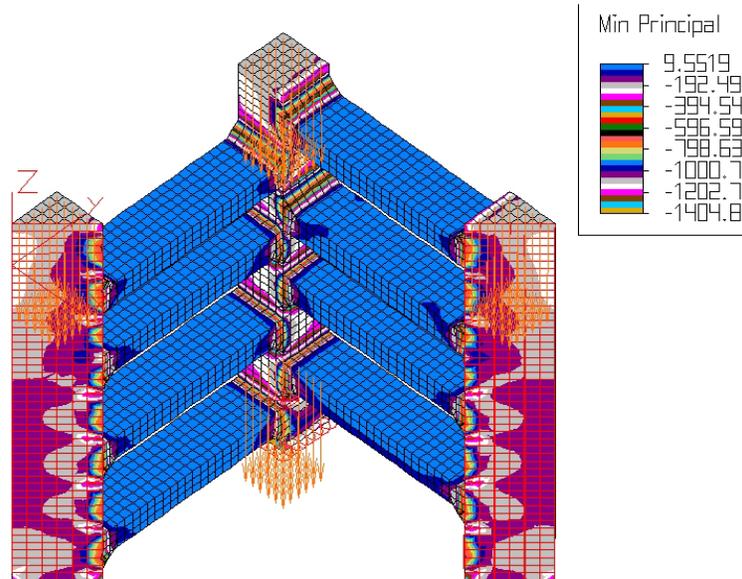


Figure 36: Minimum Principal Stress Distribution when the Crib was Failed at Maximum 93 Tons Load (Diagonal Cut View)

Laboratory Testing of Prototype Crib

Elements Testing facilities at the Illinois Coal Development Park permit testing of cribs up to 6 feet high with crib elements 30 inches long. Several cribs 4-foot high with redesigned crib elements were tested to determine their load deformation and stress – strain behavior and observe their post-failure behavior. A typical crib installed in the testing machine, ready for test is shown in Figure 37. The test results are summarized in Table 6.

Table 6 - Summary Test Data for CCBs-Based Cribs

Test no	Compressive Strength (psi)	Ultimate Load (tons)	Elastic Modulus Psi	Crib Height (ft)
1	1666	>120	119,000	2
2	1701	122.5	152,000	2
3	1555	112.0	276,000	2
4	1021	73.5	80,000	2
5	1361	98.0	110,000	t
6	1597	115.0	110,000	4
7	923	66.5	124,000	2
8	1287	92.7	92,000	3
9	1300	93.6	56,000	4



Figure 37: Prototype Second Generation Crib Element in the Test Frame

Ultimate load carrying capacity of nine (9) tested cribs varied from 90-110 tons. Localized failures, along the edges of contact areas were initiated around 70-75 tons. More extensive shear and tension cracks formation, within the contact zones in compression, initiated around 80-85 tons.

A typical load-deformation curve is shown in Figure 38. Good post-failure toughness is indicated. The crib deformed 4 in – 5 in. prior to collapse. The crib failure was slow and no violent collapse was observed. No failures were observed in the horizontal members of the crib element. Stiffness of the crib, under vertical loading, ranged 2 –3 times that of a wooden crib using good oak timber, and good post-failure characteristics.

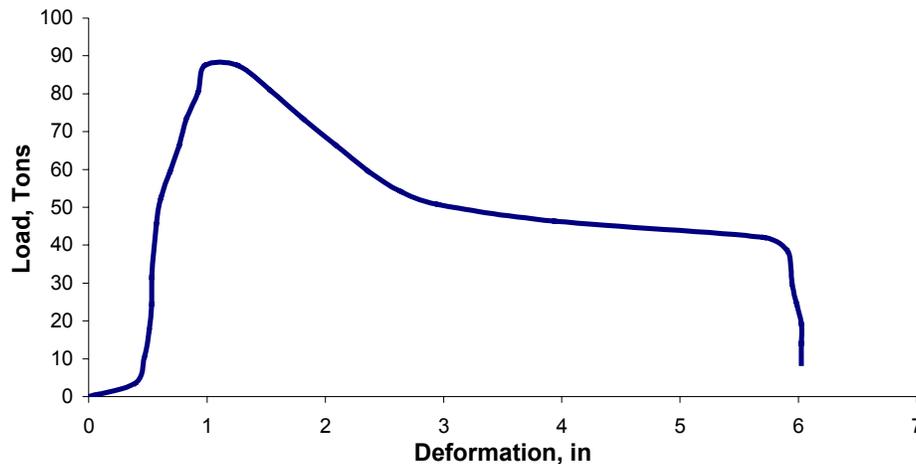


Figure 38: Typical Load-Deformation Curve for a CUB-Based Crib

Field Demonstration of Designed Crib Elements

Field demonstration studies were performed on a longwall mine in Illinois (Mine 1, left). The mine extracts Springfield #5 coal, 6-7 feet thick at a depth of about 700 feet. Field demonstration was performed using 30-inch long elements. Two 7-foot high cribs were

installed in crosscuts on the head gate side adjacent to the longwall face. The cribs were installed by mine professionals. The cribs were installed about 200 feet ahead of the longwall face. The installed cribs are shown in Figure 39.



Figure 39: Installed Cribs at Mine # 1 and Mine # 2

As mining advanced, cribs were stressed. One of the fly ash cribs was knocked out as caving occurred. The wooden crib adjacent to crib was also knocked out. The second fly ash crib sustained the entire load imposed on it without failing. Its performance was in fact better than the wooden crib. Based on these tests, the mining company decided to purchase 1,500 crib elements on a trial basis. The cribs did not show signs of brittle failure.

Another field demonstration test (Mine 2, Right) is currently being done at a longwall face in Western Kentucky. Mining depth at this site is about 400 feet and seam thickness is about 6 feet. Performance of cribs is being tested on the head gate similar to the Illinois mine above. Four cribs have been installed about 200 feet ahead of the face. Mine personnel are monitoring performance through visual observations.

POST ELEMENTS

Development of Engineered Supports: First Generation Posts

A review of literature revealed no previous attempts to develop and utilize CCBs-based engineered posts similar to concrete-fly ash cribs. Based on structural materials development for cribs, the first generation CCBs-based post element was a prismatic element 6 in. x 6 in. x 6 feet (Figure 26) cast in a removable steel mold. Such an element was cast with grout density of 95 pcf. The grout consisted of about 75% F-fly ash, and 25 % inorganic binders including fibers. The elements were cured in 8 feet long and 3 feet deep hot water tanks at a temperature of 156° F. A comparison of commercial

concrete fibers with waste carpet fibers in the grout indicated that the latter fibers performed equally well at a cheaper cost.

The CCBs-based post elements were tested in the laboratory to compare their performance with similar wooden elements currently in use. Figure 40 illustrates the relative performance of 8 in \times 8 in. \times 2 feet wooden posts and 6 in. \times 6 in. \times 2 feet CCBs-based posts. The CCBs-based post elements averaged about 3045 psi in compressive strength while the wooden posts averaged about 2320 psi. The average elastic modulus for wooden and CCBs-based posts were 435, 000 psi and 159,500 psi, respectively. This demonstrates an improvement of about 30% in unconfined compressive strength and 180% in the elastic modulus. Furthermore, there was considerable variability (25-50%) in the tested wooden posts. However, the wooden posts demonstrated plastic post-failure characteristics while the CCBs-based posts demonstrated strain-softening post-failure characteristics. The residual strength of the CCBs-based posts, about 40-50% of the compressive strength, is due to the reinforcing fibers utilized in the mix.

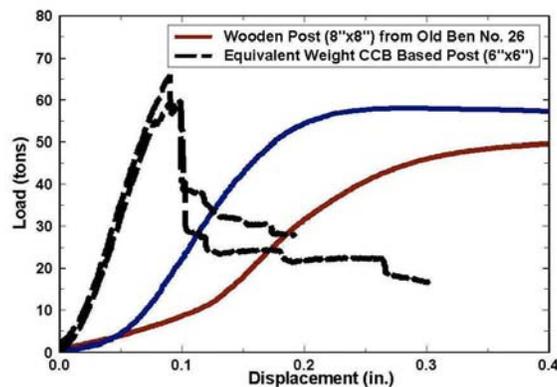


Figure 40: Load-Deformation Characteristics of Wood and CCBs-Based Posts

Field demonstration of first generation posts was done at a mine in Illinois (Chugh et al, 2000). It indicated that although the installed posts performed better than the wooden post, a large number of posts did not survive transportation from the mine mouth to the site of installation. This led to the development of second generation CCBs-based posts that involved the disposable mold concept, where the mold was left on the post after curing and marketed for final use as such.

Development and Demonstration of Engineered Supports: Second Generation Posts

The disposable mold concept basically utilizes a thin-walled plastic pipe in which an appropriate CCBs-based composite mixture is poured and allowed to cure. The composite mixture consisted of 85-88% CCBs, 10-14% inorganic binders, and 1-2% waste fibers. The weight of a typical post was 145- 154 lbs. The concept of disposable mold was developed for several reasons: 1) improve post-failure performance, 2) minimize breakage during transport, and 3) minimize mold preparation and demolding labor costs. The disposable mold was made of PVC that became an integral part of the marketed post. A mold that remains on the support would ensure that any micro-cracks

formed during the curing process would not be able to propagate, provide a confining pressure for the CCBs-based structural material under load, and increase the post-failure load bearing capacity of the supports. Typically, 6 in. diameter PVC pipe with 0.25 in. wall thickness was utilized for posts for underground mines. Other wall thicknesses were also evaluated but rejected in favor of performance achieved with 6mm wall thickness. As shown in Figure 41, posts produced in disposable molds exhibited performance characteristics very similar to wooden posts. The ultimate load carrying capacity of 6 feet high posts during initial trials ranged 38-45 tons. Development of improved mixtures increased the load carrying capacity to about 50-tons. Furthermore, there was far greater consistency in the quality of posts produced in this manner. Based on achieved success, a further modification to this concept has been made. This involves incorporating steel reinforcement along the length of the post to further increase its stiffness.

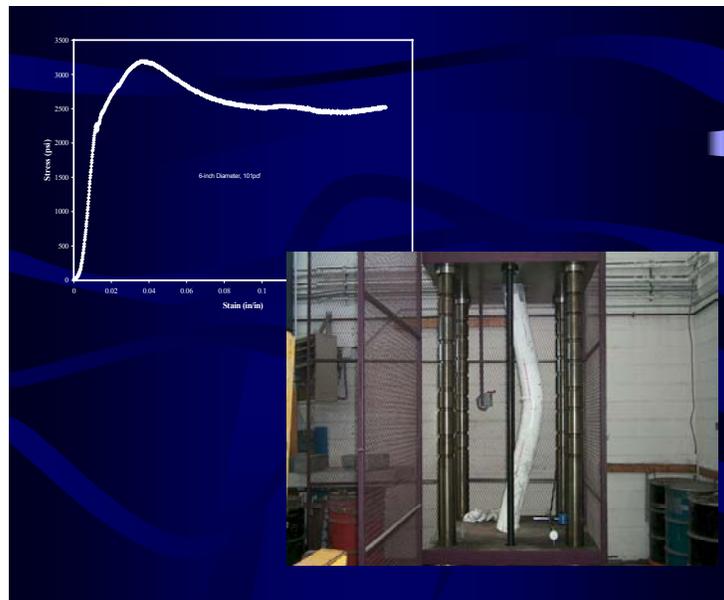


Figure 41: Performance of Full-Size CCBs-Based Post Cast Into Disposable Molds

The results for full-size posts (approx. 6.4 in. in diameter and 6 feet long), with and without longitudinal reinforcement, are included in the Table 7 below. Load-deformation data for two posts (with and without longitudinal reinforcement) are given in Figure 43. Mine Safety and Health Administration has found these posts suitable for use in mines based on a review of test data.

Table 7 – Comparison of Wood and CCBs-Based Posts

Characteristic	Wooden Post (4-ft) 6 in. x 6 in.	Fly Ash Post with Axial Reinforcement	Fly Ash Post Without Axial Reinforcement
Failure Load (ton)	≈ 25	52-55	52
Failure Stress (psi)	≈ 1495-1696	≈ 2697- 3103	≈ 2495- 3000
Elastic Modulus (ksi)	≈ 250- 300	≈ 400-450	≈ 300- 320

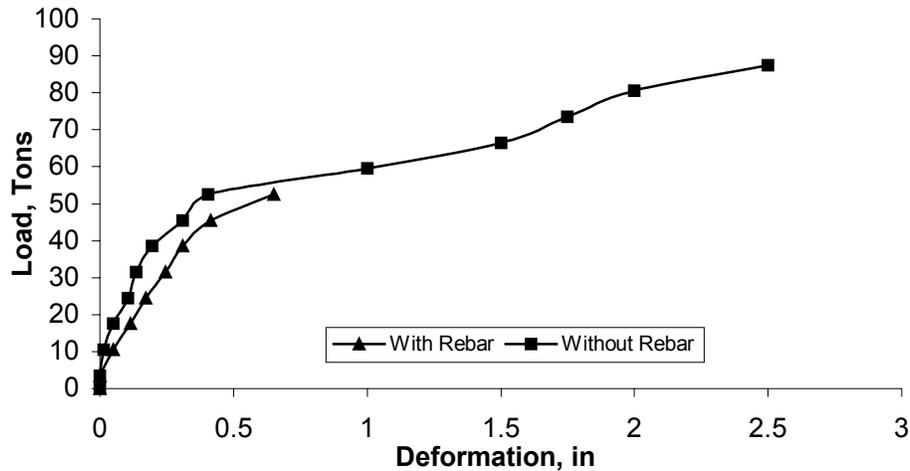


Figure 42: Load-Deformation Data for Composite Post-With and Without Axial Reinforcement

The following observations were made during the testing.

- 1) The posts started to buckle around 45 tons of load.
- 2) The buckled posts straightened when the load was reduced.
- 3) Cycling the load around the buckling load did not reduce the post's ability to carry full load.
- 4) The posts sustained load even after they were buckled.

The second-generation posts are currently being demonstrated at a mine in Western Kentucky on a longwall face (Figure 39, Mine 2). The posts were installed in August 2002 and their performance to date has been good. An additional field demonstration in a room-and-pillar mine in central mine is planned in September 2002. This application involves demonstration of posts in a weak floor setting where the posts must undergo large amount of deformation (6 in. to 12 in.) before failure.

Field Demonstration of Designed Posts

Field demonstration studies were performed on a longwall mine in Kentucky and a conventional room and pillar mine in Illinois. Both mines extract Springfield #5 coal, 6.0 –7.0 feet thick at a depth of about 350 feet deep. Field demonstration was performed using 6 feet long posts which were cut to exact specifications. Three 1.8m high posts were installed in crosscuts on the head gate side adjacent to the longwall face in Kentucky, and four (4) posts were set in a particularly high stress area along the beltline in the Illinois mine (Figure 43). In both cases, installation and monitoring were completed by mine professionals.

In Kentucky, the posts were installed in August 2002 and their performance to date has been very good and superior than wooden posts installed adjacent to the engineering

posts. In Illinois, the demonstration involves demonstration of posts in a weak floor setting where the posts must undergo large amounts of deformation (6 inch to 12 inch) before failure. The demonstration is designed to compare the performance of engineered posts with 50-ton strata prop.



Figure 43: Field Demonstration of Composite Posts in a Central Illinois Coal Mine

CONCLUSIONS

- Pilot-Scale Facility for manufacturing a variety of CCBs-based products has been constructed and it operates as planned.
- Quality ultra-lightweight ventilation blocks can be produced if relatively uniform quality fly ash can be supplied by the power plant.
- Air-entrainment in highly variable fly ash presents the biggest challenge.
- Solid blocks (16" x 8" x 6"), recently developed in August 2002, have the best potential if the fly ash quality is highly variable.
- CCBs-based crib elements have high commercial potential throughout the USA.
- CCBs-based posts also have high potential for commercialization. However, industry must be convinced of that potential through additional field demonstrations.

RECOMMENDATIONS

- Efforts to produce and market CCBs-based blocks, crib and post elements should be continued. The products have been developed, and manufacturing techniques have been established. Marketing efforts are the key now to successful commercialization of the project.
- Development and demonstration of construction products for use in rural settings, and for temporary structures should be explored.

REFERENCES

Anderson, G., and Smelser, T., 1980, "Development Testing and Analysis of Steel-Fiber-Reinforced Concrete Mine Support Members," U.S. Bureau of Mines Report, RI 8412.

Biron, C., Arioglu, E., 1983, "Design of Supports in Mines, John Wiley & Sons, Inc., New York, pp. 3-26.

Chugh, Y.P., et al., 1996, "Lightweight Combustion Residues-Based Structural Materials for Use in Mines," Southern Illinois University at Carbondale.

Chugh, Y.P., et al., 1997, "Lightweight Coal Combustion By-Products Based Structural Materials for Use in Mines," Southern Illinois University at Carbondale.

Chugh, Y.P., M. Prichard, D. Deb, H. Wilcox (2000), "Development and Demonstration of CCB-Based Structural Products For Mine Use," Transaction Society for Mining Engineers.

"Coal Data 1993", National Coal Association, Washington D.C.

Prichard, M (2000),"The production and Demonstration of Fly Ash-Based Structural Supports For Use in Mines," MS Thesis, Southern Illinois University Carbondale

Wei, L., Naik, T.R., Golden, D.M., 1994, "Construction Materials Made with Coal Combustion By-Products", Cement, Concrete and Aggregates, June issue, pp.36-42.

Yu, Z, 1987, "Evaluation of Underground Supports Made of Wood and Other materials," Masters Thesis, Virginia Polytechnic Institute and State University.

ACKNOWLEDGEMENTS

The authors sincerely acknowledge the financial and technical support of the National Energy Technology Laboratory (U.S. Department of Energy), and the Illinois Clean Coal Institute. Special thanks are due to Mr. Robert Patton, and Mr. Scott Rennings who have served as the NETL coordinators for this project. Additional thanks are due to Fly Lite, Inc. (owners of Pilot Scale Facility) for assisting with crib development and testing. Thanks are also due to Old Ben Coal Company, Pyro Mining Company, American Coal Company, Turris Coal Company, and Peabody Coal Company for their interest and permitting field demonstrations in their mines. The authors also sincerely acknowledge the support of Ms. Dorothy Porter and Ms. Michele Butcher for their unequivocal support in preparing the reports manuscript.

PUBLICATIONS AND PRESENTATIONS LISTING
September 30, 1999, through September 30, 2002

Project Title: **DEVELOPMENT AND DEMONSTRATION OF A PILOT SCALE FACILITY FOR FABRICATION AND MARKETING OF LIGHTWEIGHT-COAL COMBUSTION BYPRODUCTS-BASED SUPPORTS AND MINE VENTILATION BLOCKS FOR UNDERGROUND MINES**

Chugh, Y.P., et al., 1996, "Lightweight Combustion Residues-Based Structural Materials for Use in Mines," Southern Illinois University at Carbondale. Final Report to Illinois Clean Coal Institute.

Chugh, Y.P., et al., 1997, "Lightweight Coal Combustion By-Products Based Structural Materials for Use in Mines," Southern Illinois University at Carbondale. Final Report to the Illinois Clean Coal Institute.

Chugh, Y.P., et.al 2001, "Development and Demonstration of CCB-Based Structural Products for Mine Use," Annual Transactions Society of Mining Engineers.

Chugh, Y.P., 2001 "Coal Combustion Based Lightweight Structural Materials and Processes for Making Them," U.S. Patent and Trademark Office, Patent No. 6,277,189, 2001

Chugh, Y.P., G. Balk, Jin Rong Ma, D. Biswas, (2002) Design and Development of An Innovative Coal Utilization Byproducts-Based Crib Element for Underground Mine Support
Annual Meeting Pittsburgh Coal Conference, September 23-25, 2002

Chugh, Y.P. (2002), "Development and Demonstration of a Pilot Scale Facility for Fabrication and Marketing of Lightweight Coal Combustion Byproducts-Based Supports and Mine Ventilation Blocks for Underground Mines", Final Report to ICCI, October, 4 pp.

Prichard, M, 2000, "The Production and Demonstration of Fly Ash-Based Structural Supports For Use in Mines," MS Thesis, Southern Illinois University at Carbondale.

EQUIPMENT INVENTORY
September 30, 1999, through September 30, 2002

No funds were allocated in the project budget for equipment purchase.