Project Title: **LIGHTWEIGHT COMBUSTION RESIDUES-BASED STRUCTURAL MATERIALS FOR USE IN MINES**

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**ABSTRACT**

This project’s goal was to develop coal combustion by-products (CCB)-based lightweight structural materials with suitable compressive strength to replace wooden posts and crib members. Lightweight F-fly ash/cement grouts, with density and compressive strength ranging from 70 to 110 pcf and 1,500 to 5,000 psi, respectively, were developed. These grouts contain a very high volume (50 - 60% of the whole solid materials) of F-type fly ash produced from burning Illinois coals, ASTM Type I cement, lime, silica fume, polypropylene or nylon fibers, protein-based micro foam, water-reducing agents and superplasticizers, and fluidized-bed combustion by-products.

About 40 different mixes using low and high LOI were initially screened for the effects of different variables. Strength and environmental studies led to identifying 2 final mixes, containing about 65% higher LOI (10-12%) fly ash, which were used to develop pertinent geotechnical and environmental properties data for fabricating prototype supports.

A typical solid wooden post and a solid wooden crib element were replaced with an equal-weight hollow CCB-based 90 pcf material post and an equal-weight 80 pcf CCB-based material, respectively. Based on industry input, a unified post/crib element was also designed. Analysis of the wooden and developed post and crib supports’ load-bearing capacity and load-deformation characteristics indicated that CCB-based supports are significantly superior. Economic analyses for a commercial operation indicates this project is feasible.
EXECUTIVE SUMMARY

This project developed coal combustion by-products (CCB)-based lightweight structural materials to replace mining wooden posts and crib members. The developed materials possess: 1) a structural strength-to-weight ratio similar to the wood typically used; 2) appropriate load-deformation characteristics in tension, compression and shear; 3) time-dependent failure characteristics (ductility); 4) hydrophobic properties and low permeability; 5) low long-term degradation potential; 6) very low shrinking/swelling potential and 7) appropriate chemistry and leachate characteristics.

During the first 2 quarters, wood products and the CCB-based lightweight structural materials’ individual components were characterized and a low-pressure steam curing cycle was developed. Mix designs led to identifying appropriate materials (in the 70-110 pcf density range) that had 50% low LOI (<5%) F-type fly ash and a compressive strength of 1,500 to 5,000 psi. In the third quarter, materials similar to those above were developed using a higher LOI (>10-12%) F-type fly ash increased to about 60%. Two (2) final mixes, one containing FBC fly ash and the other containing lime to develop early fly ash strength, were identified for fabricating prototype post and crib elements and the effect of a waterproofing chemical was also tested.

Engineering Behavior of Wooden Posts and Crib Elements--The average bulk density, moisture content, yield strength, ultimate strength and elastic modulus for typical crib elements presently used are 56.1 pcf; 24.0%; 783 psi; 2,045 psi; and 36.3 x 10^3 psi, respectively. Similar data for wooden posts are 54.4 pcf; 24.3%; 2,967 psi; 3,483 psi; and 251.8 x 10^3 psi, respectively.

Characterization of Individual Component Materials for CCB-Based Structural Materials--Individual component of the CCB-based materials include F-fly ash, Type I cement, micro silica, polypropylene or nylon fibers, water-reducing agent and superplasticizer, protein-based or synthetic foaming chemical for air entrainment, FBC spent bed ash, FBC fly ash and lime.

Mixing and Curing Techniques--Mixes were generally prepared in a 3-speed 24 l Breastline mixer with a maximum speed of 354 rpm giving medium shear mixing. A low-pressure steam-curing cycle with a maximum temperature of 160°F (70°C) was utilized to achieve strengths equivalent to an ASTM 28-day cure in less than 3 to 4 days.

Results of Preliminary Mix Studies--About 40 different mixes involving over 100 samples were tested for unconfined compressive strength and elastic modulus to evaluate the effects of different variables. The relationships between density, unconfined compressive strength and elastic modulus for low and high LOI F-fly ash are given below:

For Low LOI Fly Ash:

\[ C_0 = 99.3 \text{ density} - 6039 \text{ psi} \]  
\[ E = 11.25 \text{ density} - 596.9 \text{ (psi x 1000)} \]
For High LOI Without FBC Fly Ash:

\[ C_o = 76.4 \text{ density - 4816 psi} \]  
\[ E = 14.75 \text{ density - 826 (psi x 1000)} \]

Pertinent results indicated: 1) lightweight materials can be produced with a very low water-to-solids ratio (0.17 to 0.25); 2) since the elastic modulus for developed materials is higher than that for wood, the developed materials should provide significantly better ground control than do wooden supports; 3) nylon fibers provide better reinforcement than polypropylene fibers do, and fiber reinforcement virtually eliminates brittle behavior; 4) intimate mixing of component materials is essential and mixing speed increases the strength and elastic modulus of the developed material; 5) the relationship between flexural strength and compressive strength for the developed lightweight materials is similar to that for normal concrete; and 6) 1--30% loss in strength due to higher LOI fly ash can be largely recovered by replacing lime with FBC by-products. Based on preliminary mix studies, two final mixes were identified—one contained lime and the other contained FBC fly ash to develop fly ash early strength.

**Engineering Properties of Final Mix Materials**—To evaluate the effects of density and curing cycle and to correlate different properties, over 50 samples for each mix were tested for compressive strength, indirect tensile strength, flexural strength, permeability, swelling strain, impact resistance and creep. Major findings include: 1) bulk density is the most important variable in assessing the compressive strength properties of low-pressure steam-cured materials; 2) bulk density and curing time define the above properties for ASTM-cured materials; 3) 28-day ASTM cure-strength can be achieved with a 3-day steam-curing cycle; 4) permeability values for 95 pcf and 80 pcf materials are in the $3 \times 10^{-7}$ in./sec range; 5) Mix 1, with FBC fly ash, is superior to Mix 2; and 6) creep deformations seemingly do not become significant until about 80% of the failure stress (additional studies should confirm this).

**Environmental Properties**—A material developed from a preliminary mix, several samples from final mixes, a cement grout mix and a commercially-available lightweight block (OMEGA) for mine ventilation stoppages were selected for Toxicity Characterization Leaching Procedure (TCLP) testing and leachate analysis using an inductively coupled plasma (ICP). For the preliminary mix, selenium and lead Class I (Illinois) standards were exceeded. For commercially-available mortar mix grouts and OMEGA blocks, chromium, cadmium, selenium and lead were exceeded. A 4 to 5 times dilution would bring all of the values into the compliance range. Illinois Class II standards are met for all elements, except for selenium in CCB-based material (but not in an OMEGA block). Final mix materials and TCLP data for component materials are included in the main report. Cadmium and chromium seem to exceed acceptable limits; however, a 10 to 20 times dilution should bring all values down to acceptable limits.

Samples of the 2 final mixes were subjected to ASTM 24-hour shake test. A non-waterproofed sample and a sample coated with a commercially-available waterproofing agent were tested. In addition, during the mixing stage, Mix 1 was reformulated to include cellulose in one case and a waterproofing agent in the other case. The elements selected
for ICP analysis included Se, Mo, B, Zn, Cd, Pb, Co, Mn, Fe, Mg, Va, Al, Be, Ca, Cu and Ba. The findings from these tests indicate:

1. The concentration of all examined elements is very low—often below the ICP detection limit. The only elements that may pose a marginal problem with Illinois EPA Class I standards are B, Pb and, possibly, Va.

2. When applied as a coating, the waterproofing agent reduces Ca, Va, B, Mo and Al concentrations, but the Pb concentration tends to increase, indicating leachable lead in the waterproofing chemical.

3. Wettability is significantly reduced with a surface coating of a waterproofing chemical or by adding a small amount of cellulose to the mix.

Design of Prototype Post and Crib Elements—Prototype post and crib elements nearly the same weight as wooden elements were designed (Figure 1) to provide equal or higher strength and stiffness. A hollow post with cross-ribs in the center and 90 pcf CCB-based material was finalized as the prototype post (OD = 6.84 in.; ID = 5.0 in.; T = 0.75 in.). to replace 6 in. x 6 in. wooden posts. A 6-in.-x-6-in. wooden crib element was replaced by a 5-in.-x-5-in. CCB-based 80 pcf material. The ultimate load-bearing capacity and load-deformation characteristics for CCB-based artificial supports were superior to those for similar wooden supports (Figure 2). Based on industry input, a unified post/crib element design (Figure 1) was also analyzed. This design should provide better stacking and transportation characteristics and simplify the commercialization process.

Economic Analysis of a Commercialization Project—Economic analysis of a commercialization project producing about 1,000 posts per day and utilizing 250,000 tons of fly ash annually was performed in conjunction with industrial sponsors. An initial capital outlay of about $0.7x10^6 is needed to produce a prototype hollow post 6 ft long at a cost of about $5.40 --a cost comparable to producing wooden posts. Thus, results indicate that such a project is viable.
Figure 2a Force–Deflection Characteristics for Wooden and CCB-Based Post

Figure 2b Force–Deformation Characteristics for Wooden and CCB-Based Crib
OBJECTIVES

The overall goal of this project was to replace underground mining wooden posts and crib members with similar lightweight elements manufactured from CCB. Specific objectives are in the "Executive Summary" section.

INTRODUCTION AND BACKGROUND

1.0 Concrete as Mine Supports

The advantages of concrete supports are low repair and long-term maintenance costs, high electrical and fire resistance, and low ventilation resistance. A study made by Anderson and Smelser\(^1\) indicated that steel-fiber-reinforced concrete (SFRC) support members offer significant improvements over wooden supports in stiffness and compressive strength and avoid plain concrete's brittle compressive failure mode. A field demonstration by Smelser and Henton\(^2\) concluded that steel-fiber-reinforced concrete is a cost-effective and technically-feasible mine roof supporting material. Lightweight (90 pcf) concrete cribs were tested by Manni\(^3\), and results showed a better load-bearing capacity and post-failure performance than wood. A shaft seal design\(^4\), featuring lightweight concrete as a key material component at a wet density of about 45 pcf, was developed and demonstrated a compressive strength of 200 psi at 7 days and over 300 psi at 180 days.

2.0 Fly Ash as a Cementitious Material

Fly ash is a condensation product which is primarily spheroidal (individual particles range from less than 1 μm to greater than 1mm). While particle size and surface area play a dominant role in determining the relative rates of reactivity, curing temperature and fly ash fineness also effect reactivity rates. Fly ash particles smaller than 10 μm have a positive influence on the early strength development rates of portland cement/fly ash mixtures.

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Due to high proportions of silica and alumina, F-type fly ash consists principally of aluminosilicate glass. When large spheres of molten glass do not cool rapidly and uniformly, aluminosilicates crystallize as slender needles in the interiors of the glassy spheres and large quantities of crystalline minerals reduce fly ash reactivity. To increase fly ash reactivity and strength, lime and curing temperatures can be increased, respectively.

The hydration of fly ash in the presence of portland cement involves a three-stage reaction. Immediately after mixing with water, reaction rims of impermeable coating surround the fly ash particles. No further reactions occur until alkali or calcium hydroxide and sulfates ions in sufficient concentration are available in the solution phase. Thus, during the second stage, it is primarily the hydroxide ions which activate the hydration of fly ash glasses. During the third phase, which is the main hydration stage, a slow pozzolanic reaction continues to consume calcium hydroxide and form calcium silicate hydrates as long as calcium and hydroxyl ions are available.

In high loss on ignition (LOI) fly ash, some unburned carbon may be encapsulated in glass, but a major portion occurs as cellular or lacy particles with a high internal surface capable of absorbing large amounts of water and chemical admixtures from an aqueous solution. If the proportion of carbon particles, which are usually larger than 45 μm, is high in a fly ash, using it as a mineral admixture in concrete increases the water requirement and the consumption of entraining admixtures. Adding 1-20-μm-sized fly ash supplements the effect of portland cement grains by further reducing the volume of voids in the concrete mixture; thus, less water is needed to produce a concrete of a given consistency. Berry and Malhotra5 noted that a 30% replacement of cement with fly ash reduces water requirements by 7%. Lane and Best6 and Davis, et al.7, demonstrated that the presence of a high amount of carbon causes set retardation when mineral admixtures are added. To reduce water quantity while retaining the desired consistency, a superplasticizer is added to the mix; this reduces permeability and shrinkage and attains a better surface finish. Because the compatibility between unburned carbon and the foaming chemical is critical8, the MEARL Corporation provided chemicals that were proven suitable for use with high LOI fly ash.


Although using fly ash as a cement replacement in concrete provides significant economic and technical benefits, its usage rate in the U.S. remains less than 25% of its production rate. Various admixtures have been introduced in fly ash concrete. A water-reducing agent was one of the most important admixtures for increasing mechanical properties (i.e., compressive and flexural strength and the modulus of elasticity). Since the 1970's, a high-range water reducer called superplasticizer has been widely used. In 1985, CANMET began to develop superplasticized high-volume fly ash concrete wherein a low water content and a high degree of workability were obtained by using high dosages of superplasticizers. A special superplasticizing admixture capable of improving lightweight concrete workability at a very low water/cement has been developed by Berra, et. al. The research most relevant to this study was recently completed by Berry, et. al., involving high volume fly ash concrete systems.

EXPERIMENTAL PROCEDURES


RESULTS AND DISCUSSION

1. Engineering Characteristics of Wooden Post and Crib Elements

Three 6-in.-x-6-in.-x-12-in. pieces of wood were cut from wooden posts typically used at a mine. Similarly, 3 crib elements (5 in. x 5 in. x 12 in.) were also obtained from the same mine. These were analyzed for moisture content and density and were subjected to compression for strength-deformation studies. The post elements were subjected to a uniform loading rate of 100 to 150 psi per minute axially, while crib elements were loaded along the length in a 600,000 lb. MTS stiff testing machine. The results of these studies

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were summarized in the "Executive Summary" section of this report. Stress-Strain curves for a post and a crib element are included in Figure 3.

2. **CCB-Based Structural Material Components and Their Characterization**

The constituents of developed CCB-based materials include low and high LOI F-fly ash from Illinois coal combusted in pulverised coal combustion (PCC) boilers, Type I portland cement, silica fume, polypropylene or nylon fibers, a water-reducing agent and a superplasticizer, a microfoaming chemical for air entrainment and FBC by-products (spent-bed ash and fly ash).

The chemical composition of fly ash, cement, silica fume, FBC spent bed and FBC fly ash are given in Table 1. The F-fly ash mean particle size was about 15 to 17μm. The fly ash LOI values were about 5% and 10%, respectively. The mean particle size for cement was about 20 μm and the C₃S, C₂S and C₅A were 47.6%, 26.1% and 6.6%, respectively. The mean particle size for microsilica was about 1 to 2 μm (ranging from 0.3 to 20 μm). The mean particle size for FBC spent-bed ash and fly ash were 45 μm and 8 μm, respectively. The FBC spent bed ash was washed prior to use and only the fraction passing a 600-micron sieve was used.

| Table 1. Major Chemical Constituents of Cement, Fly Ash, Silica Fume and FBC By-Products |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Chemical Composition | Fly Ash (\%) | Cement (\%) | Silica Fume (\%) | FBC Spent Bed (\%) | FBC Fly Ash (\%) |
| Silicon Oxide (SiO₂) | 56.71 | 21.60 | 94 | 9.7 | 22.1 |
| Aluminum Oxide (Al₂O₃) | 11.08 | 4.47 | - | 3.69 | 6.8 |
| Iron Oxide (Fe₂O₃) | 21.32 | 3.12 | 1 | 2.16 | 6.67 |
| Calcium Oxide (CaO) | 5.29 | 62.41 | - | 53.10 | 38.70 |
| Magnesium Oxide (MgO) | 1.0 | 3.80 | - | 0.88 | 1.29 |
| Loss on Ignition (LOI) | | | | | |
| High LOI |  \(\approx\) 10 | - | 3 | 0.80 | 5.46 |
| Low LOI | \(\approx\) 5 | - | - | - | - |

*The power plant indicated that low and high LOI fly ash had similar chemical composition, except for LOI value.*
Density Fractionation of Fly Ash--During the early stages of this project, an attempt was made to separate fly ash into fractions of differing density using a density gradient centrifugation (DGC) approach. Six (6) specific gravity zones (i.e., 1.0-1.3; 1.3-1.6; 1.6-1.9; 1.9-2.2; 2.2-2.4; and above 2.4) were used. Most of the fly ash sample (about 90%) has a density above 1.9 g/cm³, and nearly half of it has a density greater than 2.4 g/cm³. Since only a very small amount (less than 5%) of this fly ash has a low specific gravity (less than 1.3), it appears unlikely at this time that sufficient low-density material could be isolated to significantly enhance lightweight concrete. The distribution of trace elements by specific gravity were also discussed in the above reference. Most of the trace elements were also concentrated in heavier fractions.

Polypropylene and Nylon Fibers--The specific gravity, length, diameter, tensile strength, elastic modulus and melting point for the nylon fibers used in this research were 1.14, 0.83 in., 18 µm, 100 x 10³ psi, 690 x 10³ psi and 496°F, respectively. Similar data (except the melting point) for the polypropylene fibers used in this project were 0.92, 1.0 in., 1,400 micron, 40 x 10³ psi and 3,643 x 10³ psi, respectively.

Superplasticizer--A normal water reducer is capable of reducing water requirements by about 10-15%, whereas a superplasticizer is capable of reducing this up to 30%. A liquid superplasticizer (specific gravity = 1.2 and dosage ≈ 1.2 liters per m³ of mix), with the brand name "Mighty - 150", was used. The active ingredients of Mighty - 150® are 42% aqueous solution of high molecular weight of sulfo-aryl alkaline + carboxylic acid.

Foaming Equipment and Chemicals--Ten-gallon foaming equipment and 2 foaming chemicals were provided by the MEARL Corporation; one of the chemicals was protein-based and the other was a synthetic to be used if latex-based admixtures were utilized. The foaming equipment permits an expansion ratio of 10 to 30. The average size of the microbubble was 20 to 30 µm.

3. Mixing, Sample Preparation and Curing Procedures

The mixing component materials, sample preparation and curing procedures are extremely important to obtain good strength-deformation, durability and impact resistance properties for CCB-based materials. In general, procedures outlined in ASTM C31, C42, C192 and C1018 were followed for specimen preparation.

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Chugh discussed the mixing sequence in detail. In this study, accurately-weighted amounts of cement, fly ash, silica fume and lime/FBC fly ash were mixed dry and 3 mixing speeds (tip speeds of 540, 1,080 and 2,123 in./sec.) were used to mix the ingredients. Superplasticizer was added along with the mixing water.

It is well-established that fly ash continues to gain strength over a long period of time (3 to 5 years) and that lime must be added to develop early strength in fly ash/cement mixes. Even with the addition of lime, it would be uneconomic to cure fabricated supports for a period of 28-56 days prior to marketing. Therefore, it was decided to use a low-pressure steam-curing cycle. In this cycle, a sample in the mold was moist-cured for 24 hours at 90 to 100% RH and at 72°F. The sample was then demolded and transferred to a low-pressure steam chamber (150°F to 160°F and 100% RH) in which the final temperature was attained in 2 hours. After steaming for 24 hours, the temperature was lowered to 72°F in about 2 hours. The samples were air-dried for different periods of time prior to testing. Samples prepared from the final mix designs were also subjected to ASTM-approved curing cycle (i.e., 7 days moist-curing followed by 21 days of air-drying) to develop strength correlations between the two curing cycles.

4. **Mix Designs**

Despite the significant advances in the study of fly ash utilization as a significant replacement for cement in concrete, only a very small amount of fly ash (10-15%) is typically used to replace cement in a concrete mix. The number is even smaller when we consider that cementitious materials account for only fifteen percent (15%) or less of the total mix materials in concrete. In this study, a much larger fraction of fly ash was used in the mix (about 28% by volume or 43% by weight).

Since fly ash curing requires a long time, the early strength in high volume fly ash-cement grout (HVFA) is generally low. Some possible ways to increase HVFA cement-grouts' early strength are reducing the water to cement ratio through medium and high shear mixing and/or adding high-range water-reducing agents or superplasticizer, and adding silica fume, lime, etc. Furthermore, the compatibility of foam for air entrainment with fly ash organic carbon can also be a critical factor.

Seven (7) sets of preliminary mix designs were tested for progressive improvement with the specific objective of evaluating the specific effect of a variable. For example, the first set was designed to identify 1 or 2 mixes which would provide close to the desired strength,

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whereas mixes in the second set were designed to evaluate the effect of various fiber amounts on strength. Other variables considered were the water to cement ratio, the amount of lime, sample preparation in layers and the use of calcium chloride as an accelerator. Within each set, a number of trial mixes were attempted. Most of the mixes utilized in the above studies were based on 50% cement and 50% low LOI fly ash by weight.

Around March 1, 1995, the power plant disclosed that low LOI fly ash will not be available if the project is commercialized. However, about 100,000 tons of higher LOI F-type fly ash (= 10-12% unburned carbon) from another PCC boiler at the plant will be available annually. Therefore, additional high LOI fly ash mixes were made to determine the final mixes suitable for fabricating CCB-based lightweight structural materials. The mix designs considered these variables: fiber type, replacement of lime by FBC spent bed or FBC fly ash and fly ash percentage. Based on the above studies, 2 final mixes were selected for characterizing pertinent engineering and environmental properties. The final mix constituents for Mix 1 were: 34% cement; 59.4% high LOI fly ash; 1.8% silica fume; 740 ml water; 10% superplasticizer; 38.7 gm. nylon fiber; and 4.8% FBC fly ash. The final mix constituents for Mix 2 were: 34% cement; 61.8% high LOI fly ash; 1.8% silica fume; 740 ml water; superplasticizer 10%; 38.7 gm. nylon fiber and 2.4% lime.

5. Engineering Properties of Developed Materials

The developed lightweight materials were studied for physical and strength-deformation properties. The studied physical properties included: 1) bulk density; 2) permeability; 3) wettability and swelling strain (ASTM 979); 4) sulfate resistance (ASTM C 1012); and 5) impact resistance (ACI 544.2R-89). The strength-deformation properties studies included: 1) unconfined compressive strength with elastic modulus (\(C_o\) and \(E\)) (ASTM C 39); 2) indirect tensile strength (\(T_o\)) (ASTM C 496); 3) flexural strength (\(R_o\)) (ASTM C 78) and flexural toughness; 4) total stress-strain curve analysis; and 5) time-dependent deformation behavior or creep (ASTM C512).

**Preliminary Mixes**

Compressive Strength—Thirty-four (34) mixes using low LOI F-fly ash and involving 80 samples were cast, cured and tested from December 21, 1994, to February 9, 1995. The curing duration varied 3 to 11 days, including 24 hours of steam curing. These samples were primarily tested for \(C_o\) and \(E\) values, with these tests conducted in a 600,000-lb. MTS stiff testing machine. The results were presented by Chugh\(^{14}\). The best-fit equations were given in the "Executive Summary" section of this report. The data indicated that \(C_o\) of 4,500 and 2,500 psi can be achieved at density values of 105pcf and 80 pcf, respectively. These values are for typical 7-days' strength, which should increase with an increase in curing time. These values are very good and close to the goal identified for the project.

Furthermore, the lightweight structural materials are much stiffer (higher \(E\) value) than wood and should improve mining ground control\(^{14}\). Failures in the samples did not occur
violently and fibers held the sample together over a large range of deformation. Studies during this phase also demonstrated that nylon fibers provide about 12.9% higher compressive strength than polypropylene fibers provide.

The results for higher LOI F-fly ash of 6-days curing without FBC by-products were summarized by Chugh. The best-fit equations were included in this report's "Executive Summary". The $C_o$ and $E$ values for these mixes are typically 10 to 30% lower than those using low LOI fly ash. Typical stress-strain curves for several of these mixes are given in the above-mentioned report.

The results for $C_o$ and $E$ for mixes containing high LOI fly ash with FBC by-products are discussed elsewhere in this report. The addition of FBC by-products overcomes most of the negative effects of high LOI fly ash. Replacing small amounts of F-fly ash with FBC by-products may further enhance $C_o$ and $E$ values, but, to keep the mix components simple, this substitution was not studied in detail.

Load-Deformation Behavior of Hollow Cylinder--Studies indicated that wooden posts will probably need to be replaced by hollow CCB-based cylindrical posts. Therefore, strength-deformation characteristics of 2 hollow cylinders (outer diameter 6 in., inner diameter 2.762 in. and length 12 in.) were studied for a mix (38% cement; 58% low LOI fly ash; 1.8% silica fume; 2.4% lime; water to dry powder ratio = 0.18). For the same mix, 3-3-in.-X-6-in. cylinders were also cast and tested. The results were summarized by Chugh. The strength of the hollow cylinders is similar to that of cast solid cylinders.

Flexural Strength Studies--A limited number of tests using ASTM C 78 and 4-point loading on 2-in.-x-2-in.-x-12-in. beams were conducted on materials developed from a mix containing 38% cement, 58% low LOI fly ash, 1.8% silica fume and 2.4% lime. A preliminary relationship was developed between compressive strength and flexural strength as given below:

$$\text{Flexural Strength} = 14.2\sqrt{C_o}\ \text{psi} \quad (5)$$

For normal-weight concrete, the above relationship is given as:

$$\text{Flexural Strength} = 7.5 \text{ to } 10 \text{ times } \sqrt{C_o}\ \text{psi} \quad (6)$$

The flexural strength using nylon fibers was about 32% greater than that using polypropylene fibers.

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Physical Properties

Permeability--The coefficient of water permeability was determined using the falling head method under pressure. Core samples, 1.25 in. in diameter and 2.8 in. long were obtained from the center of 3 in. x 6 in. cast samples. The sides of a cored sample were coated with paraffin before placing in the test cylinder to prevent water seepage along sides. For high pressure falling head permeability test, the coefficient of permeability may be calculated from Darcy’s equation. A total of 3 samples were tested. The results are summarized in Table 2 below including data for other typical materials.

The coefficient of permeability for developed lightweight materials range $3 \times 10^7$ to $10 \times 10^7$ in./sec. These values are considered low and therefore most of the water flow should occur along the outer surfaces of the developed artificial supports and minimize leaching problems.

Table 2. Permeability Data for Selected Samples

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Sample No.</th>
<th>Density (pcf)</th>
<th>Age (days)</th>
<th>Coefficient of Permeability, k (in./s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix 1 (NC)</td>
<td>4.1</td>
<td>90</td>
<td>11 wk</td>
<td>$9.90 \times 10^7$</td>
</tr>
<tr>
<td>Mix 2 (NC)</td>
<td>61.3</td>
<td>98</td>
<td>8</td>
<td>$8.75 \times 10^7$</td>
</tr>
<tr>
<td>Mix 2 (NC)</td>
<td>9.1</td>
<td>81</td>
<td>12</td>
<td>$2.89 \times 10^7$</td>
</tr>
<tr>
<td>Clays</td>
<td></td>
<td></td>
<td></td>
<td>$3.00 \times 10^4$</td>
</tr>
<tr>
<td>Gravel</td>
<td></td>
<td></td>
<td></td>
<td>$3.00 \times 10^4$</td>
</tr>
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</tr>
<tr>
<td>Granite</td>
<td></td>
<td></td>
<td></td>
<td>$3.00 \times 10^{13}$</td>
</tr>
</tbody>
</table>

Swelling Strain--Unconfined swelling strain was determined by placing 3 in. diameter and about 2 in. high samples in water and monitoring axial increase or decrease in length (swelling/shrinkage) using a 0.001 inch resolution dial gage. The data were recorded at suitable intervals for a period of 80 hours. The results for two samples of each mix are summarized in Figure 4. Mix 1 samples show about 0.1% shrinkage for about 1000 minutes before indicating swelling behavior. The maximum swelling strain is about 0.25%. For Mix 2 samples, shrinkage of 0.05 to 0.1% occurs until about 500 minutes. Swelling occurs rapidly until about 4,000 minutes and then appears to level off. The maximum values of swelling strain range 0.3 to 0.4%. Mix 1 is considered better because of its smaller swelling potential. The range of values for both mixes are, however, considered low.
Sulfate Resistance--The test, conducted according to ASTM C1012-89, measures the resistance of developed materials to sulfate environment. Prismatic samples (1 in. x 1 in. x 11 1/4 in.) were cured in low pressure steam chamber for 24 hours and then air-cured for 7-days. The samples were placed in standard sodium sulfate solution to monitor changes in length in accordance with ASTM. C-490 specifications. The results are summarized in Figure 5. Mix 1 seems to perform significantly better than Mix 2 although weight gain as well as change in length are small for both mixes. Visually both mix samples are totally without any degradation whatsoever. Therefore, both mixes should perform well in sulfate environments. The ongoing tests will be continued to assess longer-term performance. The data above were compared with similar data for high density (140 pcf) High Volume Fly Ash Concrete (HVFAC) developed by Berry11. After 24 months, percent weight change and percent length change varied 0.22 to 0.66% and 0.0022 to 0.0160%, respectively.

Impact Resistance--The test was carried out according to ACI 544.2R-89 and it is an important attribute of fiber reinforced composite. The simplest of the impact tests is the "repeated impact" drop weight test. The number of impacts (drops) for two conditions are defined: 1) first crack on the top \(N_1\), and 2) ultimate failure \(N_2\) defined as the opening of the crack by 0.1 in. Samples, 6 in. in diameter and 2.5 in. thick, were cast and cured for different durations prior to testing. Table 3 below summarizes the results. The data are highly variable and do not show any trends with curing duration. Furthermore, the number of impacts are typically range from 4 to 12. Berke and Dallaire16 reported values ranging from 4 to 8 for polypropylene fiber reinforced high density concrete.

Initial and Final Set Times--Vicat apparatus was used to determine the final set time for a Mix 1 sample (density 80 pcf, and moisture content 13%) to be 445 minutes. Similar value for cement is about 251 minutes. Initial set time could not be accurately determined because of the presence of fibers.

Strength-Deformation Properties

Unconfined Compressive Strength with Elastic Modulus--Samples 3 in. in diameter and 6 in. long were tested according to ASTM C-39 test procedure. The testing was performed with uniform displacement rate as feed-back control to obtain post-yield stress-strain curve. The displacement rate was varied between 0.02 to 0.18 in./minute so that samples failed between 4-5 minutes. Load and displacement data were acquired through a digital data acquisition system at the rate of 200 readings per minute. The acquired data were analyzed for ultimate failure stress \(C_o\), failure strain at \(C_o\), post-failure residual stress, tangent modulus and secant modulus at 50% of \(C_o\), \(E_i\), and \(E_{sec}\). Data points at 25% and 75% of \(C_o\) values were taken for calculation of tangent moduli values at 50% \(C_o\).

16 Berke, N.S., and M.D. Dallaire. The Effect of Low Addition Rates of Polypropylene Fibers on Plastic Shrinkage, Cracking, and Mechanical Properties of Concrete. American Concrete Institute, SP 142, pp.19-43.
Table 3. Impact resistance Test Data

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>Sample No.</th>
<th>Density (pcf)</th>
<th>( n_1 / n_2 )</th>
<th>Sample No.</th>
<th>Density (pcf)</th>
<th>( n_1 / n_2 )</th>
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</thead>
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<tr>
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<td>88</td>
<td>7 / 18</td>
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<td></td>
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<td>91</td>
<td>3 / 12</td>
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<td>91</td>
<td>6 / 13</td>
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<td>5 / 13</td>
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<td>87</td>
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<td>87</td>
<td>4 / 11</td>
</tr>
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<td>84</td>
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<td>88</td>
<td>15 / 23</td>
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<td>-</td>
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<tr>
<td></td>
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<td>16.3</td>
<td>93</td>
<td>2 / 8</td>
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The data above were analyzed statistically to evaluate the effect of density and cure time. Step-wise multiple regression analyses were performed for each mix for ASTM curing cycle (normal curing) and low pressure steam curing cycle with compressive strength and elastic modulus as independent variables and density and cure time as dependent variables. Furthermore, similar relationships were developed between \( C_0 \) and \( E \) values for pooled data disregarding cure time variable. The best-fit equations and the correlation coefficients are given below and the data is illustrated in Figures 6 and 7.

Mix 1:

Normal Curing: \[ C_0 = 12.35\alpha^{0.055} + 9.25 \text{ (duration)} [R^2=0.87, N=28] \] \( (7) \)

Normal Curing: \[ E_{\text{ast}0} = 192.8 \ C_0 [R^2=0.62, N=28] \] \( (8) \)

Steam Curing: \[ C_0 = 26.11\alpha^{0.049} + 8.84 \text{ (duration)} [R^2=0.80, N=29] \] \( (9) \)

Steam Curing: \[ E_{\text{ast}0} = 203.1 \ C_0 [R^2=0.83, N=29] \] \( (10) \)

Mix 2:

Normal Curing: \[ C_0 = 18.98\alpha^{0.032} + 4.77 \text{ (duration)} [R^2=0.87, N=27] \] \( (11) \)
Normal Curing: \[ E_{\text{tan}50} = 244.7 \ C_o \ [R^2=0.86, \ N=27] \] (12)

Steam Curing: \[ C_o = 97.59 \alpha^{0.035} + 8.10 \ (\text{duration}) \ [R^2=0.070, \ N=24] \] (13)

Steam Curing: \[ E_{\text{tan}50} = 207.6 \ C_o \ [R^2=0.7, \ N=24] \] (14)

For steam cured and up to 90 days of normal curing, the compressive strength and elastic modulus for the developed materials can be predicted with confidence using the above equations. An exponential increase with increasing density and a linear increase with increasing cure time is indicated for compressive strength. The elastic modulus seems to decrease slightly with increasing cure time. For both mixes, steam curing results in greater strength, and the effect of cure time is very small as compared to the effect of density. Therefore, an appropriate additional research would be to evaluate the effect of temperature and varying steam cure time up to 24 hours. The results may have potential to save significant energy costs in commercial practice.

The modulus ratio \((E/C_o)\) is about 200 for the two mixes and the two cure conditions. This ratio is typical of coal measure rocks for the western U.S. For the Illinois basin coal measure rocks, this ratio is typically 100. The developed materials appear to have similar properties as the coal measure rocks. This is an important consideration in developing artificial supports for use in coal mines.

Large Cylinder Studies--Four 6-in.-diameter and 12-in.-long cylindrical samples, 2 for each mix, were tested for \(C_o\) and \(E\) values at a controlled loading rate. The results are summarized in Table 4 and stress/strain data are shown in Figure 8.

<table>
<thead>
<tr>
<th>Table 4. Unconfined Compressive Strength Data for Large Cylinders</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mix 1</strong></td>
</tr>
<tr>
<td>Density=79 pcf</td>
</tr>
<tr>
<td>(C_o) (psi)</td>
</tr>
<tr>
<td>(E_{\text{tan}50}) (psi)</td>
</tr>
</tbody>
</table>

Indirect Tensile Strength--The tests were conducted for normal curing samples only. The data obtained were statistically analyzed similar to \(C_o\) and \(E\) data in the previous section. The best-fit equations are:

Mix 1:

\[ T_o = 2.51 \ (\text{density}) + 1.66 \ (\text{duration}); \quad R^2 = 0.96 \ N=29 \] (15)
Mix 2:

\[ T_o = 3.28 \text{ (density)}; \quad R^2 = 0.97 \quad N=29 \quad (16) \]

The ratio of \( C_o / T_o \) for developed materials is approximately 8-10 which is again typical of the coal measure rocks in the Illinois Coal Basin. The absence of duration term for Mix 2 cannot be explained except that the data may be limited. Berry\(^{19}\) observed \( T_o \) values for 140 pcf HVFAC to vary 370-585 psi at 28-days of curing.

**Flexural Strength and Flexural Toughness**—The tests were conducted according to ASTM C-78 and ASTM C-1018. The flexural strength (\( R_o \)) as well as toughness index (\( I_5 \)) were analyzed. The best-fit equations for relationships between \( R_o \) and density for the two mixes are shown in Figure 10 and given below:

Mix 1:

\[ R_o = 4.68 \text{ (density)}; \quad R^2 = 0.32 \quad N=12 \quad (17) \]

Mix 2:

\[ R_o = 4.7 \text{ (density)}; \quad R^2 = 0.49 \quad N=12 \quad (18) \]

Thus, \( R_o \) values of 350-450 psi may be expected for the developed material. Berry\(^{11}\) observed flexural strength values to vary 510-915 psi for 140 pcf HVFAC after 14 days of curing. The values for the six samples varied 3.9 to 6.9. Similar values for fiber reinforced concrete with polypropylene fibers reported by Berke and Dallaire\(^{16}\) varied 4.0 to 4.7.

**Time-Dependent Deformation (or Creep) Studies**—Incremental creep studies were performed for two samples (one for each mix) in the MTS machine. Additional experiments are proposed next year prior to fabricating prototype supports. The stress-time and strain-time data are given in Figure 11. For Mix 1, time-dependent deformations do not appear to be significant even at 85% of the \( C_o \) value. For Mix 2 sample, time-dependent deformations were monitored for maximum stress level of 55% of \( C_o \) value. The observed time-dependent deformations were compared with those observed by Berry\(^{11}\) for 140 pcf HVFAC. For 360 days of loading at 55% of \( C_o \), Berry estimated creep strain to be between 600-700 \times 10^{-6}. For Mix 2 samples with density of 96 pcf, creep strain of 250 \times 10^{-6} was observed over an 8-hour period at 55% of \( C_o \). For Mix 1 sample with a density of 86 pcf, similar data was about 500 \times 10^{-6} at 63% of \( C_o \) for 9 hours. These values of creep strain are considered low for mine supports.

6.0 **Environmental Properties of Developed Materials**

**TCLP Studies**—TCLP data for a preliminary mix, a lightweight block (OMEGA), and a commercially-available cement-grout mix were discussed by Chugh\(^{14}\) and are summarized.
in the "Executive Summary" of this report. Similar data for six (6) additional samples prepared from final mixes are given below in Table 5.

Table 5. Toxicity Characteristics of Mix Ingredients and the Developed materials

<table>
<thead>
<tr>
<th></th>
<th>Arsenic</th>
<th>Barium</th>
<th>Cadmium</th>
<th>Chromium</th>
<th>Lead</th>
<th>Mercury</th>
<th>Selenium</th>
<th>Silver</th>
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<td>0.050</td>
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<td>U.S.</td>
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<td>0.002</td>
<td>0.010</td>
<td>0.05</td>
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<td>Cement</td>
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<td>0.000</td>
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<td>0.00</td>
<td>ND</td>
<td>0.047</td>
<td>0.05</td>
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</table>

Leachability Studies--Two mixes were chosen for analysis using the ASTM 24-hour shake test using distilled water. In each case the unwaterproofed sample and samples coated with a commercially available waterproofing agent were tested. The sample preparation technique employed followed that outlined in the ASTM test method as closely as possible but due to the samples being present as monolithic structures some deviation was inevitable. The monoliths were initially fractured into roughly even-sized fragments. Representative aliquot were then taken. Those samples that were coated with the waterproofing agent were done so by spraying the aliquot with the waterproofing agent until an even coating was observed. The samples treated in this way were then allowed to dry (18 hours at room temperature). Weight gains due to the coating of the waterproofing agent were typically less than 1%. The leachates produced were stabilized using 5% nitric acid. Table 6 reports the results of the ICP analysis of the leachates from these samples in ppm. The elements selected for analysis include Se, Mo, B, Zn, Cd, Pb, Co, Mn, Fe, Mg, V, Al, Be, Ca, Cu and Ba. The sample designations are: 1a - Mix 1 with no waterproofing coating; 1b - Mix 1 with waterproofing coating; 2a - Mix 2 with no waterproofing coating; 2b - Mix 2 with waterproofing coating; 3a - Mix 1 with cellulose; and 4a - Mix 1 with waterproofing chemical added during mixing. The designation "R" indicates duplicate sample.
Table 6. Trace Element Concentrations in ppm from 24-Hour ASTM Shake Test

<table>
<thead>
<tr>
<th></th>
<th>1a</th>
<th>1aR</th>
<th>1b</th>
<th>1bR</th>
<th>2a</th>
<th>2aR</th>
<th>2b</th>
<th>2bR</th>
<th>3a</th>
<th>3aR</th>
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</table>

* It should be noted that concentrations shown as 0.00 in this table do not mean that the concentration is absolutely zero, but that the element was not detectable.

The concentration of all the elements examined is very low, often below the detection limit of the ICP instrumentation. The only elements that may pose a problem to the Illinois EPA Class I groundwater standards are selenium, boron, lead and possibly vanadium, and then only marginally and in specific cases.

Selenium was only meaningfully detected in Mix 1 that had a waterproofing chemical coating. Comparison with Mix 1 without the waterproofing suggests that the selenium was introduced by the addition of the waterproofing agent. However, if this were true then selenium should also have been detected in the other samples where the waterproofing agent was used. Since this is not the case, the presence of selenium in this sample only (both duplicates) is puzzling.

The effectiveness of the waterproofing agent (applied as a coating) can be observed by comparing the concentrations of calcium, vanadium, boron, molybdenum and to some extent aluminum with and without its application. In all of these cases (both Mix 1 and Mix 2 and
the duplicates of each) the concentration of the elements is significantly reduced by the application of the waterproofing chemical. It is curious that the concentration of lead actually increases when a waterproofing chemical layer has been applied. Unlike the case with selenium, this is observed with all the samples that came in contact with the waterproofing agent. This result suggests that waterproofing agent contains lead that is leachable.

Surprisingly, the application of the waterproofing agent internally does not appear to effect any reduction in leachate concentration. Indeed the concentration of calcium, perhaps the best matter for leachability, actually increases for this sample compared to the sample without any waterproofing chemical. In addition, with the exception of boron and perhaps barium concentrations, the sample treated with cellulose does not deviate significantly from the sample without cellulose addition. The absence of boron in the sample treated with cellulose suggests that this element may be selectively trapped by the cellulose polymers. Increase in barium concentrations upon addition of cellulose suggest barium is either contained in the cellulose or that the cellulose interacts someway to force the release of barium from the other components in the mix.

Wettability Studies--The wettability of the developed materials that had been coated with the waterproofing agent was compared to those that had no coating. In all case where a waterproofing coating was applied water repulsion, as evidence by droplet formation and beading, was clearly observed. The response to water application by the concrete monoliths with and without waterproof coating is demonstrated in Figure 12. No beading of water droplets was observed when cellulose was used in the mix or when the waterproofing agent was applied internally.

7. Design of Prototype Post and Crib Elements

Prototype post and crib elements of about the same weight as wooden elements were designed. The designs are based on strength and modulus values obtained during this study. The developed designs must satisfy three criteria: $A_w X C_{ow} \leq A_c X C_{oc}$, $A_w X \rho_w \leq A_c X \rho_c$, and $A_w X E_w \leq A_c X E_c$, where $A$, $C$, and $E$ are area of x-section, compressive strength, density and modulus of elasticity and subscripts $w$ and $c$ represent wood and cement-fly ash paste material.

Design of a Post Element--A hollow post with 2 orthogonal ribs in the center (Figure 1) was considered to replace a typical 6-in.x-6-in. wooden post. The ribs tend to significantly reduce bending within the column. For the lightweight post to be of the same weight as a wooden post, the following design was developed:

$$ID = 5 \text{ inch}; \ OD = 6.84 \text{ inch}; \ T = 0.75 \text{ inch}$$

(19)

For this design, load-deflection and stress analysis of a wooden and lightweight posts were conducted under applied vertical load. It was assumed that the column is eccentrically loaded with an eccentricity of 1 in. The modulus of elasticity for wooden and lightweight
material that were used were 250,000 psi and 400,000 psi, respectively, and load-deflection curves for the wooden and the lightweight CCB-based posts are shown in Figure 2. The CCB-based post has a much larger load-carrying capacity and a smaller deflection than an equal-weight wooden post.

Maximum tensile and compressive outer fiber stresses in a wooden post and a CCB-based post at different applied loads are shown in Figure 13. Both tensile and compressive stresses are much higher for a wooden post. For example, at an applied post vertical stress of 500 psi, the maximum stress on the convex side is -350 psi (tension) for wooden post and 160 psi (compression) for CCB-based post. On the concave side, these values are 1,350 psi for wood, which is approximately two times larger than the values for a CCB-based post. The above analyses clearly demonstrate that a CCB-based post is superior to an equal-weight wooden post.

Design of Equal-Weight Crib Element--The coal industry typically uses 6-in.-x-6-in.-36-in. (or 42-in.) wooden (density 56 pcf) crib elements which can be replaced by 80 pcf CCB-based 5-in.-x-5-in.-x 36-in. (or 42-in.) crib elements for the same weight element. The performance of a wooden and CCB-based crib were compared using WOODCRIBX3, a computer program developed by the U.S. Bureau of Mines. This was done for the following mining conditions: mining depth = 400 ft.; opening width = 16-18 ft.; seam thickness = 6 ft.; roof strata bulk density = 131 pcf; roof strata modulus of elasticity = 2 x 10^6 psi; immediate roof strata tensile strength = 1,500 psi; and rock mass rating = 40-60. The number of elements for each crib layer was determined to be 2, and crib element size was 6 in. x 6 in. x 28.7 in. for wood timber and 5 in. x 5 in. x 26.7 in. for CCB-based material, with a spacing of 5 ft. and an overhang distance of 3 in. The ultimate load-carrying capacity and deformation characteristics of wooden and CCB-based 2-ft-x-2-ft cribs are shown in Figure 2. The CCB-based crib is significantly superior to an equal-weight wooden crib for load-carrying capacity and stiffness characteristics.

Design of Unified Post/Crib Element--Based on a limited-area industry input, a unified post/crib element, as shown in Figure 1, was proposed by industrial cooperators and analyzed. This design has several advantages: 1) it is a mechanically-stable configuration; 2) the elastic plane strain finite element analysis of this design proves that stress distribution is relatively uniform when both loading vertically and horizontally; 3) it can be used both as a post and a crib element; and 4) it can be stacked—one upon another—during transportation. However, there are two (2) disadvantages which should be considered before commercial development—namely, 1) the failure in a crib is most likely to occur in tension at the critical locations shown in Figure 1, and 2) it will be slightly heavier than a typical earlier-designed crib element since a higher density CCB-based material (90 pcf) will be utilized for a post. The ultimate load-bearing capacity and stiffness of such a crib element shows that this design has commercial potential (Figure 2).

8. Commercialization Plans and Preliminary Economic Analysis

In cooperation with industrial participants it was decided to analyze the first plant to
fabricate about 250,000 posts per year or 1,000 posts per day. The plant will be set-up within 10-15 miles of the power plant. For such a plant it was estimated that the capital cost will be about $0.7 \times 10^6$ (1995 dollars). The plant will employ seven (7) persons. The capital, operating, and materials cost for a post are estimated to be $0.26$, $0.82$, and $3.56$, respectively for 50:50 cement and fly ash mix. The transportation cost from plant to mine site was estimated at $0.50$ per post. The total cost per post at about $5.40$ is comparable to that for a wooden post. The cost numbers above are conservative. A more detailed economic analysis will be performed during year 2 after final plans on the fabrication process have been made.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions:

1. Lightweight CCB-based structural materials (70-100 pcf), suitable for fabricating mining artificial supports, can be developed using 50-60% high LOI F-fly ash. Most of the desirable characteristics for artificial supports can be achieved using these physical and engineering structural materials.

2. A low water-to-solids ratio and intimate mixing are considered the two most important factors for producing consistent quality of the proposed materials.

3. The physical and engineering properties, with the exception of low density and swelling strain, of the developed materials are similar to those of typical coal measure rocks in the U.S. The data for different properties looks reasonable when compared to similar data for the high-density (140 pcf) high-volume fly ash concrete materials developed by CANMET in 1993.

4. The permeability of the developed materials is in the range of $10^{-7}\text{in./sec}$. Surface permeability can be further reduced by spraying a thin layer of a commercially-available water-proofing chemical on the exterior surface. Leaching of trace elements, resulting from fabricated artificial supports contacting water in the environment, should be minimal, and the quality of leachate should meet acceptable water quality standards with minimal dilution.

5. In cooperation with industrial sponsors, a suitable CCB-based post, crib and unified post/crib elements have been designed which have weight equivalent to that of corresponding wooden elements. Since the developed CCB-based materials have a higher stiffness than does wood, the ultimate load-bearing capacity and load-deformation characteristics of the proposed supports are superior to those of wooden supports.

6. For a small commercial unit producing about 1,000 posts per day, the production cost per post, including transportation to the mine, is expected to be $5.40--a cost comparable to wooden posts ($6.00$ to $7.00$). There is the potential to further decrease production costs by reducing the amount of cement and implementing a higher production volume. There is a significant commercial potential for the use of the developed materials in mining as well as non-mining industries.
Recommendations:

Based on the above conclusions, recommendations are:

1. Additional studies should be undertaken to optimize Mix I for fabricating artificial supports. The goal of optimization should be to minimize cement usage, maximize the percentage of fly ash, minimize silica fume and achieve high early strength.

2. The feasibility of reducing the period of the steam curing cycle by increasing the temperature above 160°F should be investigated. Another option that should be considered is raising the normal curing cycle temperature from 72°F to 100°F at a RH greater than 95%.

3. Since the utilized water-to-solid ratio used in this study is small (≈0.2), physical, engineering and environmental properties studies should be conducted on the extruded samples rather than the molded samples as in the present study.

Figure 3: Stress-Strain Curve for Wooden Post and Crib

![Stress-Strain Curve](image)

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(B) Assumes any liabilities with respect to the use of, or for damages resulting from the use of, any information, apparatus, method or process disclosed in this report.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Department of Energy. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Department of Energy."

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Figure 4: Shrinkage/Swelling Characteristics for the Final Mixes

Mix 1
- Density = 82 pcf
- Density = 97 pcf

Mix 2
- Density = 98 pcf
- Density = 81 pcf
Figure 5: Sulfate Resistance Characteristics for Final Mixes

Mix 1

Mix 2

% Change in Length
% Change in Weight

Exposure (Days)
Figure 6: Variation of Compressive Strength for Mix 1
Figure 7: Variation of Compressive Strength for Mix 2

Mix 2 (Normal Curing)

Mix 2 (Steam Curing)
Figure 3: Deformation Characteristics of 6 in x 12 in Cylinders

Mix 1 (Steam Curing)

Mix 2 (Steam Curing)
Figure 9: Variation in Tensile Strength for the Final Mixes

Mix 1 (Normal Curing)

Mix 2 (Normal Curing)
Figure 10: Variation in Modulus of Rupture with Density

Mix 1 (Normal Curing)

Mix 2 (Normal Curing)
Figure 11: Time Dependent Deformation Characteristics.
Figure 12: Effect of Water Proofing Chemical Coating

Water Bead Formation

Coated Sample  Uncoated Sample

Figure 13: Stress Distribution in Wooden and CCB-Based Posts Under Applied Load

(Height=72 in., Eccentric distance e = 1 in.)
PROJECT MANAGEMENT REPORT
June 1 through August 31, 1995

Project Title: **LIGHTWEIGHT COMBUSTION RESIDUES-BASED STRUCTURAL MATERIALS FOR USE IN MINES**

DOE Cooperative Agreement Number: DE-FC22-92PC92521 (Year 3)
ICCI Project Number: 94-1/3.1A-12
Principal Investigator: Yoginder P. Chugh, Southern Illinois University at Carbondale
Other Investigators: Yuzhuo Zhang, Ashok Kumar Ghosh, Stephen R. Palmer, Suping Peng, and Yuan Xiao, Southern Illinois University at Carbondale
Project Manager: Dan Banerjee, Illinois Clean Coal Institute

**COMMENTS**

The project was completed in a timely manner, and the goals of the project were met. All the allocated moneys were spent.

Dr. Zhang did not return from China to participate as coordinator. He will return at the end of October, 1995, to participate in the year 2 project.
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</table>

*Cumulative by Quarter

**Budget changes made per agreement of Dr. Chugh and Mr. Shockley in July '95. A transfer of $4,100 was made to other direct costs and a transfer of $400 was made to the equipment line--both from the materials and supplies line.
CUMULATIVE COSTS BY QUARTER

Lightweight Combustion Residues-Based Structural Materials for Use in Mines

- = Projected Expenditures
□ = Actual Expenditures

Total Illinois Clean Coal Institute Award $99,772
SCHEDULE OF PROJECT MILESTONES

Hypothetical Milestones:

A. Sampling and Characterization
B. Mix Development and Assessment
C. Geomechanical Studies
D. Environmental Related Studies
E. Analytical Studies
F. Commercialization Plans and Economic Evaluation
G. Technical Reports Prepared and Submitted
H. Project Management Reports Prepared and Submitted

Begin
Sept. 1
1994