

Information Circular 9433

Backfilling Materials and Methods for Stress Transfer Modification in Deep Longwall Mines

By Charles V. Jude and Thomas L. Vandergrift

**UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary**

**BUREAU OF MINES
Rhea Lydia Graham, Director**

This report has been technically reviewed, but it has not been copy edited because of the closure of the agency.

CONTENTS

	<i>Page</i>
Abstract	1
Introduction	1
Issues affecting backfill selection	4
Resource availability	4
Handling, transport, and placement	6
Material properties	9
Candidate materials and methods	9
Conventional pulverized coal combustion fly ash mixes	10
Flue gas desulfurization mixes	12
Fluidized bed combustion mixes	13
Mine backfilling construction applications	16
CCB filling of abandoned underground coal mines	16
High-volume fly ash utilization in civil construction	17
Compaction grouting methods to infill rubble	18
Gob-filling for high-volume disposal of CCB's	19
Packwall construction with natural gypsum and synthetic dry FGD gypsum	19
Injection of fixated FGD sludge to mitigate subsidence and AMD	21
Injection of FBC to mitigate subsidence and AMD	21
Total filling of highwall mine entries with FBC materials	22
Conclusions	23
References	24

ILLUSTRATIONS

1. Stress-transfer-modification concepts	29
2. Strength properties as a function of cure time for a class C PCFA-cement mix	30
3. Strength properties as a function of cure time for a class F PCFA-cement mix	31
4. Unconfined compressive strength as a function of cure time for AFBC-PCFA no-cement mixes	32

TABLES

1. Hydraulic fill characteristics for STM concepts	7
2. PCFA-cement slurry mixes	11
3. Strength properties of PCFA-cement slurry	12
4. AFBC-PCFA no-cement paste mixes	14
5. Strength properties of AFBC-PCFA no-cement paste	15
6. Class F PCFA-cement slurry mixes	18

TABLES--Continued

	<i>Page</i>
7. Strength properties of Class F PCFA-cement slurry for foundation construction	18
8. Strength properties of natural gypsum and synthetic dry FGD gypsum fill	20

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

hr	hour
km	kilometer
m	meter
m ³	cubic meter
mm	millimeter
Mpa	megapascal
t	metric ton
wt %	weight percent
°C	degree Celsius

U. S. Customary Units

ft	foot
in	inch
psi	pound per square inch
st	short ton
yd ³	cubic yard
°F	degree Fahrenheit

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

BACKFILLING MATERIALS AND METHODS FOR STRESS TRANSFER MODIFICATION IN DEEP LONGWALL COAL MINES

By Charles V. Jude¹ and Thomas L. Vandergrift¹

ABSTRACT

This U.S. Bureau of Mines report presents a review and evaluation of existing and new backfilling materials and methods for their applicability to the problem of gate road stress reduction in deep retreat longwall coal mines. Candidate backfill materials include pulverized coal combustion fly ash, flue gas desulfurization, and fluidized bed combustion by-products from coal-fired electric power generation plants. Properties of both backfill and its component materials are presented, with particular emphasis on the unconfined compressive strength and elastic modulus of backfill mixtures. Hydraulic mix designs discussed in this report include high-water content slurry and low-water content paste fills.

Three gate road stress-transfer-modification concepts are proposed to reduce abutment stresses in gate road systems. The first concept, packwalling, involves packwall construction behind the headgate shield inby the face and adjacent to the headgate pillars. The second concept, gob-filling, involves infilling a strip of gob inset from and parallel to the headgate using paste injection methods patterned after a technology recently developed in Europe. In the third concept, entry-filling, slurry fill methods are used to fill abandoned gate roads and crosscut entries inby the face.

INTRODUCTION

Many ground control problems in longwall mining are caused by excessive abutment stresses in the gate road entry systems, especially near the tailgate corner of the panel. These problems range from relatively minor pillar spalling to violent failures such as floor heaves and coal bumps (*1*).² These failures can block the essential tailgate escapeway, endangering mine personnel and causing operational and regulatory compliance problems. The frequency and severity of stress-related ground control problems will increase as deeper coal reserves are extracted and high in situ stress levels are encountered.

¹Mining engineer. Denver Research Center, U. S. Bureau of Mines, Denver, CO.

²Italic numbers in parentheses refer to items in the list of references at the end of this report.

Current longwall mining practices implicitly assume that major portions of the load carried by the longwall panel will be transferred to the gate road systems as retreat mining proceeds. Under this assumption, gate road stress management has focused on chain pillar and artificial support design (2,3). This approach, although generally adequate for shallow (less than 600 m [2,000 ft]) mining, is a passive response to conditions caused by natural stress transfer processes. To improve the safety and technical feasibility of deeper mining, active methods of influencing these natural stress transfer processes are needed.

As a result of longwall full caving, gob areas behind the face shields and in abandoned gate roads and crosscuts are essentially destressed; the gob consists of unconsolidated rubble with poor load-carrying capacity. By backfilling abandoned gate roads and crosscuts to create monolithic support structures, or by infilling a strip of caved rubble adjacent to the headgate, it may be possible to redirect stresses that would normally be concentrated in vital tailgate structures (4).

The U. S. Bureau of Mines (USBM) has considered a number of stress-transfer-modification (STM) techniques with the goal of reducing longwall gate road stresses and improving gate road stability. To achieve this goal, three stress-transfer-modification concepts are proposed:

- 1) Packwall construction in the headgate inby the shields;
- 2) Gob-filling a strip of gob inset from and parallel to the headgate inby the face;
and
- 3) Entry and crosscut-filling in the headgate inby the face.

In each concept, structures with load-carrying capabilities superior to natural gob are created on the headgate side of the active panel. When the headgate becomes the tailgate of the subsequent panel, these structures are in place to accept redistributed panel loads that would normally be carried by coal structures in the tailgate.

Packwalling (figure 1A) involves construction of a packwall behind the headgate shields inby the face and adjacent to the headgate chain pillars. This concept requires the roof to be temporarily supported until packwall construction is completed. The packwall would influence the caving behavior over the gob of the active panel by shifting the break line further into the gob area. It would also support a portion of the load transferred from the subsequent panel.

Gob-filling (figure 1B) with full caving allows the roof strata to collapse, creating rubble behind the headgate shields. A strip of gob, inset from and parallel to the headgate, is then reconsolidated by injecting paste fill or compaction grout into the rubble voids with either a binder (cementitious) or a filler (non-cementitious) material. The infilled gob can then accept more of the load transferred from either the active or subsequent panel.

Entry and crosscut-filling (figure 1C) involves filling headgate areas that normally would be abandoned and allowed to cave. A monolithic fill placement cycle starts at a location in by the face and ends at the face line. Roof conditions in this fill area should be safe and allow the preparation and filling cycle to proceed without the need for additional artificial roof supports. The monolithic fill creates additional support for loads transferred from the panels and confines adjacent gate road pillars, thus increasing their load-carrying capacity.

Theoretical and practical aspects of these concepts were studied concurrently. On the theoretical side, the USBM nonlinear stress analysis program MULSIM/NL was used to evaluate the concepts based on their potential to reduce tailgate escapeway closure. Physical properties consistent with those of candidate fills presented in this report were incorporated into the stress analysis models. Results of the theoretical analysis of stress transfer modification are documented in a separate USBM publication (4).

The stress-transfer-modification concepts under consideration should be particularly applicable in areas where the overburden thickness varies greatly over the length of a panel and where coal combustion fly ash, flue gas desulfurization, and fluidized bed combustion by-products are available. When mining under varying topography, the gate road layout for an individual panel could be designed for a predetermined intermediate overburden thickness. As the panel is mined and deeper cover is encountered, backfills could be emplaced in appropriate areas to actively counter adverse effects of increased overburden loads.

In addition to stress-transfer-modification effects, these backfilling concepts offer ancillary benefits. They may reduce the need for other types of artificial supports, reduce frequency and severity of microseismic events, provide better ventilation control, and seal the gob to prevent spontaneous combustion. The result could be increased coal recovery and decreased panel development costs, and a mitigation of the environmental and economic consequences of surface waste disposal.

This report focuses on practical aspects of stress transfer modification. An in-depth review and evaluation of the physical properties, chemical composition, and geotechnical characteristics of coal combustion by-products (CCB's) was performed, with emphasis given to conventional pulverized coal combustion fly ash (PCFA), flue gas desulfurization (FGD), and fluidized bed combustion (FBC) by-products. Existing and new backfilling methods were evaluated for their applicability to the three stress-transfer-modification concepts under consideration. Of primary interest are backfill handling, transport, placement, and material properties issues.

ISSUES AFFECTING BACKFILL SELECTION

Resource Availability

In order to achieve the stress-transfer-modification concepts outlined, resources must be available to support the backfilling operation. For economic, safety, and environmental reasons, backfilling and extraction cycles would be integrated into one system, similar to a thick coal seam, sub-level caving mine in Slovenia (5). Resources required for the backfilling portion of such a system include land, water, and backfill component materials.

Surface areas must be available to accommodate the storage and handling of backfill materials. Land may be needed to provide a surge capacity in the materials handling and storage facilities. Generally, the surge capacity permits continuous uninterrupted operation, should untimely delays occur. Traditionally, land would be needed for quarry sites to provide natural aggregate for the fill. Sites would be determined on a mine-to-mine basis.

Water is an equally important resource. Surface areas will be needed for reservoirs, since large quantities of water are needed for slurry production and hydraulic transport underground. Where water is in short supply, paste or pneumatic backfilling methods that use relatively small amounts of water would be considered.

The third and most important resource for a backfilling system is an affordable source of backfill materials. Backfill materials may originate from a variety of sources, including

- Natural aggregates mined from quarries;
- Coal combustion and flue gas desulfurization units; and
- Synthetic aggregates manufactured from CCB's.

For the short term, local rock or gravel quarries would be the lowest cost source for conventional aggregate and sand. However, in the longer term of 5 to 10 years, it is likely that the quarry would be depleted and other potential backfill material sources would be required.

PCFA, FGD, and FBC residue are candidate backfill component materials because of their continuous availability from coal-fired electric power plants. CCB's could be hauled back to the mine in otherwise empty rail cars (6). Some coal suppliers are back hauling CCB's to the mine site in trucks, where they are slurried and discharged into coal tailings ponds (7). Some coal companies are applying for beneficial use permits which will allow slurry injection into active underground coal operations.

PCFA is a powder-like particulate substance collected in flue gas exhaust ducts on electrostatic precipitators or through fabric filter units. Composition and cementing properties depend principally on the type of coal burned and the combustion technology used. Pulverized coal fly ash is classified as either class C or class F. Class C PCFA is generated from burning subbituminous coal and lignite produced mostly in the Western United States. Class C PCFA typically has a calcium oxide content greater than 10 % (wt), making it a self-hardening (cementitious) and pozzolanic material when reacted with water. Class F PCFA is generated from burning bituminous or anthracite coal produced mostly in the Eastern United States. Class F fly ash, typically with a much lower calcium oxide content, may be pozzolanic, and as such requires the addition of either cement or lime (CaO) and water to achieve hardening and strength.

Because of these cementing properties, PCFA-based slurry (flowable fill) mixtures have been developed for use in high-volume, low-strength civil construction applications including building bridge abutments, slab foundations, filling underground storage tanks, and abandoned mine voids (8). Mix designs typically consist of fly ash and water along with sand and cement, if needed. They produce a low-strength fluid material requiring no subsequent compaction for consolidation and may be placed in layers or lifts. Since the slurry is pumpable and may be delivered by standard ready mix methods and poured in place with minimum amount of labor and equipment, these materials and methods could be used for constructing packwalls and filling abandoned entries (9).

Despite many uses of PCFA, only 22% of the fly ash produced in 1993 was utilized. Currently, unused fly ash is stored at the power plant until it is loaded into trucks and transported to a landfill, where it is spread and compacted. Alternatively, it may be slurried at the plant and piped to an impoundment (pond) area.

Remaining constituents of the conventional pulverized coal combustion process, bottom ash and boiler slag, can also be utilized in backfills. Bottom ash accounts for about 20% of conventional coal combustion waste, while boiler slag accounts for about 6%. Bottom ash consists of larger ash particles that remain in the boiler due to their weight. This ash is inert and is often used as a filler component. Major by-product uses for bottom ash are in concrete products, road base, road deicers, and structural fill. Boiler slag is simply melted bottom ash that forms glass-like particles in the boiler. Boiler slag has similar applications as bottom ash, as well as roofing granules and sand blasting grit.

FGD materials form in flue gas scrubber units, where injected lime and/or calcium carbonate (limestone) slurry combines with the sulfur dioxide gas to produce a residue composed of calcium sulfate (anhydrite), sulfite, and small amounts of unreacted calcium oxide and calcium carbonate. The chemical constituents vary with the type of coal burned and the combustor and scrubber technologies used. FGD is generated in

either a wet (sludge) or dry (solids) condition. Typically, FGD scrubber sludge is mixed with PCFA and quicklime and trucked to a landfill, where it is compacted. Alternatively, for disposal purposes, these mixes may be slurried and pumped down surface boreholes to abandoned mine workings (10). It is possible to create a synthetic aggregate by combining FGD sludge, PCFA, and quicklime (11). Synthetic aggregate is produced by excavating the previously compacted landfilled material, followed by crushing and screening to produce the desired gradation.

FBC ash materials are different from by-products produced from conventional pulverized coal combustion units. In fluidized bed combustion, crushed coal and limestone are burned in a "bed" of ash particles suspended upward blowing air in the combustion chamber. This bed of coal and limestone derived ash is turbulently mixed inside the combustion chamber in a manner resembling a boiling liquid or "fluid". The limestone is calcined and captures the sulfur emissions from the combustion of coal. Ash from FBC are of two types (1) bed ash withdrawn from the combustion chamber and (2) fly ash collected in flue gas exhaust ducts on electrostatic precipitator or fabric filter units. FBC bed ash contains larger particles composed principally of coal mineral matter, calcium sulfate and unreacted lime that result from the sulfation and calcination of the limestone. FBC fly ash, on the other hand, contains a lesser amount of the calcium sulfate and free lime than the FBC bed ash. The free lime in the FBC ashes favors its use as a pozzolanic and cementitious material, such as required in no-cement underground structural backfills. Furthermore, with their high alkaline content, they are also amenable for used in acid mine drainage (AMD) treatment (12).

CCB's are produced in very large quantities. The American Coal Ash Association (ACAA) reports that electric power generating plants produce 77 to 90 million tons (85 to 100 million st) of fly and bottom ash, boiler slag, and FGD annually (13). The generation of these materials is expected to increase to 108 million tons (120 million st) by the year 2000, an increase of about 72% over 1984 levels. Of this total, 45 million tons (50 million st), or 42%, will be FGD scrubber sludge, a by-product resulting from the implementation of the Clean Air Act of 1990. ACAA has worked since its founding in 1968 to gain recognition and acceptance of CCB's as engineering materials on a par with competing natural, processed, and manufactured materials.

It is apparent that an abundant supply of CCB's is available as candidate fill material for the STM concepts proposed in this study. Added benefits derived from the use of CCB's with these concepts are a reduction of environmental and land use problems caused by surface disposal of coal combustion by-products.

Handling, Transport, and Placement

Material preparation, mixing, transporting, and placement systems need to provide the required solids concentration, flow consistency, and slump condition to implement

the proposed STM concepts. Table 1 presents hydraulic fill characteristics for STM concepts with proposed placement methods.

Table 1.—Hydraulic fill characteristics for STM concepts

STM concept and fill method	Water content	Solids, wt %	Slump	
			mm	in
Entry-filling:				
Slurry	High	50-70	150-250	6-10
Packwalling:				
Slurry	Medium	70-85	<150	<6
Gob-filling:				
Paste	Low	70-90	<25	<1
Compaction grout . . .	Low	70-90	≈0	≈0

The evaluation and selection of available materials and placement methods depend on which STM concept is specified. High-water content entry-filling and medium-water content packwalling slurry concepts permit the selection of a wide variety of material components, gradation, flow consistency, and slump conditions, to achieve design strength characteristics (14). In contrast, low-water content gob-filling concepts impose strict criteria on fill moisture, component size and gradation. In addition to a specified amount of moisture, paste fills require a greatly reduced particle top size, and a component finer than a specified sieve size. These prescribed conditions ensure flow of paste and low-slump compaction grouts through pipes (15,16).

Additional criteria for the handling, transport, and placement of backfill are presented below.

Preparation and mixing-

- Surface backfilling facilities should be capable of blending and mixing a variety of fill components, dry solids, sludges, and slurries. Mix proportioning and testing capabilities are needed so that variations in fill component properties can be handled on a routine basis. Testing of laboratory specimens and core samples of the placed fill will be needed to maintain quality control and to ensure cost-effectiveness.
- Continuous mixing on the surface is preferred, but some final conditioning near the placement site may be necessary to control flow characteristics and in-place properties.
- Mixes should be designed to control the heat of hydration, which can cause clogging and costly maintenance. Some fill components, including accelerators, may be introduced just prior to placement.

- Mix designs should minimize the use of costly fill components yet achieve the desired in-place properties. Desired set times, curing rates, and long-term properties of the fill will be determined on a mine-to-mine basis.
- A continuous backfilling operation should be applied if the selected method requires large amounts of material delivered at relatively low flow rates, e. g., low-water content paste or compaction grout.

Transporting systems-

- Surface-to-underground transport systems should supply fill components at rates required by each STM concept.
- Energy requirements should be minimized by exploiting the effects of gravity.
- Hydraulic systems are the most likely candidates for fill transport; however, combinations of mechanical, pneumatic, and hydraulic systems should be considered to provide the required motive power.
- Surface distribution systems should be capable of supplying fill to several active panels, if necessary.
- Underground subsystems should be compact, mobile, and capable of operating reliably and with high availability.
- Systems should be designed to operate either in batch or continuous mode and be capable of starting and stopping on request. A self-cleaning (flushing) capability is required.
- Surface-to-underground fill material transfer may be down open vertical pipes (slicklines), in pressurized pipes in main shafts, or through surface boreholes distributed over the panels.
- The number of transfer points, where directional changes occur, should be minimized to reduce abrasive wear on parts and to minimize the likelihood of flow obstructions.
- Transport and pumping components required in the gate roads of the active panel should be capable of being disassembled, moved, and reused in the subsequent panel.
- Two or more delivery lines should be available to provide back-up capability and/or supply binder or other additives for conditioning prior to placement.

Placing procedures-

- Fill placement must be performed in a manner consistent with Mine Safety and Health Administration (MSHA) and Environmental Protection Agency (EPA) regulations.
- Performance criteria should be based on the total cost required to achieve a specified load-carrying capacity.
- The choice between total filling to the roof or partial filling to provide lateral confinement around abandoned coal structures will be determined by geotechnical and economic studies on a mine-to-mine basis.
- A typical fill cycle would include deployment of equipment in the headgate area while it is still ahead of (outby) the face, with remotely controlled filling inby the face line.
- The filling cycle should keep pace with production advance.

- Remotely controlled mobile equipment should be capable of self-rescue if backfilling problems, machine faults, or ground instabilities are detected.

Material Properties

Laboratory and field tests for physical, hydraulic, and chemical characteristics should be performed and evaluated to determine how the fill may influence the surrounding coal structures and rock strata, and conversely, how the surrounding mine strata and hydrological environment might impact the fill. Backfills should be physically, hydrologically, chemically, and mineralogically stable on a long-term basis. They must also exhibit adequate strength and elastic modulus (stiffness) properties to perform as load-carrying structures.

Backfills can be weakened by water migration. Therefore, fills must resist infiltration and conductance of groundwater. They should exhibit low permeability to resist internal erosion (piping) and/or leaching into the groundwater. If percolating groundwater infiltrates the fill, it may react chemically and promote mineralogic phase changes in the fill, potentially having an adverse impact on geotechnical and chemical properties of the fill material.

The long-term physical and mineralogical stability of some proposed calcium sulfate-based backfill materials have not yet been fully demonstrated. Field monitoring and laboratory analyses of shallow field samples have shown changes in mineralogic composition over a period of 3 years (17). Fill instability may affect the practical use of some CCB components in underground backfills.

Environmental issues related to disposal and/or reuse of CCB's include (1) their potential to contaminate surface and subsurface water systems, (2) their long-term chemical leaching potential, and (3) long-term changes in physical properties. CCB's are classified as non-hazardous and are routinely used in civil construction applications (18).

CANDIDATE MATERIALS AND METHODS

Coal combustion waste by-products in hydraulic mixtures were evaluated for their applicability to the STM concept. They included high-water content slurry and low-water content paste and compaction grout fills. Self-leveling and self-compacting mixtures, containing low or no manufactured cement, were evaluated with particular interest. Included in the evaluation were flow characteristics and fill properties from the initial state of the raw constituent materials prior to mixing with water, to the long-term properties developed during the hydration, cementation, and curing phases. Among the specific properties evaluated were

- Unconfined compressive strength and elastic modulus;

- Strength gains over short- and long-term cure times;
- Effects of hydration and cementation reactions on strength, permeability, and durability;
- Pumpability and flowability of slurry over a wide range of water content and slump conditions;
- Transport methods for backhauling CCB's from power plants to mine sites.

Reasons for selecting hydraulic filling methods as the primary mode of transport include (1) mechanical units inby the face are impractical, (2) hydraulic filling includes self-leveling and self-compacting slurry fill processes that are accomplished with reduced labor and fewer systems components vulnerable to failure, (3) hydraulic filling is the most likely candidate to keep pace with face production rates, and (4) the hydraulic filling process can be controlled remotely outby the face, from where total or partial void filling can be achieved.

Evaluations of CCB-based mixes and their applicability to stress transfer modification are presented below.

Conventional Pulverized Coal Combustion Fly Ash Mixes

The primary use of PCFA has been as a material component in backfill for subsidence mitigation and stabilization of large land areas. Large-scale backfilling projects for subsidence control have been performed in Rock Springs, WY, Wilkes-Barre and Scranton, PA, and Fairmont, WV. Most coal-related backfilling in the United States has been done in an effort to control mine subsidence in abandoned coal mines. In contrast, other countries have used backfilling extensively both to dispose of coal ash and increase coal recovery in active mines. In South Africa, the use of repetitive mine-and-fill methods has resulted in coal recovery increases of as much as 8% in shallow mines and 12% in deep mines (19). In Poland, some coal mines integrate backfilling operations with the production cycle (20).

PCFA-cement slurry could be designed to flow and spread into large impounded areas, making it amenable to the packwalling and entry-filling concepts. In the entry-filling concept, medium-slump flowable fill would surround abandoned gate road pillars (table 1). In doing so, it should provide confinement to the pillars in two ways, both by the pressure exerted by the weight of the fill on the floor and by the passive resistance to lateral movement of each pillar. Of the two effects, passive resistance is probably more significant for stress transfer modification. The higher the strength and elastic modulus of the fill, the greater the resistance to any lateral displacement. This reduced displacement inhibits pillar failure and roof closure (4,21).

The Electric Power Research Institute (EPRI) has funded research to promote the increased use of cement-stabilized fly ash slurry for high-volume fill applications (22). Results from this research (23) include unconfined compressive strength and elastic

modulus data from samples prepared from four PCFA-cement slurry mixes containing relatively small amounts of type I Portland cement, referred to in the text as cement. These tests are discussed below.

Table 2.—PCFA-cement slurry mixes (23)

Mix	Fly ash		Cement wt %	Water wt %	Slump		CaO, ¹ wt %, dry
	Class	wt %			mm	in	
1	C	68.9	2	29.1	150	6	31
2	C	62	2	36	225	9	31
3	F	70.8	5	24.2	150	6	6.4
4	F	69.2	5	25.8	212.5	8.5	6.4

¹Calcium content from chemical composition analysis.

Table 2 shows mixes 1 and 2 consisted of class C PCFA, 2% cement, and water. Mixes 3 and 4 consisted of class F PCFA, 5% cement, and water. The specimen size, shape, curing conditions, and cure time were varied in the tests. Each mix was tested for cement and water content, flow consistency, slump condition, and physical strength properties up to 365 days cure. Half the specimens were cured in polyethylene bags and the other half were cured in water, both at 73 °F.

Table 3 shows the effects of cement, water, calcium content, and curing time on unconfined compressive strength and elastic modulus for both class C and class F PCFA-cement slurry mixes.

Figure 2 shows unconfined compressive strength and elastic modulus as functions of cure time for class C PCFA-cement mixes with two slump conditions. After 365 days curing, the 6-in slump mix showed an unconfined compressive strength of 23 MPa (3,300 psi) and an elastic modulus of 3,320 MPa (482,000 psi).

Figure 3 shows the same relationships for class F PCFA-cement mixes with two slump conditions. Compressive strength and modulus after 365 days curing for a 6-in slump were 11 MPa (1,640 psi) and 1,720 MPa (250,000 psi), respectively.

These values compare to unconfined compressive strength and elastic modulus values of 25 MPa (3,600 psi) and 3,450 MPa (500,000 psi) for bituminous coal samples from a longwall mine in Western Colorado (24). It, therefore, appears that class C fly ash mixes, cured for one year, can attain strengths comparable to coal. If class F fly ash is used in the mix, more cement is required to achieve equivalent strength and modulus values.

Figures 2 and 3 show that compressive strength and modulus increase with cure time and follow a parallel trend. The figures also illustrate the effect of increased water content or slump; higher slump mixes generally yield lower strength and elastic modulus values.

Table 3.—Strength properties of PCFA-cement slurry (23)

Cure time, days	Compressive strength		Modulus ¹	
	MPa	psi	MPa	psi
Mix 1: ²				
14	14	2,100	2,550	370,000
28	16	2,300	2,520	365,000
91	19	2,700	2,720	394,000
365	23	3,300	3,320	482,000
Mix 2:				
14	8	1,100	1,400	203,000
28	8	1,200	1,130	164,000
91	8	1,120	1,440	209,000
365	16	2,260	2,210	320,000
Mix 3: ³				
14	5	780	840	122,000
28	7	950	940	136,000
91	8	1,220	1,230	179,000
365	11	1,640	1,720	250,000
Mix 4:				
14	3	500	480	70,000
28	4	640	710	103,000
91	5	710	650	94,000
365	7	1,000	830	121,000

¹Based on average of 18 samples at each cure time.

²Coal from Montana; class C PCFA from Powerton Station in Pekin, IL.

³Coal from Illinois; class F PCFA from Baldwin Station in Baldwin, IL.

Flue Gas Desulfurization Mixes

First generation FGD systems, typified by the wet limestone scrubber, produced an oxidized calcium sulfite hemihydrate FGD sludge that is not fully oxidized. This sludge was difficult to handle and stabilize at the disposal site. Beginning in the mid-

1980's, a second generation FGD system emerged involving forced oxidation in the scrubbing process produced a fully oxidized calcium sulfate dihydrate (gypsum) FGD sludge.

This fully oxidized FGD sludge exhibits distinct advantages over partially oxidized wastes; including: (1) dewatering the sludge is much easier, and (2) handling and disposal is more manageable. The calcium sulfate dihydrate can be transported to the impoundment and placed without the quick-sand (liquefaction) characteristics exhibited by partially oxidized sludge.

Fixation/stabilization technologies have been developed for FGD sludge to ensure that the fill mass reaches a chemically and physically stable condition acceptable under EPA regulations. Several fixation processes have been developed that optimize the use of the plant's PCFA, FGD sludge, and lime to condition it for transport, spreading, and compaction at the landfill (25).

FGD sludge mixed with PCFA exhibit pozzolanic properties, i. e., they are capable of reacting with added lime in the presence of moisture at ordinary temperatures to produce a cemented (hardened) compound. These reactions result in strength gain, reduced permeability, and physical stabilization of the fill.

Data presented by Smith (26) for fixated scrubber sludge (FSS) slurry mixes show that at 30 days of cure at 23 °C (73 °F), FSS develops a compressive strength of 6 MPa (850 psi) and a modulus of 280 MPa (40,000 psi). At 120 days under the same curing conditions, strength and modulus were 11 MPa (1,600 psi) and 1,380 MPa (200,000 psi), respectively. Although proportions were not reported, the mix contained FGD sludge, class F PCFA, added lime, and water. A comparison between these data and those reported for cement stabilized fly ash slurry in table 3 shows that the strengths of these two mixes are nearly equal. For example, a class F PCFA mix with a 150-mm (6-in) slump and a 91 day cure achieved an unconfined compressive strength of 8 MPa (1,220 psi) and an elastic modulus of 1,230 MPa (179,000 psi). Lower strengths are expected when more water is used.

FGD sludge mixes, when stabilized with PCFA and adequate amounts of cement and/or lime, are candidates for the packwalling and entry-filling concepts, provided that systems for their placement at rates consistent with mining can be designed.

Fluidized Bed Combustion Mixes

Extensive research has been performed, and is ongoing, to determine if these materials can be mixed with water, and if needed, PCFA, to develop new FBC-based slurry or paste for underground structural fill applications. Of primary concern is the long-term physical durability and mineralogical stability of FBC-PCFA no-cement slurry or paste fills.

Circulating atmospheric fluidized bed combustion (AFBC) by-products have potential for use in concrete because they generally contain an excess of unreacted lime of 10% (wt) or more. No-cement concretes can be made by mixing AFBC bed ash with PCFA and natural aggregate (27). These by-products were found to participate in the pozzolanic reactions necessary for the concrete to develop strength. AFBC bed ash was also found to serve as a fine aggregate replacing natural sand. Compressive strengths of 36 MPa (5,300 psi) at 90 days were measured, which compares favorably with cement concrete mixes. However, the solid had a lower elastic modulus than conventional cement concrete.

No-cement AFBC and PCFA formulations appear quite attractive because their cost is lower than conventional concrete since there is no manufactured cement or sand in the mix design. Typically, sand and cement are the most expensive components in concrete. Natural aggregate could conceivably be substituted with FGD- and/or FBC-based synthetic aggregate (11,28).

Considerable material characterization and engineering property data exist for AFBC-PCFA mix formulations, based on standard Proctor optimum density compaction tests. However, physical and chemical property data are not yet available from field tests, where FBC-based slurry is pumped long distances in surface pipes prior to transfer down boreholes into abandoned workings.

Tables 4 and 5 present mix design and strength data, respectively, for blended AFBC-PCFA materials produced from American and Canadian plants (29). Optimum water formulations were prepared with prehydrated blends from three AFBC-producing plants and three PCFA-producing plants. These plants exhibited diverse operating conditions and produced a variety of constituents and proportions of primary and secondary by-products. To mitigate temperature rise from initial hydration and reduce the expansion potential of AFBC materials, each blend was prehydrated with water. Once initial hydration reaction occurred, water was added to form a slightly flowable paste that was then compacted into test molds.

Table 4.—AFBC-PCFA no-cement paste mixes (29)

Mix	AFBC wt %	PCFA wt %	Water wt %	CaO ¹ wt %, dry
1	59	21	20	30
2	58	20	22	21
3	71	7	24	11

¹Unreacted lime.

Table 5.—Strength properties of AFBC-PCFA no-cement paste (29)

Cure time, days	Compressive strength	
	MPa	psi
Mix 1: ¹		
7	18	2,600
14	28	4,085
28	39	5,705
56	44	6,375
90	45	6,585
Mix 2: ²		
7	3	380
14	16	2,375
28	25	3,680
56	33	4,760
90	41	5,900
Mix 3: ³		
7	15	2,235
14	19	2,765
28	18	2,590
56	18	2,615
90	19	2,815

¹TVA Shawnee Plant, Paducah, KY.

²Chatham Plant, Chatham, New Brunswick.

³Colorado-Ute Plant, Nucla, CO.

Figure 4 shows unconfined compressive strength as a function of cure time for AFBC-PCFA no-cement paste mixes. The sources for FBC bed ash originated from: TVA (Shawnee Plant), New Brunswick Power (Chatham Plant), and Colorado-Ute (Nucla Plant). The source for class F PCFA, with 2.1 % (wt) calcium content, was from TVA's Kingston Plant. Higher compressive strengths were obtained for mix 1 (source 1) and mix 2 (source 2) because more limestone feedstock is consumed in cleaning high-sulfur coal burned at these plants (table 5). By contrast, lower strengths were obtained for mix 3 (source 3) because less feedstock is needed in cleaning low-sulfur coal burned at this plant, resulting in less unreacted lime in the blend, 11 % (wt), available for hydration and cementation (table 4).

Figure 4 shows two of the three mixes achieved a compressive strength greater than 35 MPa (5,000 psi) after 90 days cure. Elastic modulus values were not reported

however, based on the parallel trend exhibited for PCFA-cement slurries (figures 2 and 3), it is likely that the moduli for these particular mix designs would have exceeded typical coal values by more than 20%.

More research into the adverse effects of high hydration temperatures, fill expansion, and mineralogical phase changes is required. Field demonstrations and core sample tests will be required to confirm long-term physical, chemical, and mineralogical stabilization.

Mine Backfilling Construction Applications

Projects that include laboratory tests or field demonstrations of the hydraulic placement of CCB-based mixes are presented below. Materials and methods developed in these projects could be adapted to the STM concepts under consideration.

CCB Filling of Abandoned Underground Coal Mines

In 1993, Southern Illinois University and the Department of Energy (DOE) entered into an agreement to develop and demonstrate technologies to mitigate surface subsidence and AMD using CCB filling of abandoned underground coal mines (30). The project team is investigating new haulback techniques for transporting materials from power plants back to disposal sites. Ultimately, CCB mixes will be placed underground through boreholes using hydraulic and pneumatic injection methods.

The objectives of phase 1 included the design of injection equipment and laboratory-scale fill mixtures. The handling and transportation of dry powders were to be demonstrated in the field. One transport technology being considered is a heavy-duty collapsible intermodal container (CIC) system that can be used on railroad cars, flat bed trucks, and barges. This relatively new container technology will be compared with pneumatic trucks and pressure differential rail cars.

Phase 2 consists of a surface demonstration of blind backfilling methods using a simulated underground mine void. Both hydraulic and pneumatic blind placement technologies are being investigated. The performance goal of both methods is to place materials about 91 m (300 ft) away from the injection point at a rate of 45 to 90 t (50 to 100 st) per hour.

Phase 3 involves field demonstrations of the selected materials and methods at a chosen abandoned underground mine. The demonstration site is at the Peabody Coal Company No. 10 Mine in Christian and Sangamon Counties, IL. In addition to proving an efficient and environmentally sound method of managing CCB's, this phase includes an investigation of the environmental impacts associated with backfilling voids with these materials.

The phase 1 field demonstration, performed in January 1995, involved testing the strength of three heavy-duty CIC's made of rubber-coated nylon and Dupont Kevlar. The handling and transportation of 54 t (60 st) of fly ash in a railroad coal car over a distance of 4,300 km (2,600 miles) was successfully demonstrated (31). When filled with 18 t (20 st) of ash, each container is about 2.7 m (9 ft) in diameter and 3 m (10 ft) high. At the Baldwin Power Station in Illinois, three empty containers were secured to a metal frame, loaded onto a flat bed truck, and then placed under the fly ash silo discharge port. Gravity filling was accomplished at a rate of about 1.8 t (2 st) per minute. At the rail siding, the containers were loaded by a crane into a three-bay coal car. The car was transported to Norfolk, VA, where the containers were removed and loaded into a barge. They were then reloaded into the rail car and hauled back to the Peabody Coal Mine near the Baldwin Power Station and emptied.

Reuse of fly ash and other dry, powdery materials is a solution previously avoided because of logistical, cost, and transportation issues. The success of the Baldwin Power Station test offers potential benefits for railroads, utilities, and coal producers. Railroads will be able to utilize haulback capacity by taking the same car that delivered coal to a utility plant back to the mine with fly ash or other types of fine materials that need protection from the rain and wind. For the utilities, it alleviates their disposal space problem. For the coal producer, it provides an opportunity to receive revenue for the disposal service. Furthermore, it may provide the coal producer the means to integrate structural backfilling into the coal extraction cycle.

High-Volume Fly Ash Utilization in Civil Construction

Class F PCFA-cement slurry (flowable fill) was used to create two monolithic floating foundation slabs at the Delaware Solid Waste Authority's Northern Solid Waste Facility No. 2 in Wilmington, DE. Fly ash was chosen because of its availability near the project site and its lower costs relative to conventional concrete (8). It was determined that floating slabs were needed as a foundation because the dredged spoil material at the site was too soft to support trucks or normal placement equipment.

A total of 1,520 m³ (2,000 yd³) of cement-stabilized fly ash slurry was utilized on the project at an average cost of \$33/m³ (\$25/yd³). The construction specifications required two mix designs, one with a strength in excess of 0.7 MPa (100 psi), and another with a strength in excess of 1.4 MPa (200 psi), both after 28 days curing time. A mixture containing 5% cement was chosen for the weaker mix; the stronger mix contained 10% cement. Tables 6 and 7 show the mix design and compressive strength data, respectively, for two slurry mixes after curing for 7 and 28 days.

At the site, the fill was placed from the transit trucks directly into the excavation. Both 0.6-m (2-ft) and 1.2-m (4-ft) slabs were poured in single lifts. Within 24 hours, the surfaces of the slabs were firm enough to walk on, and within 3 days the surfaces

Table 6.—Class F PCFA-cement slurry mixes (8)

Mix	Cement wt %, dry	Slump		CaO ¹
		mm	in	wt %, dry
Mix 1	5	150	6	0.4
Mix 2	10	150	6	0.4

¹Calcium content from chemical composition analysis.

Table 7.—Strength properties of class F PCFA-cement slurry for foundation construction (8)

Cure time, days	Compressive strength	
	MPa	psi
Mix 1:		
7	0.6	83
28	0.9	132
Mix 2:		
7	0.9	128
28	1.9	270

would support pickup truck traffic. Fast set times and early strength gains are important for the packwalling and entry-filling concepts, as they require the construction of fill structures at rates compatible with face advance.

Compaction Grouting Methods to Infill Rubble

Compaction grouting involves the use of low-water content suspensions capable of high internal friction. As the paste-like suspension intrudes voids under high pressure, it remains a homogeneous mass capable of displacing neighboring rubble. The result is the formation of a grout bulb surrounded by compacted rubble with increased stiffness and load-carrying capacity. Compaction grouting techniques have been used for many years in civil construction (32), and it appears that they could be readily adapted to the gob-infilling concept. Two examples of their application are presented below.

At a Wanaque, NJ, site, compaction grouting was used to stabilize a rock fill prior to the construction of a plant addition (33). The cobble stone fill was placed during original plant construction and extended 8 m (27 ft) below the proposed new footing. The fill contained both voids and significant nests of boulders and cobbles. Vertical

compaction grouting was used to fill voids, densify loose zones of soil, and provide a foundation for subsequent construction of the plant addition.

As part of an Abandoned Mine Lands (AML) subsidence project in Rock Springs, WY, a new gob-infilling (compaction grout injection) technique was developed to remotely construct load-carrying grout columns within rubble zones formed from the collapse of abandoned mine roof (34). Low-slump compaction grout was injected vertically into the rubble to fill voids and displace the rubble aggregate radially from the grout hole (table 1). In this process, a central core of uniform grout is created with a diameter of about 2.4 m (8 ft). The process is repeated upward in 0.6-m (2-ft) lifts until a competent roof stratum is reached. Further research would be necessary to modify this method for application in deep retreat longwall mines, since gob infilling would most likely be accomplished using horizontal injection pipes.

Gob-Filling for High-Volume Disposal of CCB

During the period from 1988 to 1991, Deutsche Montan Technologie (DMT) in the Federal Republic of Germany developed a gob-infilling process for disposing of CCB's behind caving faces before the gob rubble gets compressed by the caving roof strata (35). A high-solids, low-water content suspension is blended and mixed on the surface from relatively fine particle residue (< 5 mm [0.2 in] top size). In addition to water, mixtures contain precisely proportioned amounts of incinerator ash, PCFA, FGD, and FBC materials. The fill is pumped through pipelines from the surface directly to the working longwall face, where the suspension is injected into the gob via parallel pipes trailing on the floor. In addition to CCB's, municipal sludge, and fine-particle coal tailings have been pumped into the gob. The pilot system at the Walsum Mine is designed for a total capacity of 200 m³/h (260 yd³/h) at a depth of 800 m (2,600 ft) and total piping distance of 6,000 to 7,000 m (19,700 to 23,000 ft). The demonstration confirmed that high-pressure conveyance of fine CCB's can be delivered to underground cavities reliably and safely.

Paste fill systems have the following features: (1) rheological flow characteristics are monitored in real-time during blending and mixing to adjust to composition variations in the raw feed constituents; (2) the total amount of water required is much less than for flowable fills, the amount of binder required for solidification is considerably lower, and may not be needed at all; and (3) provided no binder is in the mix, pumping can be stopped and restarted after several days.

Packwall Construction with Natural and Synthetic Dry FGD Gypsum

Roadside packwall construction is used in coal mining in Britain and Western Europe (36). During the initial development period, two types of fill materials were used for roadside packs (37). The first type was a manufactured cement-based material consisting of up to 50% cement with 50% fly ash. The second type was

calcium-sulfate based anhydrite material, which originates from natural mined rock or is produced synthetically from dry FGD scrubber units.

Research on the physical properties and utilization of mined anhydrite in underground fills occurred in Europe and Britain in late 1970 (38). When anhydrous calcium sulfate (anhydrite) absorbs water, the reaction forms gypsum, with the evolution of heat. Pneumatic and hydraulic systems are used to convey and place synthetic anhydrite mixes with particle size less than 1 mm (0.04 in.), whereas pneumatic systems handle natural anhydrite mixes with particle size less than 8 mm (0.32 in.).

Table 8 presents strength properties of natural and synthetic dry FGD gypsum fill. An accelerator blend of equal parts of potassium sulfate and ferrous sulfate is used to reduce the setting time. The proportion of accelerator to anhydrite by weight is 1 to 100. In pneumatic systems, the dry mix is blown to the placement site where about 8 % (wt) water is added just before ejection (39). Minimum support requirements for early load-carrying packwall fills are compressive strength of 5 MPa (725 psi) after 5 hours, 10 MPa (1,450 psi) after 12 hours, and long-term strengths above 20 MPa (2,900 psi).

Table 8.—Strength properties of natural gypsum and synthetic dry FGD gypsum fill (39)

Cure time	Compressive strength ¹	
	MPa	psi
Natural mined rock:		
5 h	6	870
1 day	20	2,900
28 days	45	6,500
Synthetic, dry FGD:		
5 h	3	435
1 day	11	1,595
28 days	33	4,730

¹Accelerator blend of potassium sulfate and ferrous sulfate, with addition of water before ejection.

Some potential problems must be overcome when designing gypsum packwalls. Synthetic gypsum fills will not set properly at temperatures above 32 °C (90 °F), while natural gypsum fills will not set properly at temperatures above 40 °C (104 °F). Also, the heat from hydration must be dissipated, otherwise it can cause difficulties with massive pack structures, such as bulkheads or stoppings (37).

Gypsum-based mortars and backfills are used extensively throughout the European mining industry, especially in deep coal mines. It has been demonstrated that synthetic FGD gypsum can replace natural gypsum for longwall packs, in a manner consistent with existing mining processes. FGD gypsum is briquetted and broken for pneumatic application, in which it is used as both the filler aggregate and, in another form, as the binding medium (40).

Injection of Fixated FGD Sludge to Mitigate Subsidence and AMD

An evaluation of the use of fixated FGD scrubber sludge (FSS) is being conducted through the collaboration of Indianapolis Power and Light Company (IP&L), EPRI, and other organizations (10). FSS will be used to mitigate surface subsidence over abandoned deep coal mines and to control acid mine drainage. A pilot-scale remote backfilling test was conducted in the fall of 1994 at IP&L's Petersburg Generating Station. The project encompasses approximately 5 acres underlain by abandoned coal workings and involves the hydraulic placement of approximately 11,400 to 15,200 m³ (15,000 to 20,000 yd³) of FSS. The project is being conducted in two phases.

In phase 1, laboratory tests were performed to determine the optimum composition (fly ash, FGD filter cake, quicklime, and water) for fluid placement in mine voids that range from dry to flooded. Flow, pumping, setting time, and compressive strength characteristics were determined for various FSS formulations. These parameters were used to select the placement system for the field demonstration.

In phase 2, a suitable abandoned mine site was identified. Accessibility, void space, and the ability to monitor the hydrogeologic environment were assessed. Exploratory boreholes were used to determine fluid levels and chemical quality of water pools in the mine. These boreholes were later used to monitor placement of FSS. Surface and ground water were tested for 6 months prior to, and will be tested for 12 months following, FSS placement.

During tests performed in November of 1994, flowability of FGD mixtures near the Petersburg plant in Indiana was observed with a portable borehole video camera (41). Complete filling of a large cavity was achieved at a rate of about 46 m³/h (60 yd³/h). The next phase involves retrieving core samples for laboratory tests to determine compressive strength and permeability coefficient data.

Injection of FBC to Mitigate Subsidence and AMD

In February 1994, West Virginia University's Branch of National Mine Land Reclamation Center (WVU-NMLRC) was awarded a three-phase 5-year cooperative agreement to evaluate the technical, economic, and environmental feasibility of filling abandoned underground mine voids with FBC ash to mitigate subsidence and acid mine drainage (12).

In phase 1 of the project, WVU-NMLRC will develop grout formulations for hydraulically injecting ash into the mine. Grout constituents will include fresh water, mine water, lime, cement, fly ash, set retarders, and water reducers. In the laboratory, grout mix designs will be analyzed for strength, permeability, leachability, pumpability, and spreading characteristics. A subcontractor will optimize the design of a new air-jet method for pneumatically stowing dry FBC ash into the mine via surface boreholes (42).

In phase 2, a small-scale field test will be performed in a mine in West Virginia. A contractor will hydraulically place about 760 m³ (1,000 yd³) of ash grout into voids of a mine generating acid mine waters. Another contractor will inject 36 to 45 t (40 to 50 st) of dry FBC ash into the mine using the air-jet ejection system.

In phase 3, a large-scale field demonstration of hydraulic injection and/or pneumatic ejection placement techniques will be conducted. Mine water samples will be analyzed before, during, and after backfilling to assess the impact on water quality.

Total Filling of Highwall Mine Entries with FBC Materials

This project, cosponsored by the University of Kentucky's Center for Applied Energy Research, and others, will remotely emplace FBC materials into a highwall entry left by a previous highwall mine operation (43). Mine pillar forms and hydraulic transportation will be used to simulate the use of FBC materials as artificial pillars in room-and-pillar coal mines. In-place fill properties will be examined for strength development and volume expansion, and an attempt will be made to verify that the backfill becomes a load-carrying support structure. The final phase consists of data analysis and economic assessment, which will contain both general and site-specific cases.

Laboratory tests of PCFA and FBC mixtures show that high hydration temperatures result when all slurry mix water is added at one time. This problem was mitigated by adding 10% to 15% of the water to the initial slurry mix and allowing hydration and subsequent cooling to occur prior to the addition of the remaining slurry water. The mix temperature for the prehydrated slurry was about 20 °C (68 °F), whereas the nonprehydrated mix temperature was about 80 °C (176 °F). Prehydration also improves fill strength. Unconfined compressive strengths for nonprehydrated samples ranged from 3.4 to 5.5 MPa (500 to 800 psi), and prehydrated samples ranged from 6.9 to 10.3 MPa (1,000 to 1,500 psi). Modulus values for the prehydrated fill ranged from 345 to 3,450 MPa (50,000 to 500,000 psi).

Beneficial characteristics of no-cement FBC materials include --

- Ability to utilize two coal combustion by-products, FBC and PCFA, without the need for manufactured cement;

- Relatively low cost;
- Potential for very low permeability and controlled expansion;
- Unreacted lime content may be useful in developing new methods for neutralizing acidic coal refuse piles and abandoned acid mine drainage systems.

No-cement binding materials are attractive for stress transfer modification because slow setting and strength development, expansion, and the potential for long-term changes are acceptable. An underground backfill structure may cure and gain strength up to a year before it is expected to carry abutment loads when the next adjacent longwall panel is mined.

CONCLUSIONS

Conventional pulverized coal combustion fly ash, flue gas desulfurization, and fluidized bed combustion by-products are good candidate fill materials applicable to the problem of gate road stress reduction in deep retreat longwall coal mines. An evaluation of existing and recently developed placement methods indicates that the proposed STM fill concepts are technically feasible and could be implemented within the constraints imposed by retreat longwall mining.

Hydraulic fill characteristics, such as pumpability and slump, and properties of the solidified mass, such as compressive strength and elastic modulus, are principal criteria for acceptance of a candidate fill. Candidate fills should meet the following criteria:

- Unconfined compressive strength and elastic modulus comparable to coal;
- Fill must exhibit strength gains over both short- and long-term curing times;
- During the hydration and cementation phases, acceptable strength, permeability, and durability standards must be achieved;
- Slurry must be pumpable and flowable over a wide range of water content and slump conditions;
- Acceptable transportation methods for backhauling by-products from power plants to mine sites should be developed.

The candidate fill materials studied are classified into three categories:

1) PCFA-cement slurry mixes with class C fly ash and relatively small amounts of cement can achieve compressive strength and elastic modulus values comparable to coal. To minimize the amount of cement used, class C PCFA-cement mix designs would be preferred for the proposed backfilling concepts, since class F PCFA-cement mix designs develop strength and modulus values of about half of those with class C fly ash.

2) FGD sludge mix designs exhibit pozzolanic and cementitious properties that require a source of calcium oxide, silicon oxide, and aluminum oxide to ensure solidification after slurry placement. FGD mix designs containing class F PCFA,

sludge, and small amounts of lime yield strength and modulus values about 60% less than typical coal values.

3) FBC materials are cementitious, since the raw materials typically contain unreacted calcium oxide. Some paste mixes containing AFBC and PCFA exhibited unconfined compressive strength in excess of 35 MPa (5,000 psi) cured to 90 days. At this time, strength gain was still rising and it is estimated the elastic modulus value would be comparable to coal.

In addition to strength and stiffness properties of the placed fill, other properties, such as long-term permeability and durability, will be important for the successful implementation of the stress transfer concepts under consideration.

Pumping and long-distance transport technologies are well proven for handling PCFA-cement flowable fills over a wide range of water content. In entry-filling and packwalling concepts, medium-slump flowable fills can be used to flow and spread materials into impounded areas. In the gob-infilling concept, low-slump paste or compaction grout would be injected into gob voids.

Presently, pumping and long-distance transport technologies are less proven for handling FGD and FBC mixes with solids concentration greater than 65% (wt). Fluid flow behavior and pumping methods for delivering FGD- and FBC-based flowable fills down surface boreholes into abandoned mine workings are currently being investigated.

These and other research efforts will likely contribute toward the development of materials and methods for stress transfer modification. By integrating the filling and extraction cycles, ground conditions in the gate roads can be improved while surface waste disposal problems are mitigated.

REFERENCES

1. Bauer, E. R. Recognizing Signs of Excessive Loading in Underground Coal Mines. USBM IC 9017, 1985, 30 pp.
2. Iannacchione, A. T., C. Mark, R. C. Repsher, R. J. Tuchman, and C. C. Jones (eds.). Proceedings of the Workshop on Coal Pillar Mechanics and Design. USBM IC 9315, 1992, 302 pp.
3. Tsang, P., and S. S. Peng. A New Method for Longwall Pillar Design. Paper in Proceedings of 12th Conference on Ground Control in Mining, (Morgantown, WV, Aug. 3-5, 1993), ed. by S. S. Peng, Dept. of Min. Eng., WV Univ., pp. 261-273.
4. Vandergrift, T. L., and C. V. Jude. Numerical Modeling Analysis of Stress Transfer Modification Concepts for Longwall Mining. USBM RI 9579, 1995.

5. Runovc, F., and U. Bajželj. Backfilling in an Integrated Operation Involving Coal Mining and Power Generation. Paper in Proceedings of Minefill 93, ed. H. W. Gelen, the South African Inst. of Min. and Metal., pp. 397-401.
6. Halvorson, D. SEEC System: Building Bridges Between Industry and the Environment. Paper in Proceedings of Management of High Sulfur Coal Combustion Residue: Issues and Practices, ed. by Y. P. Chugh and G. A. Beasley, (Springfield, IL, Apr. 5-7, 1994), Dept. of Mining Engineering, SIU-C, Carbondale, IL, 1994, pp. 206-208.
7. Caldwell, M., and W. Giles. Integrating Coal Supply With Ash Disposal, Freeman United Coal Company. Paper in Proceedings of Management of High Sulfur Coal Combustion Residue: Issues and Practices, ed. by Y. P. Chugh and G. A. Beasley, (Springfield, IL, April 5-7, 1994) Dept. of Mining Engineering, SIU-C, Carbondale, IL, 1994, pp 209-213.
8. Patelunas, G. M. High-Volume Fly Ash Utilization Projects in the United States and Canada (2nd ed.). Final report CS-4446 to EPRI, Palo Alto, CA, by GAI Cons., Inc., Mar. 1988, 244 pp.
9. American Concrete Institute. Filling Abandoned Underground Facilities with CLSM fly ash slurry. Printed in Concrete International Design and Construction, July 1990, v. 12, No. 7, 7 pp.
10. Meirs, R. J., D. M. Golden, R. E. Gray, Wei-Chung Yu, and R. Hemmings, Fluid Placement of Fixated Scrubber Sludge to Reduce Surface Subsidence and Abate Acid Mine Drainage in Abandoned Underground Coal Mines. Paper in Proceedings of 11th International Symposium on Use and Management of Coal Combustion By-Products (Orlando, Fl, Jan. 15-19, 1995), v. 2, No. 58, Am. Coal Ash Assoc. and EPRI, 1995, pp. 1-14.
11. Smith, C. L., Commercial Aggregate Production from Fly Ash and FGD Waste. Paper in Proc. Tenth Int. Ash Use Symp.: Ash Use R&D and Clean Coal By-Products, Orlando, Fl, Jan. 18-21, 1993, v.1, TR101774, 13 pp.
12. West Virginia University Branch of National Mine Land Reclamation Center. Disposal of Fluidized-Bed Combustion Ash in an Underground Mine to Control Acid Mine Drainage and Subsidence. (DOE contract DE-FC21-94MC29244, WV Univ, Morgantown, WV), Annu. Tech. Prog. Rep., Feb. 16, 1994-Aug. 15, 1995, 100 pp.
13. The American Coal Ash Association, Inc. 1993 Coal Combustion By-Product-Production and Use. Washington D. C., 1 p.

14. Spearing, A. J. S., and N. R. Steward. Slurry, Not Paste, Will be the Fill of the Future. *Can. Min. J.*, v. 113, No. 3, June 1992, pp. 31-40.
15. Brummer, R., and A. Moss. Paste: The Fill of the Future? Part I, *Can. Min. J.*, v. 112, No. 8, Nov.-Dec. 1991, pp. 31-35.
16. Brummer, R., and A. Moss. Paste: The Fill of the Future? Part II, *Can. Min. J.*, v. 113, No. 2, Apr. 1992, pp. 39-43.
17. Weinberg, A., and J. Harness. Performance of FBC and FBC/FLY ASH Landfill Test Cells. Paper in Proceedings of Management of High Sulfur Coal Combustion Residue: Issues and Practices, eds. Y. P. Chugh and G. A. Beasley, Springfield, IL, Apr. 5-7, 1994, Dept. of Mining Engineering, SIU-C, 288 pp.
18. Jagiella, D., Regulatory Requirements: Coal Combustion Byproduct Reuse. Paper in Supplemental Proceedings of 11th International Symposium on Use and Management of Coal Combustion Byproducts (CCBs) (Orlando, FL, Jan, 15-19, 1995), *Am. Coal Ash Assoc.*, 1995, 15 pp.
19. Galvin, J. M., The Significance, Behavior, and Influence of Ashfill on South African Thick Seam Mining Operations, Chamber of Mines of South Africa, Res. Rep. No. 9-82, Jan. 1982, 5 pp.
20. Palarski, J. The Use of Fly Ash, Tailings, Rock, and Binding Agents as Consolidated Backfill for Coal Mines. Paper in Proceedings of Minefill 93, ed. H. W. Gelen, the South African Inst. of Min. and Metal., pp. 403-408.
21. Galvin, J. M., and H. Wagner. Use of Ash to Improve Strata Control in Bord and Pillar Workings. Proceedings Symp. Strata Mechanics, New Castle Upon Tyne, Apr. 1982. Elsevier, pp. 264-270.
22. McLaren, R. J., and N. J. Balsamo. Fly Ash Design Manual for Road and Site Applications, Volume 2: Slurried Placement. Prepared by GAI Consultants, Inc. for EPRI, Palo Alto, CA, Int. Rep. CS-4419, Oct. 1986, 166 pp.
23. Clogowski, P. E., and J. M. Kelly. Laboratory Testing of Fly Ash Slurry. Prepared by GAI Consultants, Inc. for EPRI, Palo Alto, CA, final report CS-6100, Dec. 1988, 460 pp.
24. Hackett, T. D., D. L. Boreck, and D. R. Clarke. Multislice Mining for Thick Western Coal Seams. USBM IC 9239, 1990, 27 pp.
25. Michael Baker, Jr, Inc. Consulting Engineers. State-of-the-Art of FGD Sludge Fixation. Final report FP-671 for EPRI, Palo Alto, CA, v. 3, Jan. 1978, 240 pp.

26. Smith, C. L., 15 Million Tons of Fly Ash Yearly in FGD Sludge Fixation. Paper in Proceedings of Tenth International Ash Use Symposium: Ash Use R&D and Clean Coal By-Products, Orlando, FL, Jan. 18-21, 1993, v. 1, TR-101774, 10 pp.
27. Bland, A. E., C. E. Jones, J. G. Rose, and M. N. Jarrett. Production of No-Cement Concretes Utilizing Fluidized Bed Combustion Waste and Power Plant Flyash. Paper in Proceedings of 9th International Conference on Fluidized Bed Combustion, Boston, MA, v. 2, May 3-7, 1987, pp. 947-953.
28. Bland, A. E., R. Cox, A. Rowen, E. R. Lichty, and R. A. Schumann. Pelletization as an Ash Management Option for CFBC Ash Handling and Utilization. In Proceedings of the 12th International Conference on Fluidized Bed Combustion, La Jolla, CA, May 1993, v. 2, ASME 1993, pp. 1341-1350.
29. Burwell, S. M., R. K. Kissel, A. E. Bland and D. M. Golden. Fluidized Bed Combustion Ash Concrete. Paper in Proceedings of the 12th International Conference on Fluidized Bed Combustion, LaJolla, CA, v. 2, May, 1993, pp. 847-858.
30. Southern Illinois University at Carbondale. Management of Dry Flue Gas Desulfurization By-Products in Underground Mines. Annual Technical Progress Report, Oct. 1, 1993-Sept. 30, 1994. DOE contract DE-FC21-93MC 30252, SIU-C, Dep. Min. Eng., Carbondale, IL, 138 pp.
31. Electric Light & Power. New Container System Expands Coal-Ash Markets. PennWell Publishing Co, v. 73, No. 8, Aug. 1995, 2 pp.
32. Warner, J. Compaction Grouting- The First Thirty Years. Paper in Proceedings of Grouting in Geotechnical Engineering, New Orleans, LA, Feb. 10-12, 1982, ASCE, New York, pp. 694-707.
33. Chastanet, J. D., and P. M. Blaitka. Wanaque Filtration Plant Subgrade Stabilization- A Case History, Paper in Proceedings of Grouting, Soil Improvement and GeoSynthetics, GT DIV-ASCE, New Orleans, LA, Feb. 25-28, 1992, pp. 265-273.
34. Wilbert, K. L., W. L. Johnson, T. P. Brunsing, and A. M. Allen. Subsidence Mitigation Approaches Used in the Number 7 Coal Seam. Paper in Proceedings of Conference on Mine Subsidence in Urban and Developed Areas, Rock Springs, WY, Sept. 9-10, 1993, Wyoming Dept. of Environmental Quality, Abandoned Mine Land Division, Cheyenne, WY, pp. 115-141.
35. Mez, W., and F. Sill. New Possibilities in Disposal of Residual Material by the Techniques of Filling-up Goaf Cavities in Coal Mining. Paper in Proceedings of Second International Conference on Environmental Issues and Management of Waste

in Energy and Minerals Production, Calgary, Canada, Sept. 1-4, 1992, eds. Singhal et al., Balkema, Rotterdam, pp. 379-388.

36. Callis, A. V., and S. R. Newson. Progress into Roadway Reinforcement Techniques in the UK. *The Mining Engineer*, v. 147, No. 314, Nov. 1987, pp. 233-238.

37. North American Mining Consultants, Inc.. Single-Entry Longwall Study. DOE contract AC01-77-ET-12558-T1 (v. 2), formerly USBM J0177036, May 1982. Available from NTIS, Springfield, VA, 312 pp.

38. Arioglu, E., and R. K. Dunham. Physical Properties of Anhydrite/Accelerator Mixtures for Use as a Gateside Packing Medium. *Colliery Guardian*, v. 224, No. 1, Jan. 1976, pp. 31-33.

39. Statham, C. A., Roadside-Pack Construction Demonstration. *Colliery Guardian*, v. 228, No. 12, Dec. 1980, pp. 553-555.

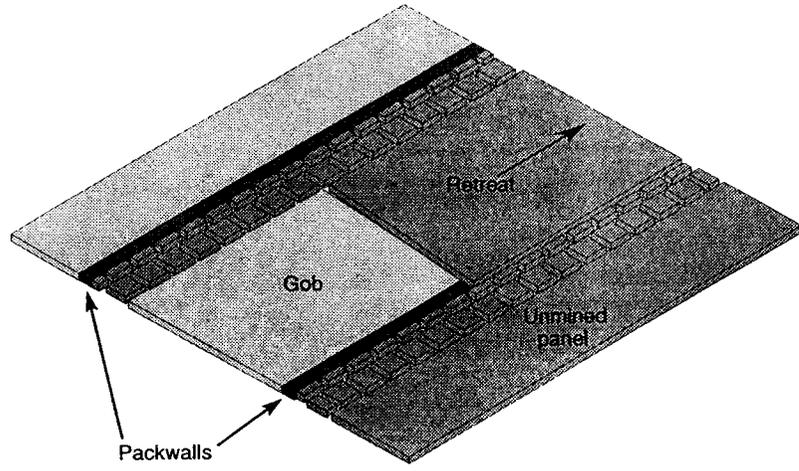
40. Venta, G. J., and R. T. Hemmings. FGD Gypsum, Utilization: Bridging the "Two Solitudes." Paper in Supplemental Proceedings of 11th International Symposium on Use and Management of Coal Combustion Byproducts (CCBs) (Orlando, FL, Jan. 15-19, 1995), Am. Coal Ash Assoc., 1995, 19 pp.

41. Electric Power Research Institute. Reducing Mine Subsidence with FGD Sludge. EPRI Quarterly Report (RP-3176) Combustion By-Product Utilization Research, EPRI, Palo Alto, CA, v. 2, No. 2, Dec. 1994, 4 pp.

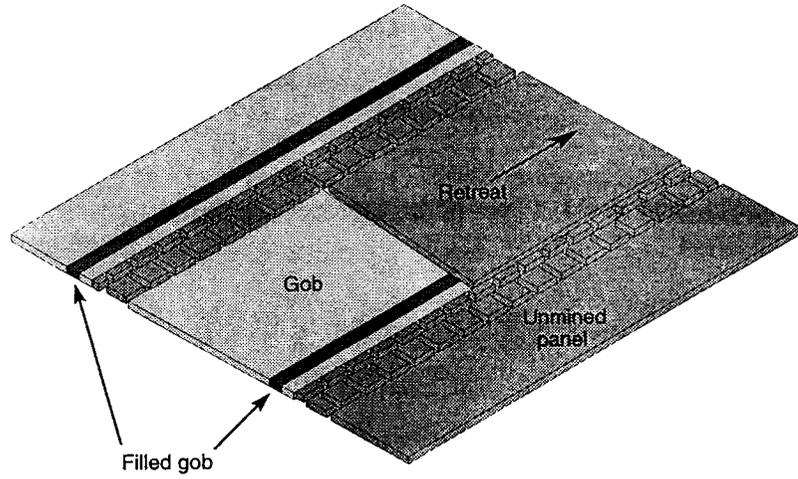
42. Burnett, M., and J. M. Burnett. Pneumatic Backfilling of Coal Combustion Residue in Underground Mines. Paper in Proceedings of Management of High Sulfur Coal Combustion Residue: Issues and Practices, eds. Y. P. Chugh and G. A. Beasley, Springfield, IL, Apr. 5-7, 1994, Dept. of Mining Engineering, SIU-C, pp. 182-188.

43. Kentucky University's Center for Applied Energy Research. High Volume--High Value Usage of Dry Gas Desulfurization By-Products in Underground Mines. Quarterly Report, Phase I: Laboratory Investigations, Jul. 1, 1994-Sept. 30, 1994. DOE contract No. DE-FC21-93MC30251, KY Univ., Lexington, KY, 1994, 36 pp.

A



B



C

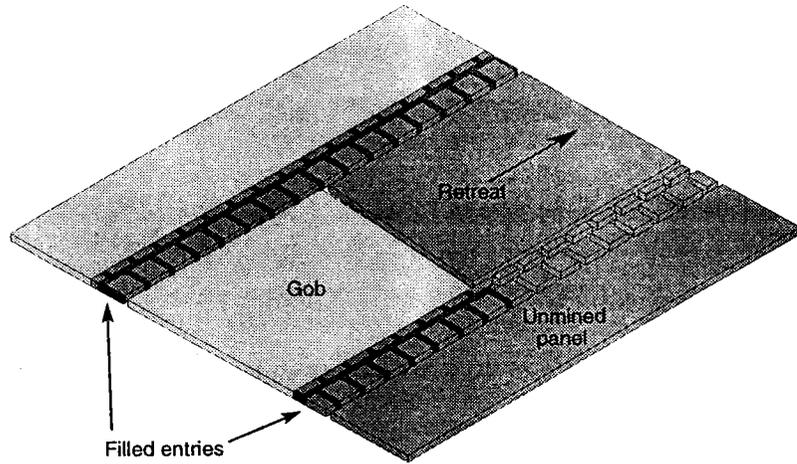


Figure 1.—Stress-transfer-concepts. A, Packwalling; B, gob-filling; C, entry-filling.

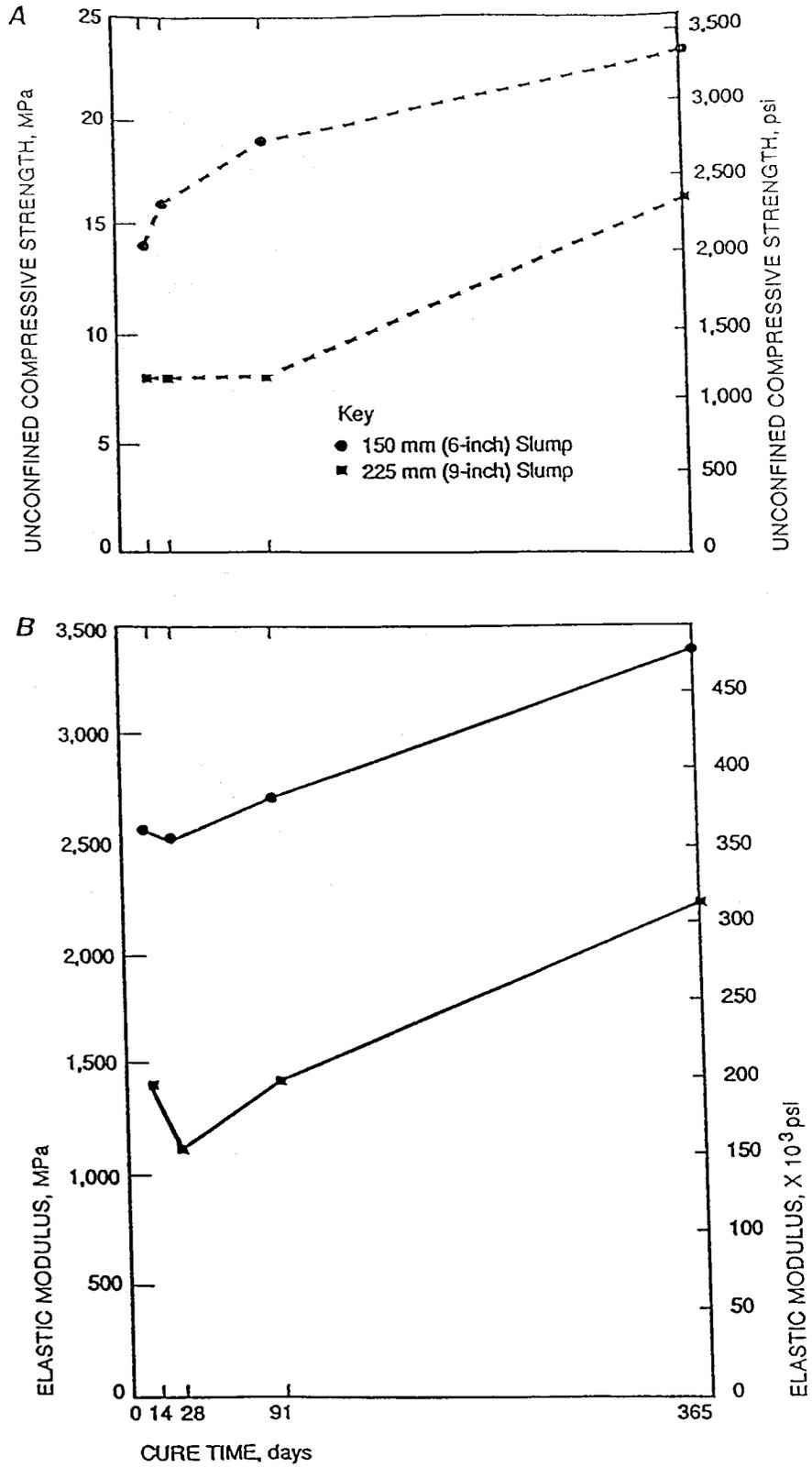


Figure 2.—Strength properties as a function of cure time for a PCFA-cement slurry containing class C fly ash, 2 % cement, and water (23). A, unconfined compressive strength; B, elastic modulus.

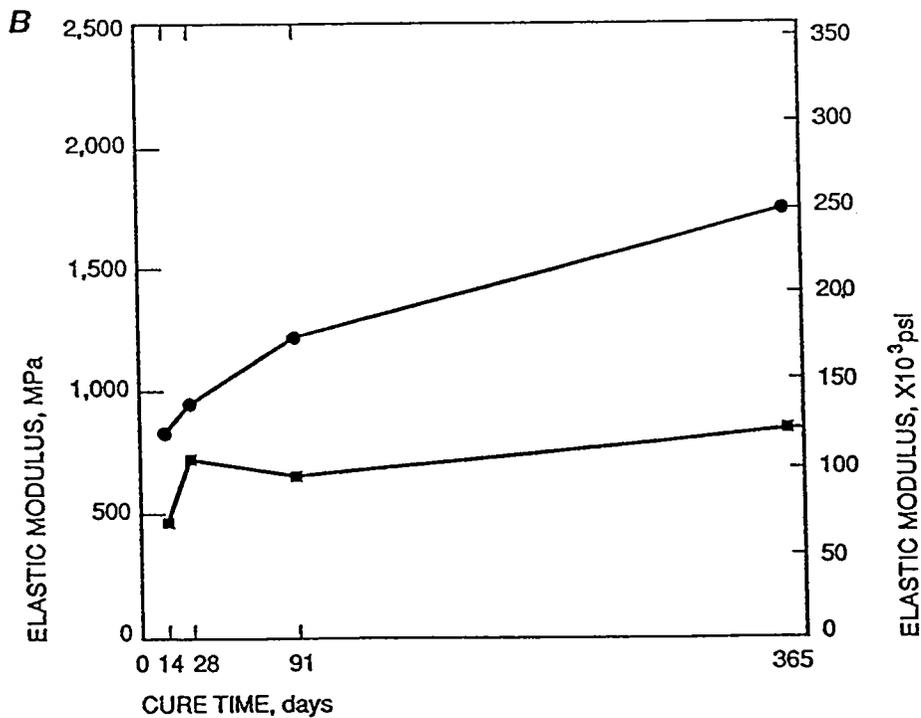
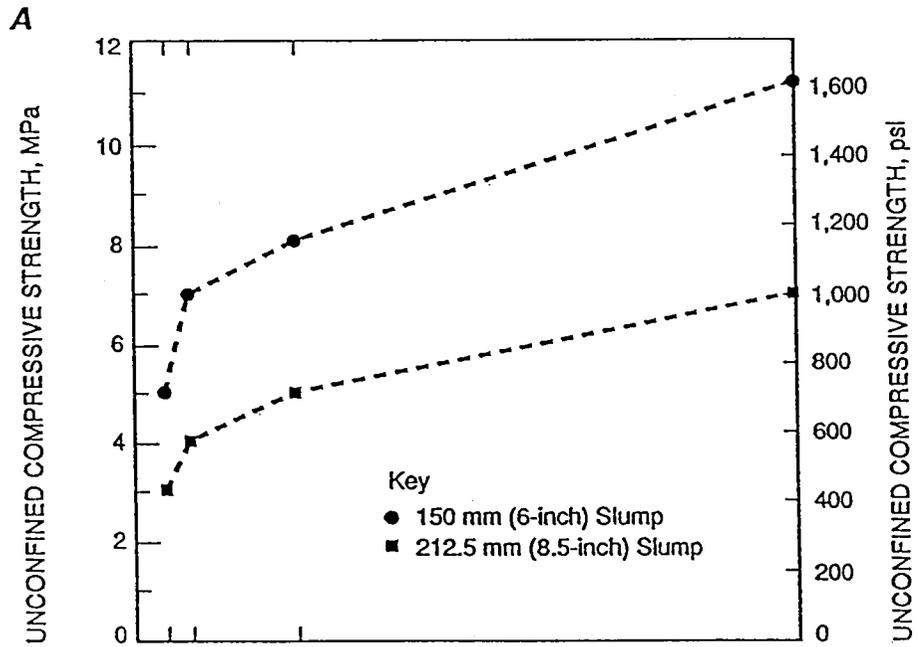


Figure 3.—Strength properties as a function of cure time for a PCFA-cement slurry containing class F fly ash, 5 % cement, and water (23). *A*, unconfined compressive strength; *B*, elastic modulus.

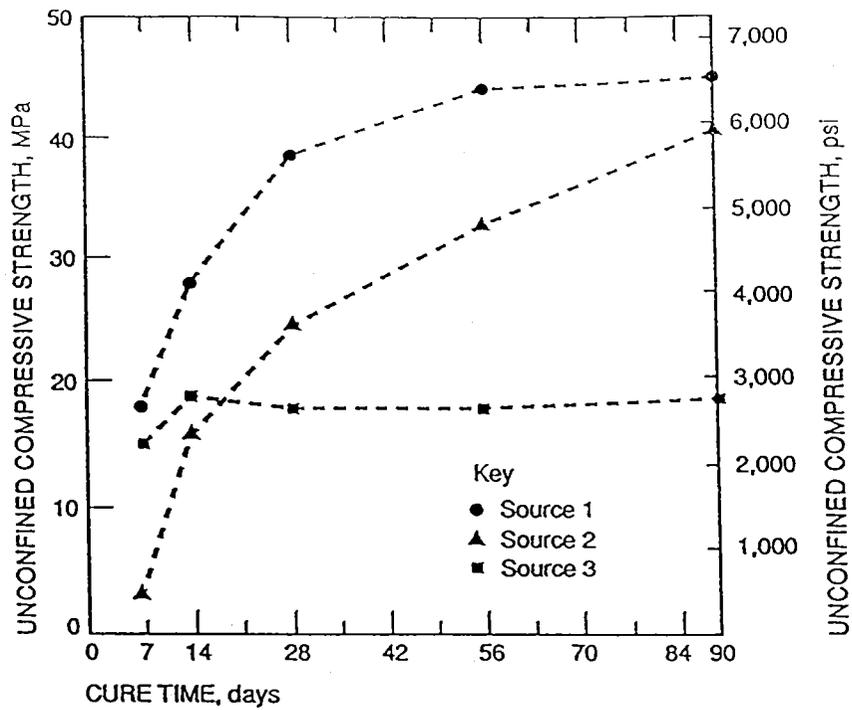


Figure 4.—Unconfined compressive strength as a function of cure time for AFBC-PCFA no-cement paste (29). Source 1: AFBC from TVA; Source 2: AFBC from Chatham; Source 3: AFBC from Colo-Ute. All PCFA from Kingston.