Development and Demonstration of CCB Based Structural Products for Mine Use

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Abstract

Environmental considerations, resulting from the disposal of coal combustion by-products (CCBs) and the impacts of deforestation associated with the harvesting of timber for utilization as roof supports in mines, should become more severe in the future as landfill space and suitable timber reserves become more scarce. To help address these concerns, lightweight, artificial supports such as post and crib elements, utilizing large percentages of coal combustion by-products as aggregate, have been developed for use in underground mines. These structural products show equal or better engineering characteristics as timber and have the potential to replace timber support in underground mines.

CCBs-based ultra-light structural material (ULSM) also has been developed and commercialized for utilization in construction of ventilation stoppings in underground mines. The bulk density of these blocks are in the range of 25 to 40 pounds per cubic foot (pcf) with over 75% CCBs. Efforts are also given to develop and demonstrate large volume CCPs based sub-grade improvement technique for road construction. Soil treated with SIUC fluidized bed combustion (FBC) fly ash developed an immediate bearing value exceeding 25%, with swelling strain less than 1%, over untreated soils and met Illinois Department of Transportation (IDOT) standard specifications.

In this paper, development procedures, engineering characteristics, and beneficial use of CCBs-based structural products are given.

Introduction

Over the past five (5) years or so, the Department of Mining and Mineral Resources Engineering at Southern Illinois University (SIU) has been developing CCBs-based structural products for use in mines. It was thought this would provide the mining industry with better and more uniform quality structural materials throughout the year, reduce deforestation, and allow for the return of CCBs underground. The replacement of wooden cribs and posts was identified as a high priority based on input from the mining industry. Later, the replacement of currently used ventilation blocks (cinder, concrete, Omega, etc.) by lightweight or ultra-lightweight CCBs-based blocks and fill materials were included for development. It was estimated that utilizing these materials in Illinois Basin coal mines would consume about 40,000 – 50,000 tons of fly ash annually.

Research into the utilization of CCBs was divided into two classifications, fill materials and lightweight structural materials. Fill materials developed at SIUC include paste backfill mixtures for underground mine excavations, as well as flowable fills and sub-base stabilizers for the construction industry. Structural materials include ventilation blocks as well as posts and crib elements, the demonstration of which will be the main focus of this paper. Structural materials consisted of lightweight (85-95 pcf) support members and ultra-lightweight (30-40 pcf) ventilation blocks. The lightweight support members consist of 5-inch × 5-inch × 36-inch crib elements at 85 pcf and 6-inch × 6-inch × 96-inch posts at 95 pcf, while the ventilation blocks are 8-inch × 12-inch × 16-inches in size at about 30 pcf.
Review of Pertinent Literature

Fly Ash Types and Usage

Fly ash is the fine by-product of coal combustion that exits from the top of the boiler with the combustion gases and is classified as Class C or Class F by the American Society for Testing and Materials (1994). Class C fly ash is produced from burning western bituminous coal, subbituminous coal, or lignite, while Class F fly ash is produced from burning anthracite coal or eastern bituminous coal. These classes differ mainly in the level of calcium oxide (CaO) present in the ash. Typically, Class F fly ash will contain less than 10% CaO, while Class C fly ash will often contain levels of CaO from 15 to 35% (Wei, Naik, and Golden, 1994).

Over the last several years, interest has been shown in developing new uses for fly ash. These include fill material for mine reclamation (Kim and Cardone, 1997), subsidence control (Chugh et al., 1996), and lightweight, artificial, supports suitable as substitutes for wood products in mines (Chugh et al., 1997).

Characteristics of Wooden Supports

Wood is the traditional material utilized for supplemental roof support in underground mines. It is easy to work with and, until recently, has been in abundant supply and reasonably priced. Wooden support members are relatively lightweight, easily trimmed to length, and fairly durable. Wood, however, has many disadvantages as a structural member. As a naturally occurring material it is subject to wide variances in strength and density, and is subject to seasonal fluctuations in supply. Wood also absorbs moisture and is subject to decay. Because it is a natural product, wood is subject to considerable variance in strength characteristics. Soft spots, knots, moisture content, and voids within the wood will all cause the wood to be weaker than anticipated. For instance, Yu (1987) indicated drops in strength of up to 50% from a two-inch knot for a given specimen. A section of wood may appear to be free of defects to the naked eye, but may include one, or all, of the aforementioned defects.

The strength characteristics of wood are unidirectional; wood products are much stronger when loaded axially, with the grain, instead of 90° to the grain. Biron and Arioglu (1983) reported maximum safe stresses for Class I Oak at about 1,700 psi parallel to the grain (post configuration), and about 425 psi perpendicular to the grain (crib configuration). Yu (1987), and Biron and Arioglu, (1983) identified the moisture content of wood as a major limiting factor on the strength of wood products. In general, as the moisture content of the wood increases, the strength of the wood decreases. For pine, crushing strength decreases about 82% as the moisture content increases from 0% to 50%. This is a significant reduction in strength and will affect the performance of wood when utilized as post or crib members, especially within the humid environment of a mine.

Concrete Supports – Previous Attempts and Results

Anderson and Smelser (1980) investigated the effectiveness of steel-fiber-reinforced concrete (SFRC) crib supports and found them to be significant improvements over their wooden counterparts. Tests of open, SFRC cribs (30-inch × 30-inch) averaged 2373 pounds per square inch (psi) in compressive strength with an elastic modulus of 0.68×10^6 psi, while wooden cribs of the same configuration averaged 811 psi compressive strength with an elastic modulus of 24.5×10^3 psi. A series of field demonstrations conducted by Smelser and Henton (1983) at seven coal mines and one trona mine demonstrated that SFRC supports were a technically superior and potentially cost effective alternative to wood supports in mines. In all but one of the demonstrations, the supports were used as a direct replacement for wooden supports in the tailgate entries of active longwall panels at mines.

Smelser and Henton concluded that it was technologically and economically feasible to utilize these supports as substitutes for wood cribbing; however, the configuration and dimensions of full-size cribs constructed of these materials affect their ultimate compressive strength and “after-failure toughness.”
They determined that supports with solid, smaller cross-sections with fewer joints have the highest strength per unit area with the greatest post-failure “toughness.”

**Development of Structural Materials**

**Advantages of Engineered Supports vs. Wood**

CCBs-based artificial supports have several advantages over their wooden counterparts. Specifically, CCBs-based supports are much stronger and stiffer than wood products; they are dimensionally stable, will not decay or absorb water, and will not burn. In addition, these artificial supports can be excavated with today’s mining machinery, unlike wood, which shreds and becomes wrapped around the cutter head.

**Performance Advantages of CCBs-Based Artificial Supports**

Figure 1 illustrates the relative performance of 8-inch × 8-inch × 24-inch wooden posts and 6-inch × 6-inch × 24-inch CCBs-based posts, tested axially, while Figure 2 illustrates the relative performance of wooden and CCBs-based cribs.

The CCBs-based posts averaged about 3,000 psi in compressive strength while the wooden posts averaged about 2,300 psi with average elastic modulus of 450,000 psi and 160,000 psi respectively. This demonstrates an improvement of about 30% in unconfined compressive strength and 180% in the elastic modulus. 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, was supplied by the reinforcing fibers utilized in the mix.

A comparison of the performance of the crib members, tested in a crib configuration, shows even greater improvements. The artificial 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% improvement in the elastic modulus.

**Other Advantages of CCBs-Based Artificial Supports**

The use of CCBs-based artificial supports in place of wooden supports would help address the problems of deforestation, and seasonal fluctuations in the supplies and cost of supports, as well as disposal of CCBs. In addition, the use of these supports would enhance worker safety, since CCBs-based supports are
substantially stronger and stiffer than wooden supports, are not effected by moisture, and are incombustible. Since the moisture content of wood adversely affects its strength, wood gradually becomes less effective as a support over time in a humid mine environment. A replacement for wood that shows good time-dependent strength characteristics will enhance safety by providing superior long-term roof support. Wood not only degrades over time, it is dimensionally unstable; it is subject to shrinkage, and supports constructed of wooden materials require periodic retightening to provide an acceptable level of support. Supports manufactured from CCBs-based materials are dimensionally stable; they will not shrink (or swell) over time; they do not absorb moisture and will not decay. An additional benefit of CCBs-based supports is they will not burn. Composed of about 70% fly ash and 30% binding agents, the finished products are incapable of supporting combustion.

Potential for Utilization

It has been estimated that the substitution of CCBs-based post and crib members in lieu of wood could utilize about $0.25 \times 10^6$ tons of coal combustion by-products in the Illinois Basin alone (Chugh, et. al., 1996). This would amount to about $2.5 \times 10^6$ tons nationwide, an amount that could double if the materials were utilized in non-coal operations as well. The utilization of CCBs-based artificial supports in place of wooden supports will help address the problems of deforestation, seasonal fluctuations in supplies of supports, non-uniform support quality, and disposal of CCBs and associated environmental problems.

Prototype Fabrication and Field Demonstration Studies

Development of Facilities for Production of Prototype Supports

Laboratory studies resulted in mix development for lightweight CCBs-based structural materials in the 75-105 pcf density range. The mixes typically consisted of about 70% F-fly ash, binders, and appropriate fibers (Chugh, et. al, 1998). Experience gained in the production of laboratory sized specimens was used in assembling a facility for producing full-sized prototype post and crib elements. The facility consisted of a large mixer, mold preparation/handling operations, curing equipment, and finished product storage. The posts and crib members produced in this facility were utilized in two (2) field demonstrations to test the viability of CCBs-based artificial supports in a mine environment. Experience gleaned from the assembly and use of the prototype facility was utilized in the design of a full-size pilot scale facility.

Fabrication of the prototype, CCBs-based artificial supports began during August 1996 and concluded in May of the following year. Approximately 230 crib members (5 inch × 5 inch × 30 inch) and 20 posts (6 inch × 6 inch × 96 inch) were produced at the facilities for use in two field demonstrations and for characterization testing.

Support Characterization

Engineering properties of the crib elements were obtained utilizing a 600,000 lb. MTS stiff testing machine. Testing of the posts was conducted utilizing a large-scale testing machine, designed by the department staff, 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 specimens up to 7 ft. in length.

Characterization of specimens was accomplished by determining the unconfined compressive strength and elastic modulus as a function of density. Crib members were trimmed to a length of 24 inches and tested in the MTS stiff testing machine under a constant rate of loading, approximately 3000 lb./minute. Posts were trimmed to a length of 7 feet and tested in the full sized testing machine. Poisson’s ratio was determined for the crib elements utilizing dial gages setting in the longitudinal direction.
Figure 3 shows the relationship between the unconfined strength, \( C_0 \), and the density, \( \rho \), where \( C_0 \) (cribs) = 142.76e^{0.0304\rho}, \( R^2 \) (cribs) = 0.8207, and \( C_0 \) (posts) = 364.98e^{0.035\rho}, \( R^2 \) (posts) = 0.9341, \( N \) (cribs) = 19 and \( N \) (posts) = 3. A total of twenty-eight (28) crib elements, 5-inches \( \times \) 5-inches \( \times \) 24-inches in size, and four (4) posts, 6-inches \( \times \) 6-inches \( \times \) 72-inches in size were tested.

Figure 4 shows the relationship between the elastic modulus, \( E \), and the density, \( \rho \), where \( E \) (cribs) = 0.5206e^{0.0249\rho}, \( R^2 \) = 0.4724, and \( E \) (posts) = 0.7142e^{0.035\rho}, \( R^2 \) = 0.7618 and \( N \) (cribs) = 19 and \( N \) (posts) = 4.

A significant problem manifested itself during the manufacturing of the prototype supports. Of the twenty (20) posts manufactured, 10 broke immediately after removal from the curing tanks, six were sent underground at Old Ben #26 for the initial field demonstration, and four were set aside for characterization studies. Of the ten posts that were successfully produced, six eventually broke before utilization. The breakage problem was successfully addressed when the concept of a disposable mold, one that remains on the support after completion of the manufacturing process, was introduced. 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.

Initial studies of CCBs-based supports cast into plastic pipe were very encouraging. The supports, both solid and solid core designs, exhibited performance characteristics very similar to wood products, as shown in Figure 5. Figure 6 shows a full size support utilizing a disposable mold of circular cross-section after failure.

**Old Ben Coal Field Demonstration**

The first field demonstration of the prototype CCBs-based post and crib elements took place at the Old Ben Coal Company Mine #26, located near Sesser, Illinois, during the months of November and December, 1996. Old Ben #26 was mining the Illinois #6 seam at a depth of about 600 feet with an immediate roof composed of approximately 30 feet of competent gray shale. The coal seam averaged 8 feet in thickness and roof conditions in this area were generally favorable.
Test Area and Instrumentation

The posts and cribs were placed in the tailgate entry, illustrated in Figure 7, of the last longwall panel of the mine; Old Ben Mine #26 ceased operations after this panel was completed. Two cribs and three posts were erected and equipped with load cells designed at SIUC. However, the load data for two posts were unobtainable. Two wooden cribs and one wooden post were equipped with load cells as controls. The outbye wooden crib, located at station 893+00 was damaged during the test and its data was discarded.

![Figure 5. Performance of CCBs-based supports cast into disposable molds.](image)

![Figure 6. Full size post cast into a disposable mold.](image)

The load cells, developed as part of this study, are relatively inexpensive, accurate, and durable instruments for measuring dynamic loads in the field. They were designed to be disposable and easily assembled and consist of a 3 ½ inch × 3 ½ inch × 1 inch polyurethane wafer placed between two 7 ½ inch × 7 ½ inch × 1 inch steel plates. The lower plate has ¼ inch diameter holes at each corner where the compression of the wafer was to be measured by use of a bottoming micrometer. The load deformation curve for the polyurethane wafers was determined with the use of the 600,000 lb MTS stiff testing machine at SIUC. The load on each cell was determined by averaging the compression, or displacement, measured at each corner of the load cell. The equation describing the load characterization curve of the polyurethane wafers is Load = $2 \times 10^7 \times \text{Disp}^3 - 7 \times 10^6 \times \text{Disp}^2 + 1 \times 10^6 \times \text{Disp}$.

![Field Demonstration #1 - Old Ben Coal Co. Mine 26](image)

![Figure 7. Old Ben #26 Field Demonstration.](image)
For the cribs, one of these load cells was placed at each corner during assembly, approximately halfway between the roof and the floor. For the posts, the load cells were placed between the top of the post and the existing wooden crossbar.

Convergence points, consisting of ½-inch × 18-inch diameter pins driven into the mine floor beneath a roof bolt, were installed adjacent to each post and crib utilized in this demonstration. An extensometer was utilized for measuring the roof-to-floor convergence.

**Data Gathering and Analysis**

Initial measurements were taken on the load cells immediately after erection of the CCBs-based artificial supports with a second set of measurements taken 2 ½ weeks later. When the longwall face approached to within 200 feet of the inby support, load cell measurements were taken every shift until the face passed the last instrumented support. A bottoming-type micrometer was utilized to measure the compression of the load cells to the nearest 0.001 inch. Convergence measurements were taken with an extensometer to the nearest 0.01 inch.

**Mine #26 Demonstration Results**

The results of the Old Ben demonstration are shown in Figures 8 and 9. Figure 8 compares the performance of the wooden and CCBs-based cribs as load vs. deformation while Figure 9 compares the performance of the wooden and CCBs-based posts. 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.

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.

![Figure 8. Crib Performance at Old Ben Mine #26.](image1)

![Figure 9. Post Performance at Old Ben Mine #26.](image2)

**Costain Coal Co. – Pyro Mine Demonstration**

The second field demonstration of the CCBs-based artificial supports took place at the Pyro Mine of Costain Coal Co., located near Clay, Kentucky, during the month of June, 1997. For this demonstration, the 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.
Test Area and Instrumentation

The test area at the Pyro mine, illustrated in Figure 10, was located one crosscut in by 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.

The seam height in the test area averaged around 6½ feet and roof conditions were generally poor. The immediate roof consisted of weak gray shale that was difficult to support during panel development. Mine management indicated that the maximum depth of a cut was usually only about 10 feet before roof bolting and most attempts at achieving a deeper cut resulted in a major roof fall. Cable type truss bolts are utilized as secondary supports to provide long-term entry stability throughout the mine.

After bringing the artificial crib elements inside, mine personnel proceeded to install 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 the Old Ben Mine #26 demonstration.

After erecting the cribs, mine personnel determined that a ventilation wall was required behind the CCBs-based cribs and materials were brought in to complete this job. In the process, two of the cribs were severely damaged by a utility tractor and required reinstallation. Several crib members were cracked or broken and one crib was assembled with broken elements. This is referred to as the “remnant” crib. This crib survived the demonstration, however, and was reportedly still standing as of January 1999.

Figure 10. Costain Coal Pyro Mine Field Demonstration.

Data Gathering and Analysis

The cribs were monitored for load and vertical displacement, utilizing the same procedures as the Old Ben demonstration except that monitoring of the supports took place from the startup of the face until subsidence was observed on the surface. Convergence stations were installed adjacent to the monitored supports to determine the amount of vertical displacement; however, the readings indicated that the roof and floor were diverging rather than converging. A closer inspection revealed that the roof in this area was moving laterally, toward the mined-out, or gob area, indicating high lateral stresses in the immediate roof. Approximately 14 inches of horizontal roof movement was observed in this demonstration, precluding the
use of the convergence stations to determine displacement. Without convergence data, the field information from this demonstration was analyzed for load as a function of time and distance of face retreat.

**Pyro Mine Demonstration Results**

The results of this demonstration can be observed in Figure 11 and Figure 12. Figure 11 shows the loading of the cribs as a function of time while Figure 12 shows the loading of the cribs as a function of face location. In this 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.

The observed elastic modulus of the CCBs-based posts were about 1.5 to 2.0 times higher than the wood post and the observed elastic modulus for the cribs was 2.0 to 2.5 times higher than the wooden crib at Old Ben #26.

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 Pyro Mine reported that the test cribs remain intact, despite the failure of most wooden cribs in the area immediately adjacent to the test area.

Mine management at Pyro has expressed an interest in these supports due to the difficulty in obtaining quality wooden supports at a reasonable price during the winter months. The only objection to the artificial supports was breakage. The extremely rough handling the members were subjected to (being run over by a utility tractor) resulted in several broken pieces and management at this operation felt that the supports should be as durable as wood to find acceptance within the mining industry.

**Assessment of Field Demonstrations**

Field demonstrations of the CCBs-based artificial supports were generally successful and the superior performance characteristics and the potential for utilization as direct substitutes for wooden supports were clearly documented. At Old Ben #26, the CCBs-based cribs supported loads that were, on average, 62% higher than the wooden crib while the CCBs-based post carried over 2 ½ times the load of the wooden post. At Pyro mine, the CCBs-based crib supported loads that were on average 26% higher than the wooden crib.
Development and Demonstration of Mine Ventilation Blocks

The developed blocks are 8 inch × 12 inch × 16 inch in size and have a density of 30-40 pcf. The mix design for the blocks includes about 80% FBC fly ash and F-ash in appropriate proportions, binding agents, and fibers. The strength of the finished blocks ranges from 150-280 psi. The blocks have been subjected to strength and fire propagation tests by MSHA and have been approved for use to construct mine ventilation stoppings. These blocks are shown in Figure 13.

![Figure 13. CCBS-Based Ventilation Blocks.](image_url)

Design and Development of Commercial Scale Facility

Three of the industrial cooperators involved in the research into the development of CCBs-based structural materials, Webb Oil Co., Eagle Seal, Inc., and Woodruff Supply Co., have recently formed a joint venture, Fly-Lite, Inc., to produce CCBs-based products on a commercial basis. Construction of the plant began in December 1998, and limited production scheduled began in late 1999. At the date of this writing, the facility is producing approximately 100 ventilation blocks per day utilizing a batch mode of operation.

Initial production will be about 20 tons per day of fly ash and binding agents, using a batch method. As product demand increases, the process will evolve into the high capacity, continuous operation. Utilizing a batch process during the initial production phase will help minimize waste of materials while training the labor force and making adjustments to the manufacturing process. The plant is designed to process 100 tons per day of dry materials.

The Fly-Lite Plant is designed to produce lightweight post and crib members as well as ultra-lightweight mine ventilation blocks.

Conclusions

Viability of Structural Materials

If CCBs-based artificial supports are to gain acceptance within the mining industry, they must not only possess superior performance characteristics and be cost competitive, but also have similar physical dimensions. These engineered supports must also utilize existing equipment and techniques for installation, and should not require special training before use. In general, the mining industry within the U.S. is very conservative and prefers to maintain the status quo. The general feeling within the industry may be to utilize wooden supports because “that’s the way we’ve always done it.”

Detailed cost analyses have demonstrated that CCBs-based cribs (5-inch × 5-inch × 30-inch) can be manufactured for around $2 while 8-inch × 8-inch × 96-inch posts can be produced for around $15, prices that are very competitive with traditional wooden support members.
Marketability of CCBs-Based Supports

The work presented in this paper has demonstrated that CCBs-based artificial supports have superior strength characteristics as compared to their wooden counterparts, and can be produced in sufficient quantities at a competitive price. This work may change some minds within the industry, causing some to take a better look at CCBs-based artificial supports. So far, the response from individuals within the industry that have been exposed to these supports is strongly positive. In addition, by utilizing disposable molds of square cross-section, these supports can be produced in shapes and sizes very similar to existing wooden supports. Field experience has also shown that CCBs-based supports can be cut to length with commonly used hand and power tools and will readily accept a mine spad or screw. No special equipment or tools should be required in the utilization of these products as direct replacements for wooden supports.

References


Acknowledgements

The authors sincerely acknowledge the financial support of the Office of Coal Development and Marketing of the Illinois Department of Commerce and Community Affairs and the Federal Energy Technology Laboratory of the U.S. Department of Energy. The cooperation and financial support of the industrial cooperating organizations is also sincerely acknowledged.

1Paul Chugh has BS, MS, and Ph.D. degrees in Mining Engineering; the latter two are from The Pennsylvania State University. Dr. Chugh has been at Southern Illinois University for the past 23 years. For the past 9 years, he has been actively engaged in research, development, and demonstration studies related to coal combustion by-products. He has commercialized three CCBs-based lightweight structural materials for use in mining industries. Currently, he is developing utility poles from CCBs and hopes to commercialize them in the near future. He is currently Director, Combustion By-products Recycling Consortium-Midwestern Region.