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REPORT OF INVESTIGATIONS/1990

Structural Uses and Placement Techniques for Lightweight Concrete in Underground Mining

By Eugene H. Skinner

1910 ★ 80 YEARS ★ 1990

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR
Manuel Lujan, Jr., Secretary

BUREAU OF MINES
T S Ary, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft^3/min	cubic foot per minute	lb/yd^3	pound per cubic yard
°F	degree Fahrenheit	m^3	cubic meter
ft	foot	μin	microinch
ft^3	cubic foot	min	minute
gal	gallon	oz	ounce
gal/min	gallon per minute	oz/yd^2	ounce per square yard
gal/yd^3	gallon per cubic yard	pct	percent
h	hour	psi	pound per square inch
in	inch	rpm	revolution per minute
in^2	square inch	s	second
in H_2O	inch of water (pressure)	st	short ton
kg	kilogram	V	volt
L	liter	yd^3	cubic yard
lb	pound	yr	year
lb/ft^3	pound per cubic foot		

STRUCTURAL USES AND PLACEMENT TECHNIQUES FOR LIGHTWEIGHT CONCRETE IN UNDERGROUND MINING

By Eugene H. Skinner[1]

ABSTRACT

The U.S. Bureau of Mines conducted experiments on the use of lightweight concrete in the density range of 100 lb/ft^3 for liners in underground mines. Three test sections were completed: a monolithic, portal-type structure with integral walls and arch constructed aboveground; an underground test section constructed in a mine drift using plywood forms; and a second section constructed in a drift using an air-supported formwork. The lightweight concrete in the two underground test sections was placed using piston pumps and a slickline. Fiber reinforcement was added to the concrete in the mine sections without any apparent problems with either pumping or placement of the concrete. In another experiment, the Bureau and Hecla Mining Co., Mullan, ID, used lightweight concrete in the density range of 25 lb/ft^3 to replace timber blocking in a raise preparation structure. Other experiments are described in which low-density, lightweight concrete blocks were produced for mine ventilation doors, stoppings, and barricades. Other mine uses reviewed include pillars and collapsing beams. An advantage of low-density concrete is that it will display up to 50% deformation at a constant yield stress.

These innovative concepts in deformable concrete lining systems will aid mine operators by decreasing capital and maintenance costs, increasing the available space in underground haulageways, and providing productivity gains and improved resource recovery in the soft, caving, squeezing, or bursting ground conditions often found in deep mines.

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INTRODUCTION

The selection and design of ground support systems are of concern to mine management from the initial premining investigation to exhaustion of the ore body. Not only must the type of support (both initial and final) be evaluated, but also the method of excavation and the character of the ground.

The U.S. Bureau of Mines has long been involved in research concerning ground support in deep underground mines. Prior work has investigated the magnitude, direction, and nature of loads on artificial supports through in situ stress measurements and the application of the principles of rock mechanics (*1*).[2]

The structural behavior of the total support system is a complex function of interactions among the individual components in the system. Lack of predictive knowledge about the ground support characteristics around an underground opening leads to inappropriate support selection, which in turn increases both mining costs and safety hazards.

Multiple research tasks are necessary to define rock and support interaction problems: (1) an analytical interpretation of ground support interaction phenomena, (2) characterization of in situ rock properties, (3) development of suitable support materials, and (4) integration of new support technology into the underground mine environment. This last goal includes the promotion of practical methods for conducting research on artificial supports in a typical deep underground mine.

The research goal of this current Bureau project was to improve ground control technology in deep mines where deformation occurs under heavy ground conditions and where there is danger of rock bursts. Work reported herein focuses on tasks 3 and 4 and describes the experimental placement of innovative, lightweight concrete, continuous lining systems. Whenever possible, methods familiar to mine operators and within the technical state of the art had to be used for ease of adoption by industry. Health and safety considerations in support placement were also factors in the experimental underground work.

ACKNOWLEDGMENTS

The Bureau appreciates the cooperation of the Hecla Mining Co., Mullan, ID, and the special assistance of Fred Brackebusch, former manager of mining research, for allowing the use of sites in Hecla mines and use of Hecla shop facilities. Special acknowledgment is extended to A. J. Boyt of Precision Air Structures Co., Des Moines, IA, and L. E. Hale of Concepts in Concrete, Tulsa, OK, who provided, respectively, the air-supported formwork and valuable technical assistance during field work for the air-supported formwork portion of the project. The Generic Minerals Institute of the College of Mines of the University of Idaho, Moscow, ID, under the direction of Professor J. R. Hoskins was instrumental in obtaining the assistance of several students. Special recognition is extended to James Vickery, mining engineer, Spokane Research Center, Spokane, WA, and Michael Werner for their contributions and valuable project work in low-density, lightweight concrete while they were graduate students at the University of Idaho.

BACKGROUND

UNDERGROUND CONCRETE APPLICATIONS

Concrete has been used extensively in surface and underground mines for a number of decades and for a variety of purposes. Early use began in coal mines where its fireproofing ability was first recognized. Some early state mining laws were directed toward promoting the use of concrete by specifying concrete in shafts and certain entries where the danger of fire was greatest.

Much of the hazard in working with heavy, cumbersome steel and timber supports, as well as the hazards of repairing these supports, is eliminated when concrete is used. Cleanup of drifts is made easier because concrete openings have less obstructions and more clearance than comparable openings constructed of other types of support.

The high electrical resistance of concrete makes conditions safer for underground use of electrical equipment. Concreted drifts supporting high-voltage trolley wires are inherently safer than equivalent timber or steel supports because of improved clearance and less clutter in the drift. Concrete haulageways reflect more light and generally result in better illumination. Further information on these

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

hazards is published in Bureau Bulletin 644 (*2*) and much of this material is applicable to mine haulageways. Mine Safety and Health Administration (MSHA) Informational Report (IR) 1058 analyzes injuries associated with maintenance and repair in metal and nonmetal mines (*3*).

By far the most compelling reason for the use of concrete in mining is the lower cost of long-term support maintenance. Even though data from the literature are often outdated and direct cost figures are not comparable with the costs of today, this lower cost is still a major consideration A study by the National Coal Board (NCB) of England has shown that one-third of all NCB spending is on support materials and that the basic methods of installation and maintenance have remained unchanged during the past 50 yr (*4*). A company study in the United States has shown that 35% to 50% of the total mine maintenance effort at one large coal mine was spent on repair and cleanup of mine openings (*5*).

The high maintenance cost for underground support has been noted as a possible threat to the life of the mine. The life of most mines is 20 to 30 yr, while most supports may have a useful life of less than 5 yr; therefore, several replacements of ground support may be required. Many mines have documented figures showing that a large percentage of their underground work force (up to 25%) is allocated to maintaining mine openings (*6*). It may be argued that such a statement was made in the days before modern mechanization. However, the nature of ground support repair is such that extensive mechanization cannot be wholly achieved, even today. In mining areas where concrete has been used, the efficiency per work shift is higher than in areas where other support methods are used.

Concrete also creates smoother drifts, which have decreased air resistance. In the present period of increasing electrical energy costs, moving air through smooth openings may greatly decrease long-term mine-ventilation costs.

Bureau cost studies show that the support function accounts for about half the direct cost of driving, depending on type and amount of support. As a capitalized cost during mine development, the future worth of permanent concrete support distributed over the life of the mine is actually lower.[3] Traditional support practices have even resulted in an increase, rather than a decrease, in initial support costs as well as future repair costs. Even under the most severe ground conditions where the support is expected to be destroyed, the ability of concrete linings to survive has been noted.

Pricing, markets, and availability of support materials have changed over the years. Acquiring adequate timber supplies for many mines is more difficult. Mines that once were supported with magnificent 12- by 12-in and larger timbers, at a cost of mere pennies per foot, now find timber of these dimensions and quantities unavailable. Timber consumption in those mines often exceeded several hundred board feet per foot of drift. The cost of other support materials has increased markedly as part of general inflationary trends. In contrast, increases in costs of cement and concrete products have not been nearly as much (*7*).

Perhaps at no other time in the history of cement and concrete technology has more progress been made, particularly in areas suited to the needs of the mining industry. For example, a variety of concrete pumping machines is now available that are suitable for underground operation. The development of special additives reduces water requirements of the concrete mix, thus resulting in lower water-to-cement (w-c) ratios and greater concrete strength. Additives such as superplasticizers, which give better slump control, allow the formulation of underground concrete mixes virtually unheard of just a few years ago. Other additives like fly ash and silica fume offer equally astounding improvements to concrete mixes. Steel and polypropylene fibers hold promise of allowing concrete to sustain greatly increased flexure and tensile forces–very useful properties for underground concrete. Portable ready-mix plants are now available for use at the mine site, and many mines have installed these plants. Several of these technical innovations were incorporated into the research conducted during this project and are discussed in this report.

LIGHTWEIGHT CONCRETE

One of the project objectives was to develop materials and methods that would complement present underground concrete technology while providing the degree of lining flexibility suggested by many previous researchers. For reasons of simplicity and economy, this research has led to a continued investigation of concrete materials with particular emphasis on concrete containing large amounts of entrained air. The addition of large volumes of air places the resulting concrete density into the category of "lightweight concrete."

Specifically, lightweight concrete is a material defined as having less than the normal unit weight of concrete, which is commonly about 150 lb/ft^3. It is produced by using porous aggregates weighing less than gravel or sand, i.e., volcanic cinders, pumices, expanded shale, artificial aggregates, etc. For this project, the choice of material was an air-foaming agent that entered into the mix calculation directly as volume.

[3]One example is from a mine in the Coeur d'Alene Mining District in Idaho where the main haulageway crossed a major fault zone. Fifty years of continual maintenance was tolerated before the entire zone was solidly lined with concrete. Maintenance was then eliminated.

Two broad categories of lightweight concrete are discussed in this report: (1) a structural-grade, lightweight concrete in the range from 75 to 125 lb/ft^3 to be used as permanent support in tunnel-type openings such as main haulageways, etc., and (2) a nonstructural-grade, lightweight concrete in the range from 25 to 65 lb/ft^3 to be used as a crushable (frangible) liner. During preliminary laboratory experiments, a general rule was formulated relating unit weight to 28-day compressive strength: for 100 lb/ft^3, compressive strength is in the range of 2,000 psi, and for 25 lb/ft^3, compressive strength is about 100 psi. For all practical purposes, a linear relationship holds between these values.

By far the most important reason for the underground use of lightweight concrete is its inherent ability to deform under load. Selecting a unit weight of lightweight concrete designed for underground application means that the support can deform as the enclosed ground deforms and thus yield at a constant rate. This appears to be a significant design concept not known to be tested previously in mining under squeezing ground conditions.

An immediate underground construction advantage of lightweight concrete is that a large volume of coarse aggregate (sand and gravel) is no longer needed. Because this coarse aggregate usually amounts to two-thirds to three-fourths of the total weight of normal concrete, an enormous savings in materials as well as a savings in the cost of transporting aggregates underground is readily seen. Because less materials are used and the volume of foam simply replaces the volume of the aggregates, the overall handling problems are greatly simplified. Even the weight of the large amount of heavy aggregates used in liners is a design disadvantage reduced by the use of a foaming agent.

Placement of lightweight concrete is much easier because vibrating the mix is not necessary. Workability behind a closed formwork is exceptional, and pumping and placement is easier. Because the concrete is lighter in weight, less pumping power is required. Lower weight also means that a formwork can be reduced in proportion, and less formwork strength and bulk are required. Formwork mobilization and demobilization are less. Finally, the cured lightweight concrete can be easily sawn and nailed, an advantage underground where numerous mine utility lines have to be carried along mine drifts. It is easier to attach suitable fasteners to walls made with lightweight concrete. Also, if localized ground pressures are of such magnitude that repair of the drift is necessary, then the lightweight concrete can be easily removed with ordinary power tools and the section replaced.

Adequate lightweight concrete strengths can be achieved for most mining applications. With the use of additives and fiber reinforcement, an economical, continuous liner support system that is moderately deformable can be placed. All these advantages are well within the present state of the art in underground concrete technology.

PREVIOUS WORK AND CONCRETE LINER DEFORMATION LIMIT

A review of the performance of concrete drift linings under severe ground conditions such as those that occur in block-cave mines has shown that concrete liners survive as well as or better than traditional methods of support (*8-9*). Even after concrete liners appear to have failed, they still serve the original mining purpose.

In the 1940's, Terzaghi (*10,* pp. 66-76) suggested the importance of support flexibility while discussing the arching effect in soils. This recommendation was apparently reinforced by personal observations of soft-ground tunneling during the 1930's. By deforming with the stress applied, damaging point load stresses were redistributed around the liner to the surrounding material.

Perhaps the strongest endorsement of flexible supports was based on an extensive field study by Panek (*11,* p. 353). "If a flexibility of this order of magnitude can be designed into a support system without excessively sacrificing its resistance to closure, support failures can be substantially reduced." The liner flexibility suggested was on the order of a 0.2% change in the inside diameter.

A corresponding study from the civil engineering field was Peck's historic survey on the structural behavior of a wide range of tunnels in soft ground (*12*). The author noted that soft-ground tunneling resulted in changes in the state of stress in the ground and corresponding strains and displacements in the tunnel structure, a situation that occurs under many mining conditions. (Although numerous other geotechnical factors are also involved, they are beyond the scope of this report.) One point made in Peck's study was that most tunnel linings are relatively flexible and some linings have deliberately been made more flexible, yet irrespective of the rigidity of the lining, "the changes in diameter of the linings...rarely exceeded 0.5%" (*12,* p. 254). This work was followed by a more theoretical paper in 1972 (*13*) describing design procedures to accommodate flexible linings.

After nearly a decade of research at one large underground block-cave mine, Bureau personnel concluded that an inside diameter change of about 0.2% is a useful criterion for concrete support up to the point where the support fails (*11, 14-16*) even though deformations greater than this have occurred. The correspondence between independent research results in both the mining and civil engineering fields is remarkable and lends further support to the suggested design criterion for concrete lining failure in mines.

Bureau research by Corp (*17*) in 1967 completed laboratory model tests of simulated sand-backpacked circular openings and reviewed the theory of flexible liners. However, no full-scale field experiments were undertaken at that time. This report is considered an update of Bureau research and discusses the results of several field tests.

TEST SITES

All experimental work for this project was conducted at the Star and the Lucky Friday Mines under a memorandum of agreement with Hecla Mining Co. in the Coeur d'Alene Mining District. The Star Mine was a producing lead-zinc mine until June 1982 when it was closed because of depressed metal markets. Its colorful history spans some 90 yr; it once was the deepest producing mine in North America, and reached a depth of 8,100 ft. It is located about 6 miles northeast of Wallace, ID, along Canyon Creek near the town of Burke. The Lucky Friday Mine is principally a lead-silver mine and has produced ore since the late 1940's. This mine is located about 1 mile east of the town of Mullan, ID, which is 6 miles east of Wallace. General mining practice in both mines is much like that in other Coeur d'Alene mines and abundant documentation is available.

The site selected for experimental work at the Star Mine was an abandoned ventilation drift located a short distance west of the Star Mine surface plant. The drift was about 750 ft long, had a nearly square 10- by 10-ft cross section, and had been driven between the surface and the main haulage level, which extends some 2 miles further to the southwest. This haulageway was completed in the early 1950's and the ventilation drift soon afterwards. Thus, all mine openings at the test site were at least 30 yr old. Overburden at the test site did not exceed 500 ft. Year round temperature is constant at 42° F; temperature was not considered a factor in the placement of the lightweight concrete. Typical rock structure before construction is shown in figure 1.

The test site in the Lucky Friday Mine was located on the 5100 level, where a transition from cut-and-fill to a new underhand longwall mining method (called the Lucky Friday underhand longwall or LFUL) is under development. The test site was at the first horizontal cut along the underhand longwall and below the area of previous cut-and-fill mining.

The wall rock at the test site in the 106 raise is typical of the well-jointed, brittle Revett Quartzite on the 5100 level (fig. 2). Contacts are generally poorly defined, and lithologic variation and altered zones make mappable geologic divisions especially difficult. The Revett Quartzite shows strong contact with the ore, although local faulting of the vein is apparent. During the typical cut-and-fill mining sequence, closure of the stope walls is commonly about 1 ft or more, although closures up to 22 in have been measured, after only a short period. Mining operations at the 106 raise are about 2-1/2 yr old and do not show the effects of full deformation. The average temperature on the 5100 level is about 85° F and humidity is 100%, even with ventilation.

In conclusion, mining problems are often acute in the Lucky Friday Mine, and indeed in all mines of the district, due to the depth, the hard, brittle nature of the Revett Quartzite, and the high rock stress.

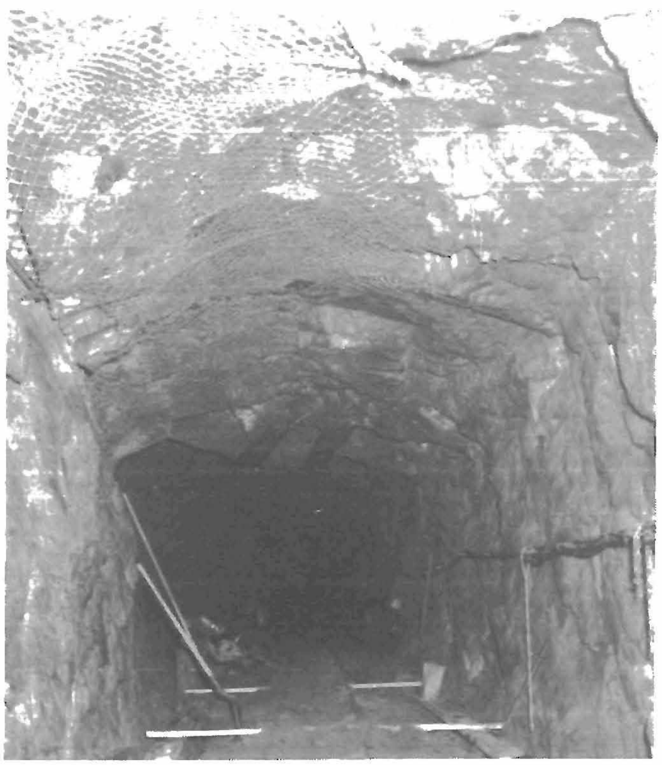

Figure 1.–Test drift at Star Mine before formwork construction.

Figure 2.–Typical wall rock structure at test site in Lucky Friday Mine.

SIMULATED PORTAL TEST STRUCTURE

EXPERIMENTAL OBJECTIVES

A simulated portal-type structure was constructed at a Bureau research center to gain experience with ready-mix batches of lightweight concrete in the density range to be used in later field tests. It was also important to learn if the foaming agent used to create lightweight concrete could withstand pneumatic pumping pressures up to 100 psi. Pneumatic equipment supplied with high-pressure air from the regular mine system is economically justified for low-density, lightweight concrete.[4]

WALL AND ARCH FORMWORK

A greatly simplified formwork was constructed with 12 sheets of CDX-grade 1/2-in plywood cut to convenient panel sizes with forty-eight 2- by 4-in studs for inside panel reinforcing and twenty-six 2- by 6-in studs for reinforcing outside walls (fig. 3). The inside and outside wall panels were nailed onto sill timbers on each side of the form. All formwork stiffeners were on 12-in centers. Both an inside and an outside wall form were fabricated, leaving an intervening 6-in void for the concrete shell. The inside wall was 6 ft 4 in high. The inside width of the section was 5 ft, and the length was 8 ft. The height at the center of the arch crown, based on uncut plywood sheet dimensions, was 8 ft 6 in. The arch was braced on the inside with 2- by 6-in studs and on the outside with 2- by 4-in studs. Common oil was sprayed on the forms upon assembly to allow easy removal of the forms after the concrete had cured. This formwork proved adequate during the pour.

PLACEMENT TECHNIQUE

A Reed shotcrete machine, Sova III model,[5] was equipped with two 50-ft lengths of 1-1/2-in inside diameter (ID) refractory gunning hose. All couplings were internally smooth. A shotcrete nozzle was not used. The end of the hose was simply placed in the chimney on the top of the form and concrete discharged into the form. The lightweight concrete was not vibrated in the form. During concrete pumping, it was soon found that adequate pumping through the 1-1/2-in hose could be done with air pressure reduced to about 60 psi, and portions of the test were run at 40 psi. A production goal was not a requirement and much experimentation was done during the pour. It was concluded that pneumatic placement of lightweight concrete would be satisfactory.

[4]The pneumatic method was one of the first used to place concrete underground (*18*), and pneumatic equipment is still being manufactured for use in mines. With the development of piston concrete pumps in the 1930's, use of pneumatic equipment to place concrete underground diminished greatly. Some manufacturers of shotcrete equipment advertise their machines as being used for pneumatic placement of regular concrete.

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

MIX DESIGN

To test the concept that the formwork could support the wet mix and that a structural grade of concrete could be used, a density of 100 lb/ft^3 was chosen. Using this mix density, nearly one-third of the mix was foam volume. The mix design was taken from a manual on lightweight concrete provided by the manufacturer of the foaming agent.[6] A modified mix was made by adding slightly more cement (687.96 versus 674.56 lb/yd^3) and water (32.24 versus 33.69 gal/yd^3). This actually reduced the w-c ratio to 0.408. The sand weight was 1,859 lb/yd^3. The water content of the sand was unknown, but was assumed to be minimal. These values gave a calculated unit weight of 106.1 lb/ft^3. The amount of water in the foam to be added to achieve the desired unit weight, along with the additional water from the sand, was expected to equal the original w-c ratio of 0.453 using 7.176 sacks of cement per cubic yard. These mix design remarks are based on early laboratory batches having a volume of 2 ft^3. Extrapolation to larger batches was unknown before this portal section was poured.

[6]Gorsline, L. Personal communication and literature, NEOPOR Co., Half Moon Bay, CA, Aug. 1983.

Figure 3.–Formwork for simulated portal structure.

The resulting ready-mix batch order for 3 yd^3 was as follows:

Cement (Type I-II)	lb	2,065
Water	gal	80
Sand	lb	5,575

The sand was reported by the ready-mix company as a "blended sand." The screen size gradations (table 1) by standard test method on similar stockpiled material were as follows:

Table 1.-Screen size gradation, percent

Sieve Size	Retained	Passing
10	31.8	68.2
16	18.8	49.4
30	14	35.4
50	19.3	16.1
100	12.4	3.7
200	2.9	.8
Pan	.8	0

FIBER REINFORCEMENT

Concrete suppliers have recently introduced a concrete reinforcement material manufactured from polypropylene. One packaged bag, sufficient for 1 yd^3, was poured into the hopper of the shotcrete machine near the end of the pour to test the response of the machine. There was no discernable effect on the concrete pumping. Several pounds of steel fiber were also fed into the machine without an effect on pumping. Both types of fiber could be seen in the mix at the end of the concrete hose. No attempt was made to distribute fiber according to batch weight.

INSTRUMENTATION

An effort was made to measure concrete form pressures by mounting a soil-type, flat-face pressure gauge at the bottom of the formwork through a hole drilled in the form and connecting it to a chart recorder. The face of the gauge was not flush with the inside edge of the formwork, a serious problem when measuring soil pressure. Although calibration of the instrument showed it was operating correctly, results indicated a pressure of about 2 psi. This reading decreased linearly during the pour and was probably caused by setting of the concrete. These results are only suggestive and not considered definitive of any trend in formwork pressures in lightweight concrete.

CONCRETE TEST RESULTS

Eighteen 6- by 12-in sample concrete cylinders were taken during the pour. The first three cylinders were obtained from the raw mix without foam and each exceeded a compressive strength of 5,000 psi at 28 days. The remaining samples were taken at various times during the pour. A general pattern was an increase of density and strength with duration of the pour.

The samples with the lowest density and lowest 28-day compressive strength were taken at the beginning of the pour (about 99 lb/ft^3 and 900 psi, respectively); the sample with the highest density and strength (125.7 lb/ft^3 and 3,713 psi) was taken halfway through the pour; three samples taken at the very end of the pour averaged 116.2 lb/ft^3 and 2,461 psi. The average dry unit weight of the 15 samples was 106.1 lb/ft^3 and the average compressive strength at 28 days was 1,690 psi. The spread in the low densities and the low strengths of some samples was disappointing.

The possibility that air pressure in the line might have refoamed part of the foaming agent to produce a lighter weight concrete was considered and may account for some of the erratic results; especially when the air pressure is changed, the revolving feed, bowl-type machine produces a pulsing type of flow. The small 1-1/2-in ID of the hose may have been a factor in density control.

EVALUATION

The lightweight concrete was allowed to flow into the form without vibration or other means of moving mix within the form. The only attempt to regulate the flow was to distribute mix evenly on one side of the arch and then on the other. An example of the transition from the wall to the arch section is shown in figure 4 along with an illustration of the ease of nailing lightweight concrete.

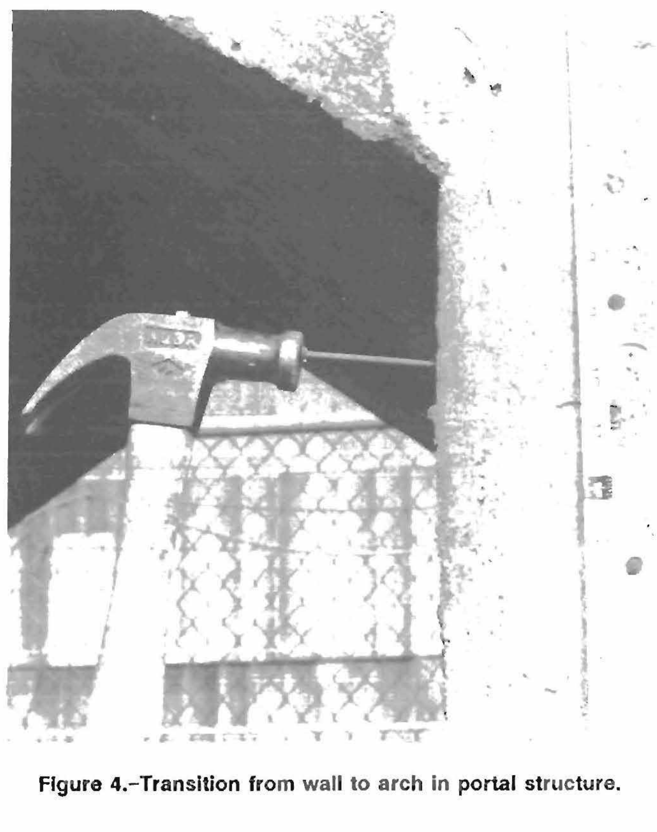

Figure 4.-Transition from wall to arch in portal structure.

The lesson learned from this test section was that lightweight concrete can freely flow into all portions of the form without the use of vibrators. The portal structure has been exposed for 5 yr to weather changes, including the annual freezing and thawing cycles of the Pacific Northwest, without visible structural deterioration.

UNDERGROUND PLYWOOD FORMWORK STRUCTURE

EXPERIMENTAL OBJECTIVE

Based on the success of the portal-type test structure, the next experiment was to construct a lightweight concrete structure underground. This section was three times longer than the simulated portal structure and was scaled up to use 15 times the amount of concrete. The design rationale was that a pour of this length and volume would be about what a mine heading crew could make in two to three shifts before they dropped back and placed a permanent concrete lining. Also, the amount of concrete was predicated on a 1-day underground pouring schedule for a regular mine crew. The formwork was fabricated with plywood and nominal 2- by 4-in timber reinforcing, as before. Although wooden formworks for concrete are well known in industry, such a simple reinforcement would not be acceptable for supporting normal-weight concrete.

INVERT FORMWORK

Some attention was given to preparing the foundation (invert section) for later formwork erection and to making a trial run of the concrete pumping equipment. A hand-dug trench 6 in below the track level was made along each rib for the length of the test section. A 2- by 8-in wood sill plate was placed horizontally, blocked, and leveled along the length of each rib (fig. 5). A 2-yd^3 pour of lightweight concrete was made without incident. This invert pour had a dry density of about 120 lb/ft^3 and a 28-day compressive strength of nearly 1,900 psi for the two samples taken. The invert pour was found to be beneficial for the reason that it prevented later concrete leakage along the invert sill and made a foundation for the plywood formwork installed over the sill plate.

WALL AND ARCH FORMWORK

Attention was given to the arch and wall formwork to make erection as simple as possible and to conserve materials. Thus, plywood dimensions were in units of 2, 4, or 6 ft simply so there would be less cutting. The general schematic of the formwork is shown in figure 6. The geometry was chosen to match a mine design shape given in Stewart (*19*, p. 230), called the "flatback," and used at the Henderson Mine, 80 miles west of Denver, CO. AD-grade 3/4-in plywood was available, and the 2 by 4's were stud-grade lumber. The gusset plates were made from 1-ft-wide strips of 3/4-in plywood with one diagonal saw cut near the middle.

Using power saws and air-operated nailing tools, all panels were fabricated in 2 days by a woodshop crew of two. The formwork was then erected in the shop and matching joints painted for identification in the field. Two coats of form oil were also applied in the shop. At the mine, all materials were hauled underground by railcar and hand-carried to the test site. Electric lights and compressed air were installed for a power saw and air wrenches. A crew of five needed three shifts to erect the form, including placement of mine timbers at the ends, with stulls and whalers across the bottom and across the back of the form. Excellent use was made of lightweight hydraulic roof support jacks developed by the Bureau (*20-21*) for quick support of the centerline stull across the underside of the flat arch (fig. 7). It was proposed that measurements of concrete weight on the formwork could be taken using hydraulic pressure on the jacks, but the plywood forms displayed no significant loading, and the attempt to obtain form pressures through the hydraulic jacks was not successful.

PLACEMENT

Delivery

Standard ready-mix trucks from the local supplier were used from the batch plant to the mine, a one-way trip of about 10 miles with a one-way trip time of about 20 min. The concrete slurry was batched at the plant, transported to the mine, foam added, and the truck unloaded directly into the concrete pumping unit. A modest-sized hopper on the concrete pump allowed storage of 12 ft^3 of mix with an agitator mounted in the hopper. A wire-screen mesh was laid over the hopper to catch any oversized aggregate material.

Foaming

At the mine, water was obtained from the mine domestic water system and added to 55-gal barrels, which were premarked in 200-lb increments. Foaming agent was added to the water in the recommended 40:1 ratio by weight, after which about 10% more foaming agent was added. It was assumed that the barrels of water-and-foam mix came to the air temperature of about 40° F. The water supply was 50° F.

No apparent difficulty was caused by the low temperature other than more foaming time was required to achieve the desired lightweight concrete density. With experience, foaming time can be judged visually. The foam was mixed into the concrete slurry for 3 min of fast rotation by the ready-mix truck.

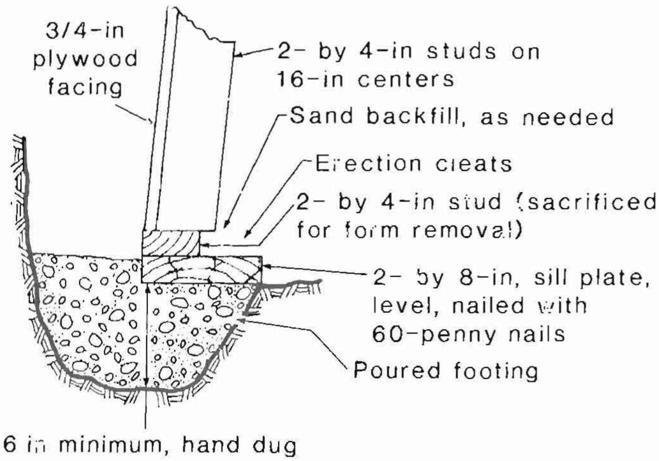

Figure 5.–Details of invert formwork for plywood section.

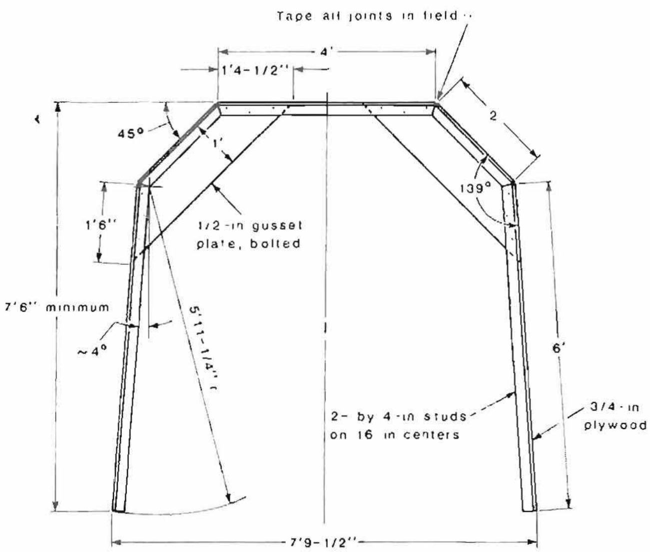

Figure 6.–Schematic of plywood formwork.

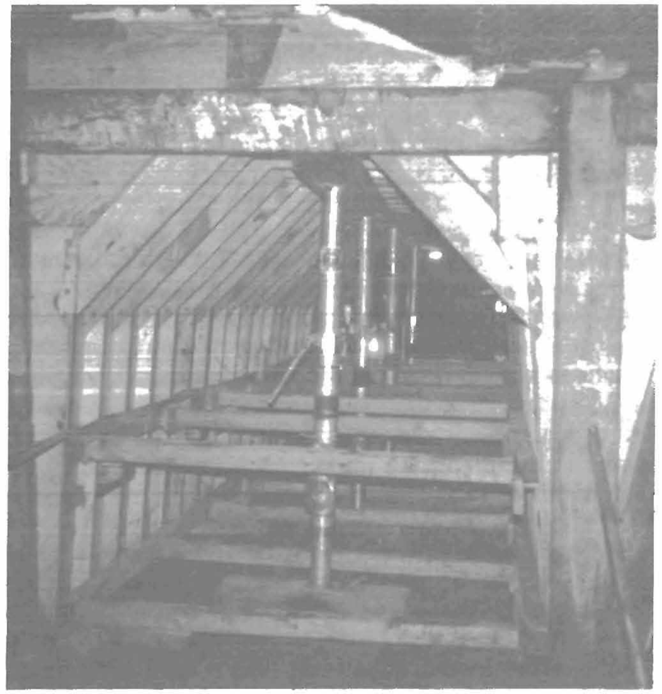

Figure 7.–Completed plywood formwork as erected in the field. Note use of hydraulic jacks to support formwork.

Pumping

The concrete pump used for this pour was a Conspray Model 530 skid-mounted unit powered by a Deutz model F3L-912W diesel equipped with a scrubber for underground use. The model 530 is a twin-cylinder, hydraulic piston pump with swing tube (fig. 8). The hydraulic pistons are 5 in. in diameter and have a stroke of 30 in.

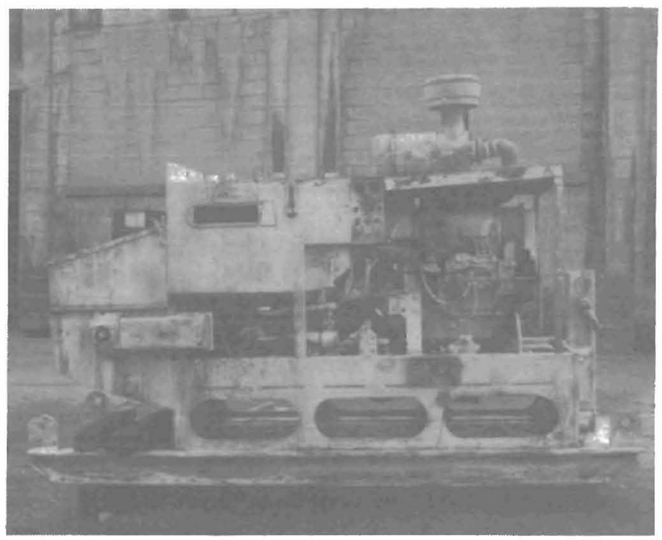

Figure 8.–Conspray Model 530 concrete pump.

Pump calibration showed the following speed-versus-cylinder pressures:

	Cylinder pressure
1,500 rpm	1,000
2,000 rpm	1,500
2,500 rpm	1,750

These values may be at variance with the manufacturer's rating because of the wear on this particular pump.

During the pumping operation, the Conspray was operated at about 1,500 psi piston pressure with a line pressure of about 200 psi. Engine speed was below 2,300 rpm during pumping. Because the foamed concrete was more like grout slurry than regular concrete, the Conspray pump was not overloaded at any time; in fact, the model 530 specifications show that 1,500 psi is at the lower end of its operating range of up to 3,000 psi.

The discharge line was about 150 ft of used 4-in rubber hose in assorted lengths having internally smooth Victaulic couplings. Near the formwork, cross braces elevated the line to the top of the formwork and the line was tied to the wire mesh across the back. No special slickline discharge connection was used for the foamed concrete. No line problems developed and the Victaulic couplings disassembled easily when the line was removed for cleaning.

To pump concrete, the line was initially primed with a slurry of at least two sacks of cement added to the pump hopper full of water. Foamed concrete was then slowly added to the hopper and pumped until it was discharged at the end of a section of disconnected hose just before the formwork. When the line was bled of this slurry and fresh foamed concrete appeared, the pump was stopped and the short section of line reconnected. This procedure assured that very little slurry would be placed into forms where it could not be removed.

Cleanup

Cleanup deserves mention because of the volume in the line (it was calculated that 150 ft of 4-in line contained 1/2 yd^3). At the conclusion of pumping, all Victaulic couplings were broken and each section of hose drained. Because foamed concrete does not yield the quantities of material that a regular concrete containing sand and aggregate does, another advantage of foamed concrete is ease of underground cleanup.

MIX DESIGN

The density of foamed concrete in this test pour was chosen to be 100 lb/ft^3 because the behavior of the concrete at this density was known from the previous experiment. The mix design was based on absolute material quantities for the 3-yd^3 pour, but was doubled to 6 yd^3. Therefore, the main differences in this second test mix were higher quantities of cement and water.

Type I-II cement was provided by the local ready-mix company. The sand screen analysis provided by the company was 60% passing 16 mesh, 15% passing 50 mesh, and 2% passing 200 mesh.[7] This sand was recovered from the fine screens at the gravel plant and combined with crushed residue from the crushing plant, but met State of Idaho Department of Highway, Boise, ID, specifications for concrete. Angular sand was noticeable. The Conspray pump manufacturer recommends pea gravel as the maximum size that should be used in a 3-in line and suggests that pumped concrete use a mix with slightly more slump.

The batch plant order for 6 yd^3 was as follows (table 2), with a calculated density of 104.0 lb/ft^3:

Table 2.–6 yd^3 batch plant order

	Quantity	Pound	Cubic foot
Cement, Type I-II		4,130	21.0
Water .... gal ..	160	1,350	27.0
Sand, S.G. 2.66 .... lb ..	[1]11,150	[1]11,150	67.2
Foam .... lb/ft^3 ..	4.63	216	46.8
Total			162.0

S.G. Specific gravity.
[1]Assumed as 3% water, already subtracted from water quantity.

The problem of foaming in a ready-mix truck with such a large quantity of foam received attention. It was found that the foam hose had to be placed far into the truck to ensure proper mixing. A larger quantity of concrete would require even more foam, hence debate focused on the proper mixing of large amounts of foam. It was finally decided to use about two-thirds the capacity of the truck; therefore, a concrete load of 4-1/3 yd^3 was foamed to a volume of 6 yd^3. No problems were experienced with this size of load and no doubt even larger quantities could have been foamed in the truck without trouble. It was also thought that rotation of the concrete in the ready-mix drum might cause breakdown of the foam structure, but no problems occurred.

FIBER REINFORCEMENT

A concrete reinforcement fiber manufactured from polypropylene was used in the mix placed across the arch. Bags of Type A-5, 3/4-in-long material were hand fed into the Conspray hopper and mixed with foamed concrete by the agitator paddle on the pump. Each bag contained 1.6 lb of the Type A-5 fiber, and one bag was recommended for each cubic yard of concrete. A fairly even distribution of fiber was achieved by hand-feeding. The fiber apparently did not impede concrete pumping and was observed to be remarkably well distributed in the mix.

[7]A sample of the sand was later obtained, and a screen analysis of material at the plant closely matched the above analysis. No quality control inspections were made of the batch plant operations. A sand sample taken during the winter at the ready-mix plant 1 month after the pours showed a water content close to 7%.

Three test cylinders of mix containing fibers were taken from inside the form; when tested, these cylinders did not physically break as had the others, but had to be forcibly broken to separate the remnant cylinder pieces. A count of the fibers showed well over 100 fibers distributed across the broken 6-in-diameter section. No change in concrete strength was noted. (However, the manufacturer does not represent the product as a means of changing concrete strength.)

INSTRUMENTATION

Four strain gauges were placed in the concrete across the flat back several feet from the slickline port and read periodically for several months. Very little change occurred in the readings until a pronounced shift to near zero for all gauges suggested that the gauges were inoperative.

CONCRETE TEST RESULTS

Twenty-one random samples, three samples per load,[8] were taken from the seven ready-mix loads used to complete the test section. The physical process of pumping seemed to achieve better foam concrete homogeneity, and, in the opinion of job personnel, the foamed concrete appeared very workable in the forms, being able to flow into the entire 24 ft of formwork from the point of placement (fig. 9).

[8]The procedure was to cast the cylinders at the site, transport them to the laboratory within 3 days, strip the forms, and cure the samples in a fog room at 68° F and 100% humidity until the 28th day. Sulfur capping was placed after air-drying for at least 12 h. American Society for Testing and Materials (ASTM) standards were closely followed.

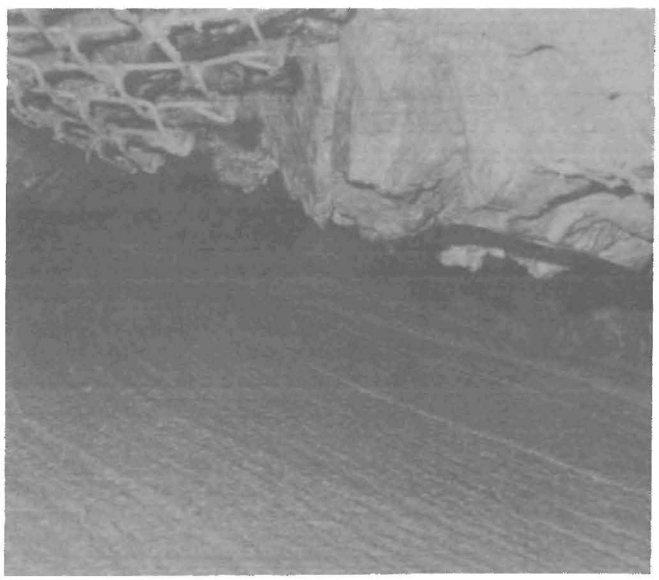

Figure 9.–Flow of lightweight concrete in arch of formwork.

Nine samples taken from loads 4, 6, and 7 represent loads that had been foamed with different quantities of foam and hence had slightly different densities (table 3). Foaming times of 3-1/2, 4, and 4-1/2 min are applicable only to the conditions of this test and are not representative of other lightweight concrete densities under other field conditions. Although this limited number of samples yielded inconclusive results, it appears that a foaming time of about 4 min would give a density nearest to 100 lb/ft^3 with the greatest strength. The longer foaming time indicates that the increased foam volume decreased the density with a corresponding marked decrease in strength.

Table 3.–Comparison of samples with different foaming times

Sample	Dry density, lb/ft^3	Compressive strength, psi	Foaming times, min
7	96.0	1,259	3-1/2
8	94.1	1,204	3 1/2
9	102.2	1,768	3-1/2
14	99.6	1,482	4
15	97.0	1,413	4
16	98.0	1,379	4
19	95.6	1,166	4-1/2
20	96.5	1,023	4-1/2
21	96.1	1,195	4 1/2
Av ...	97.23	1,321	

A comparison of the samples taken from load 6 both at the truck and in the formwork at the end of the hose discharge (table 4) illustrates how better mixing was apparently achieved through pumping. These latter samples were obtained simultaneously at the pump and inside the formwork.

Table 4.–Comparison of samples at concrete pump (samples 11-13) and at hose discharge (samples 14-16)

Sample	Dry density, lb/ft^3	Compressive strength, psi	Remarks
11	94.3	972	At beginning of load.
12	95.7	953	Near middle of load.
13	98.6	1,215	At end of load.
14	99.6	1,482	At discharge inside form.
15	97.0	1,413	Do.
16	98.0	1,370	Do.

There are two conclusions to be drawn from this group of samples. The first is that the density increased about 5 lb/ft^3 as a result of pumping the concrete for a distance of about 150 ft through a 4-in-diameter line during the half hour of unloading. The second conclusion is that even after pumping, the density increased about 5 lb/ft^3 while the strength increased about 300 psi. All things being equal, the strength increase is believed to be due to the additional homogeneity resulting from mixing during the pumping process.

The average dry unit weight of 20 samples was 100.5 lb/ft^3 with a range from 89.0 to 123.8 lb/ft^3. The standard deviation in density was 9.7 lb/ft^3. The average compressive strength was 1,489.5 psi with a range from 889 to 3,871 psi. The standard deviation was 728.5 psi. Four samples from the first two loads ranged from 111.6 to 122.4 lb/ft^3 and the compressive strength ranged from 2,077 to 3,871 psi, with the samples having the highest density and highest strength corresponding. These first loads were placed on the bottom, or invert, of the pour. All succeeding loads were higher in the pour and were of lower density and less strength.

Following the field pours, and using quantities of the same sand and cement obtained from the ready-mix plant, a 2-ft^3 batch was prepared to duplicate the original mix design as closely as possible. This mix was without foaming agent. All aggregates were oven dried. All materials were placed in a freezer and brought to the field pour temperature of about 40° F prior to laboratory mixing. The w-c ratio of this mix was 0.407, but the resulting mix was obviously harsh and the water content was brought up to a ratio of 0.50 by adding increments of water. The resulting 6- by 12-in cylinders tested between 4,728 and 5,435 psi compressive strength at 28 days with an average of 5,067 psi and a standard deviation of 994 psi. These results suggest that the basic mix design is acceptable as a basis for lightweight concrete. They also confirm the compressive strength results of the simulated portal pour without foaming agent.

EVALUATION

Concrete pumping through a rubber 4-in line at distances up to 150 ft with a piston concrete pump was shown to be a satisfactory method of placing lightweight concrete in the density range of 100 lb/ft^3. A mine drift about 10 by 10 ft with formwork 6 ft wide by 8 ft high and 24 ft long was successfully poured in one 8-h shift (fig. 10). There was apparently little or no degradation of the foaming agent within the concrete mix when pumping at line pressures up to 200 psi and under hydraulic piston pressures of 1,500 psi. Concrete compressive strengths below 2,000 psi at 28 days and at a density of 100 lb/ft^3 are believed to have been caused by the excess water in the mix as well as the variable quantity of foaming agent. Water control must be carefully addressed during production mining.

The flow of the mix in the forms was considered exceptional in that all joints and crevices were filled without the necessity of vibrating the forms. Corners and angular intersections were nearly perfectly filled without surface evidence of vugular structure. No additives of any kind were used in the mix–only the basic design mix was used.

Plywood formwork was found adequate to support a concrete density of 100 lb/ft^3. Across the top of the arch, the concrete exceeded a depth of 2 ft. Fresh concrete along the walls reached a depth of nearly 10 ft without noticeable effect on the forms. Minor leakage developed at one end between the rock and the forms, but no leakage developed along the form joints. Project personnel suggested that a sealant be applied in those areas prior to concrete placement to seal the rock and wall contact (the Bureau has developed a number of mine sealants, but a discussion of these materials lies outside the scope of this report). Lightly oiled forms were stripped without unusual effort. Lightweight concrete does not appear to bond to plywood, perhaps due to lack of form vibration. Forms were stripped at 5 days merely to give more curing time at the mine drift temperature of about 40° F.

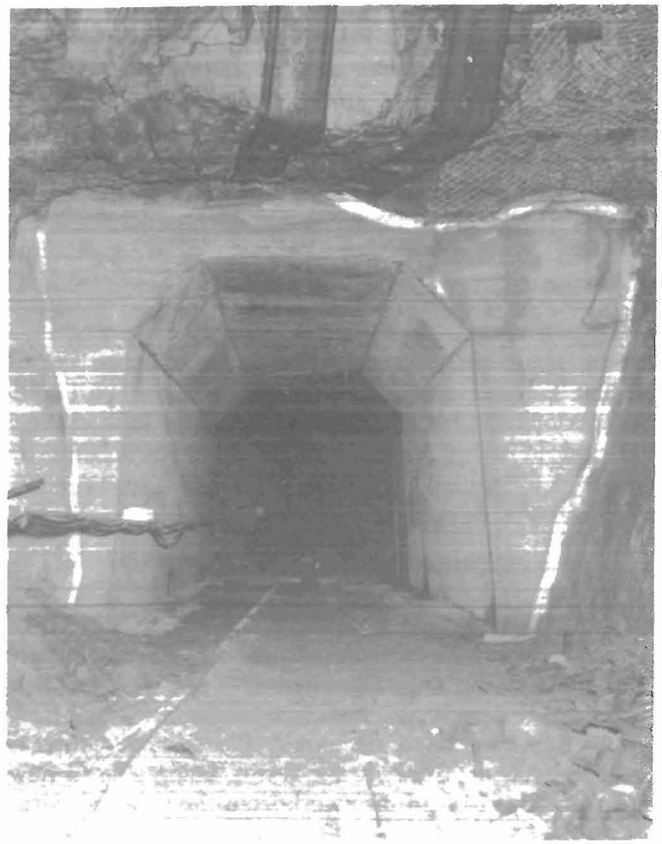

Figure 10.–Completed lightweight concrete test section.

The completed test section has been carefully monitored for the past 4-1/2 yr without any structural changes noted.

AIR-SUPPORTED FORMWORK STRUCTURE

EXPERIMENTAL OBJECTIVES

The successful completion of two pours using structural grades of lightweight concrete and a proven means of placement illustrated that underground use of lightweight concrete was technically feasible. However, the amount of material used in the wooden forms, the short life of such forms, and the time necessary for erecting and dismantling the forms led to the development of a more economical, air-supported formwork. A vast literature from throughout the world has shown this method to be technically feasible (*22-23*). The American Concrete Institute and the

American Society of Civil Engineers formed Joint Committee 334 on air-supported formwork in the spring of 1985 and published a special issue of Concrete International (*24*) devoted to air-supported formworks.

Air-supported formworks should be capable of being rapidly erected and dismantled. The support requirements for wet lightweight concrete weighing one-third less than regular concrete can be achieved using inflation pressures well within maximum pressures achievable. For this experiment, the Bureau worked closely with Precision Air Structures[9] to develop an air-supported formwork capable of supporting lightweight concrete. Therefore, the objective of this second underground test was to concentrate on the logistics of using an air-supported formwork structure for underground concrete placement. It is believed this is the first use of an air-supported formwork in mining.

INVERT PREPARATION

A line of horizontal holes was drilled 18 in into the wall rock slightly below track level. These holes were drilled on 1-ft centers along each rib for a distance of 25 ft. The purpose of these holes was to support a line of rebar and steel banding designed to control the flotation forces of the air-supported structure while it was being embedded in wet concrete. Fifty pieces of No. 6 rebar were fabricated to just touch the wall of the air-supported structure when cemented in the horizontal hole. The upper rebar end was also bent to attach a predetermined length of high-strength steel banding that went around the arch of the formwork. The rebar and the steel bands were not recovered after concrete placement although the steel bands could be easily stripped from fresh concrete.

AIR-SUPPORTED FORMWORK

During the initial site examination, cloth tape surveys of the test section were made to determine the rib and arch dimensions. These data were used to approximate the size of formwork to be fabricated and the estimated amount of concrete required. (If this method of forming is adapted, the drift size will have to be carefully controlled such as in the "A" and "B" lines of civil construction.) Later, when the formwork was erected, it was possible to crawl onto the form and make further measurements between the rock and the airbag along each rib and across the arch. From these data, estimates of the quantity of concrete needed were made.

The air-supported formwork was specifically designed for this test site. However, the dimensions and general configuration could be used at other underground sites having about the same size of drift. A cylinder 8 ft in diameter and 25 ft long was planned to fit the nearly 10-ft-square drift. The wall thickness was based on a nominal 1-ft thickness of concrete while the circular arch was to be covered with at least 2 ft of concrete over the crown. The fabric chosen was a heavy-duty polyester material (weight = 7.5 oz/yd^2) used for similar air structures and for mine ventilation ducts. This fabric meets numerous civil and military specifications for similar uses.

A design innovation was to enlarge each end as a sphere to provide self-sealing bulkheads. The spheres added another 16 ft to each end, resulting in a total form length of about 57 ft. The ends were centered on the cylinder section, which, at full inflation, was held about 2 ft above the ground. With the air-supported formwork inflated in the drift, the restraint of the surrounding rock held the formwork well within desired tolerances (fig. 11).

For purposes of observation, the contractor elected to install a double-airlock door section through which personnel could enter the air-supported structure while it was fully inflated and while concrete placement was under way. This door section was designed as a small sphere attached to the self-sealing bulkhead and was operated by closing valves on both the inside and outside doors. Under full inflation, the valve on the outside door was first opened, collapsing the airlock sphere. When the inside pressure was released, the outer door was removed and up to three people could then enter the small sphere. The door was replaced, the outer valve closed, and the inner valve opened to bring air pressure to equilibrium between the two doors in the airlock. With air pressure at equilibrium, the inner door could be removed and personnel could enter the main air-supported cylinder (fig. 12). At full inflation, the door position was about 4 ft above track level.

Two people were stationed inside the formwork to monitor concrete placement operations during pours. A general view inside the formwork is shown in figure 13. Communications were established with a phone line, since two-way radios did not work well inside the formwork. An attempt to gauge the concrete depth in the ribs was made visually by using expendable electric lights strung just below the arch. Although the illumination was helpful, and some light could be seen through the fabric, concrete draining over the formwork largely obscured precise depth measurements.

Perhaps the greatest advantage of the air-supported formwork was the ease of transportation underground. The shipping weight of this particular air-supported formwork was 465 lb. The entire package was simply placed on a mine car and moved to the underground test site (fig. 14). At the test site, the packaged formwork was unloaded and partially unfolded while dragged to the proper location. Further unfolding and repositioning with manual tugging and pulling at appropriate places positioned the formwork precisely in the test drift. The entire formwork installation did not require over 1 h. The position of the air-supported formwork at the beginning of inflation and with the high-strength steel banding installed is shown in figure 15.

[9] Boyt, A. J. Personal communication, Precision Air Structures Co., 3120 Delaware, Des Moines, IA.

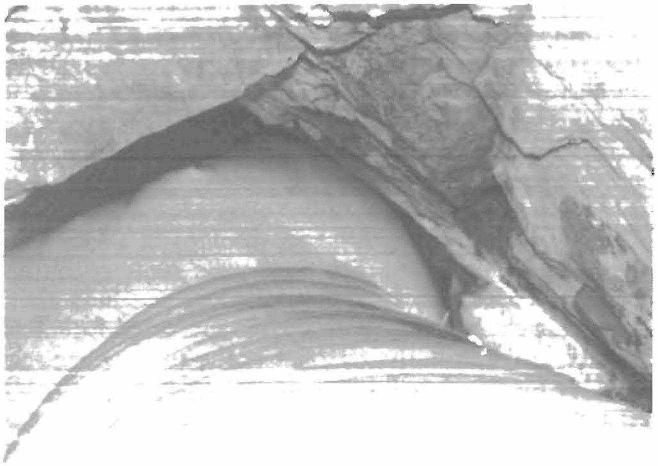

Figure 11.–Inflated air-supported formwork.

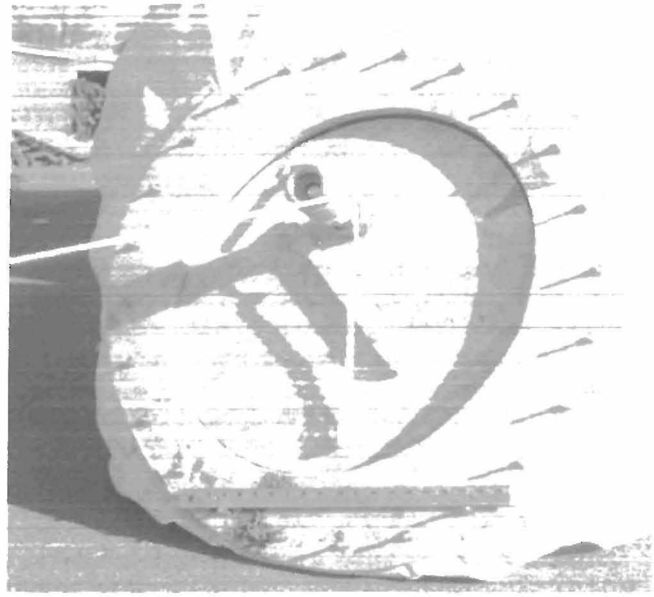

Figure 12.–Access door for air-supported formwork.

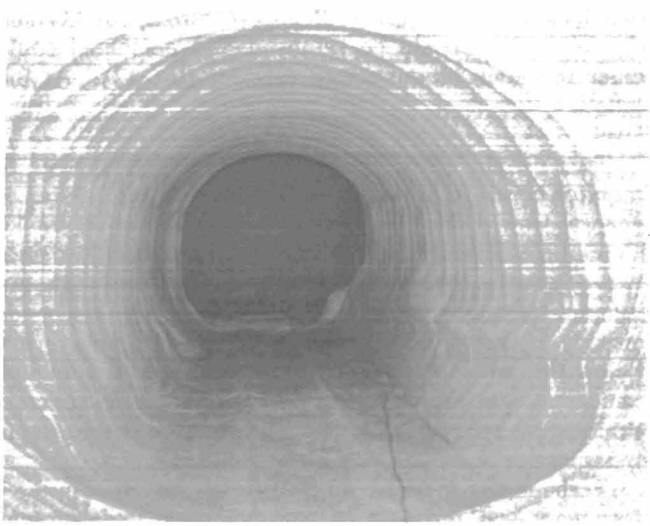

Figure 13.–Inside view of inflated air-supported formwork.

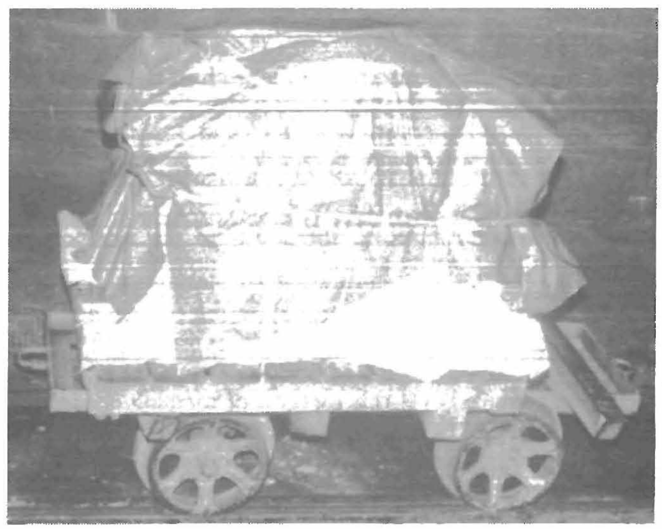

Figure 14.–Air-supported formwork packaged for transporting in mine.

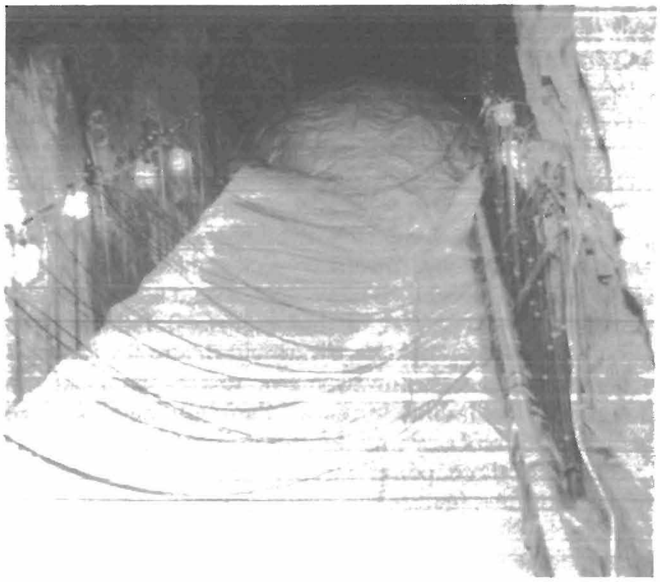

Figure 15.–Air-supported formwork positioned for inflation.

A decision was made in the field to provide a means of access behind the air-supported formwork while concrete placement operations were under way. This was achieved by placing a 14-ft length of 18-in-diameter culvert at the crown of the arch and fitting it into the recessed vein. Even though the culvert section was slightly offset to the centerline, this arrangement served perfectly. Personnel were able to crawl back onto the formwork and direct concrete placement exactly. With the formwork fully inflated, the superior fit of the fabric against the rock under air pressure was evident. At a few places where especially jagged rock appeared, ordinary fiberglass batting was placed between the rock and the fabric and provided additional protection from puncturing.

The air-supported formwork was inflated with 110-V double blower fans mounted in parallel with one-way check valves on the blower side of each fan (fig. 16). The check valves prevented air leakage through the fans in case of power failure. A special uninterrupted line was run to the test site by mine electricians. These industrial fans were rated at 107 in H_2O at 105 ft^3/min. Plastic pipe was used between the fans with a 25-ft length of 1-1/2-in flexible vacuum hose from the output of the blower fans to the inlet of the formwork. An external gate valve was placed at this point to regulate the air supply in the formwork.

Pressure monitoring was done simply with a length of clear surgical hose bent to a U-shape with colored water added. A tape measure provided the reference length for a manometer. One person was assigned to monitor the fan and manometer, with a telephone to the inside of the formwork and to the outside concrete pump. No problems developed while operating this system. The fans were left on continuously and unattended between pours, as well as for 3 days after completion of concrete placement, without any loss of air pressure.

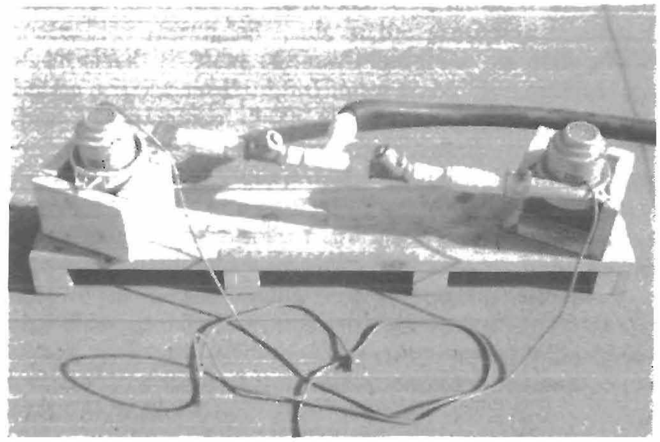

Figure 16.–Blower fans for inflation of air-supported formwork.

With both fans running, the formwork could be inflated in about 20 min. Normally only one fan was used to maintain a constant pressure. During the concrete pours, the formwork was inflated to between 24 and 26 in H_2O. One pressure-loss test was made during the initial startup and it was found that for the formwork to lose 1 in H_2O, 1 min 19 s was required. A large air pressure loss would occur if there were a malfunction while operating the air doors. For this reason, personnel assigned to monitor concrete from inside remained inside for the shift.

A suggestion for future work is to use the mine air supply to inflate the formwork quickly and as a standby in the event of a fan malfunction. Normally a fan of this size is well adapted to inflate an air-supported structure of these dimensions.

PLACEMENT TECHNIQUE

Delivery

Turnaround times between truckloads were about 2 h for the round-trip distance of about 20 miles to the batch plant. The ready-mix batch plant operation of delivery, foaming, and unloading was exactly the same as in the previous test with the plywood formwork. Temperatures ranged from 50° to 70° F throughout the test period. No problems were encountered with the concrete delivery operations.

Foaming

The foaming equipment was the same as that used in the previous test. Mine water for domestic use was added to 55-gal barrels premarked in 200-lb increments. Foaming agent was first added to the barrel in the recommended 40:1 ratio by weight. A 6-yd^3 truckload of concrete required nearly the full barrel of water and foaming agent. A fresh water and foam solution was made up for each load of concrete. The length of time between ready-mix deliveries allowed careful calibration and preparation of the water-foam solution. A beam balance scale was used so that frequent on-site calibration tests of the foaming equipment could be made.

Pumping

The Conspray model 530 concrete pump was used again for this test. A change of Victaulic fittings from a 4-in to a 2-in pumping hose was made at the discharge point. Most of the pumping operations were in the range of 2,000 rpm with cylinder pump pressures of 1,500 psi or less. Line pressures seldom exceed 200 psi while pumping the lightweight concrete. Although the pumping equipment was never used to capacity, the pumping hose did develop considerable pulsation slap just beyond the pump discharge point where the line was constricted from a 4-in line to a 2-in line. Hose tie-downs were not used at the formwork.

The 150-ft-long pump discharge line was laid on the drift floor. Elevation changes where sand segregation could cause possible line blockages were examined. An initially well-greased line helped prevent line blockage. The pumping line consisted of several 25- and 50-ft lengths of hose fitted with internally smooth Victaulic couplings. The short lengths made removing and cleaning the pump line easier. No special slickline pipe at the discharge was used. There were no significant line problems in spite of the numerous bends and elevation changes and the reduced placement rate using the 2-in hose. Full pumping continued (fig. 17) until the top of the arch was reached. The culvert section was then boarded shut and the pumping hose embedded in the mix until the arch was filled.

Cleanup

Cleanup between pours was similar to that described for the previous test. With use of 2-in pumping line, considerably less concrete remained in the line. At the finish of a pour, the Victaulic connections were broken and the lengths of pumping line flushed with water from the mine fire line system. No problems requiring emergency breaking of the line for cleaning occurred. During both underground tests, concrete pumping was completed without any major spilling or dumping.

MIX DESIGN

The unit weight of the lightweight concrete was again selected as 100 lb/ft^3. Calculations suggested that the air-supported formwork would support at least 2 ft of lightweight concrete at this unit weight. Thus, the test drift dimensions would be a maximum test for concrete support with the air-supported formwork method.

Two mix designs were chosen for this test. The first two pours for the invert were smaller, only 3 yd^3 each, and of higher unit weight. This weight would help hold the steel banding in place and thus control flotation of the airbag, as well as provide a stronger concrete for the later wall pours above the invert. The smaller pours at the beginning would allow testing of the pumping procedure and correction of any problems that might have arisen.

The first three pours exceeded 100 lb/ft^3, while the remaining pours (except the last one) were directed toward a goal of 100 lb/ft^3 and 6 yd^3 each. The last pour was heavily foamed merely to create enough volume to fill the void across the arch and averaged about 70 lb/ft^3.

The first two pours were batched with the following mix design (which was exactly half the previous full 6-yd^3 batch), in pounds:

Cement (Type I-II)	2,065
Water (80 gal)	666
Sand (plant mix)	5,788
Foam for 3 yd^3, added by sight	

Figure 17.–Pumping lightweight concrete into air-supported formwork.

The water content of the sand was assumed to be the same (3%) as in the previous test. The success of the first test prompted the use of calcium chloride ($CaCl_2$) in an attempt to provide a high-early-strength for use in conjunction with the air-supported formwork. The first two batches were poured with 1% liquid $CaCl_2$ by weight of cement. All remaining pours were made with 1-1/2% $CaCl_2$, which is equivalent to about 7-1/2 gal. This was added to the ready-mix truck as the last step just before feeding into the concrete pump. The ready-mix company recommended that a water reducer be used and so 103 oz of Master Builders 344-N were added to the first two batches; Master Builders was added to all subsequent batches at the rate of 5 oz per 100 lb of cement. Possible degradation of the foam by the additives was considered. However, this was not noted even when $CaCl_2$ was added directly into the mix at the ready-mix truck.

A shortage of ready-mix trucks at the mine site allowed only one load every 2 h. Test cylinders collected during the pours with the 1-1/2% $CaCl_2$ did obtain a noticeable concrete set in the time between loads. Therefore, each load was placed upon an earlier load having some degree of stiffness. The detrimental effects of some concrete additives on the foaming agent should be taken into account with regard to lightweight concrete.

The invert pours tended to exceed the desired target unit weight. For this reason, emphasis was placed on better foaming and water control during the remaining pours. The following mix design was provided in batches 3 through 9 for 6 yd^3, in pounds:

Cement (Type I-II)	3,725
Water (105 gal)	875
Sand (plant mix)	8,600
Foam (for 6 yd^3, av)	340

All of these quantities were provided by the ready-mix batch plant. The water reducer was added at the plant and the $CaCl_2$ was added just before pumping. In those loads following the invert pours, the incremental foaming and the addition of water brought the mix water up to 125 gal. This amount proved excessive as the resulting dry unit weight at 28 days averaged 124.1 lb/ft^3. On the fourth load, the water was reduced to 115 gal, which later gave a dry unit weight of 97.3 lb/ft^3. It was decided to reduce the water another 10 gal per batch and make up the batch with foaming water until the mix appeared to be correct. All subsequent loads were batched with 105 gal of water. At 28 days the dry unit weights showed a range from 93.5 to 109.8 lb/ft^3 distributed as follows, in pounds per cubic foot:

Load	
4 ...	97.3
5 ...	104.0
6 ...	97.3
7 ...	109.8
8 ...	99.1
9 ...	93.5

Load 10 was a heavily foamed load designed to simply fill space. As shown, all loads in the preceding tabulation were within ±10 pct of the design goal. Results of the compressive strengths of these concrete tests will be discussed later.

Loads 3 through 7 were poured in 1 day and loads 8 through 10 the following day. Although the final three loads more-or-less simply filled the void in the arch caused by the nearly square cross section, the air-supported formwork contained the wet concrete with only the vertical support provided by the concrete poured 17 h earlier. The total weight of these last three loads foamed to 6 yd^3 was three times the batch weight of each product, that is, the total load of wet concrete placed in the arch was about 41,000 lb within 6 h.

In summary, the concrete mix design was satisfactory and was successfully pumped without serious problems. The lack of quality control at the ready-mix batch plant was apparent, and ways to improve control of the amount of water and foam need to be developed. The use of lightweight concrete for simply filling voids should also be noted. This will be discussed in the section "Raise Preparation Structure."

FIBER REINFORCEMENT

Polypropylene fibers were introduced into the Conspray hopper during the pours of loads 5 through 10 at the recommended rate of one bag per cubic yard of concrete mix. The fibers were mixed with the foamed concrete by the agitator paddle revolving in the hopper. Considerably more fiber was introduced in this test than in the previous test.

The use of fiber did not interfere with the concrete pumping, and the fiber was well distributed in the mix even though the hose was only 2 in. in diameter. Fiber could be observed in the mix at the discharge end. The fiber did not cause an apparent change in concrete placement.

As the fiber was hand-fed into the mix, it was possible to exceed the recommended quantity by several times to determine if any pumping difficulties would arise. However, no pumping difficulties occurred under all pumping conditions on this test.

INSTRUMENTATION

Weldable strain gauges (Ailtech CG-129) were installed along a 60° rosette placed in the concrete wall at a distance of 12 ft 8 in from the portal side and 4 ft 6 in above the track level. The gauges in the rosette configuration have been monitored every 2 months for the past 3 yr. Each gauge lost about 3,000 μin within the first 3 months, but since then change has been only a few hundred microstrain, apparently changing with the seasonal water inflow into the drift. The interpretation of these rosette data is quantitative and rock loads are assumed to be minimal at the test site. The probable cause for the initial decrease in the readings is assumed to be either moisture- and temperature-related or the result of concrete shrinkage following curing. The annual ambient temperature in the test drift is nearly constant at about 42° F.

CONCRETE TEST RESULTS

Fifty-one 6- by 12-in test cylinders were taken from the 10 ready-mix loads of lightweight concrete. Each sample was taken from the hopper of the concrete pump after agitation and was weighed. The samples were then capped and placed nearby until the project was completed. Temperatures were believed to reach the low 40's during the night. The samples were transported to the Bureau research center and stripped, weighed again, and placed in a room where temperature and humidity were controlled for 28 days. Table 5 lists the results of the sample tests.

Table 5.-Results of sample tests from different loads

Samples	Load	Av. dry wt, lb/ft^3	St. dev., lb/ft^3	Av. comp. strength at 28 days, psi	St. dev., psi
10	[1]1- 3	117.83	7	3,606.5	957.7
29	4- 8	101.55	7.9	1,756.5	890
12	[2]9-10	70	NAp	NAp	NAp

NAp Not applicable.
[1]Invert pours.
[2]These batches were poured merely to fill the arch and so the mix design was deliberately low density.

A point to consider in foaming technology is that for any w-c ratio, the cement reaction will take water from whatever source is convenient to complete the reaction. Thus, experience derived from this project shows that if the water content of the mix is below a w-c ratio of 0.40, the cement reaction will probably use water from the foam. This results in a loss of foam volume and a higher unit weight. Additives may alter the mix properties, but additives should be carefully considered in lightweight concrete. A deliberate use of a higher w-c ratio, say 0.50, will probably not take water from the foam, but will simply be too wet a mix. The result is a lower strength concrete. Field foaming requires a certain amount of experience and adequate monitoring at the ready-mix plant. On all these tests, each load from the ready-mix plant varied and, therefore, the quantity of foam added to each load produced a concrete of variable characteristics.

Calcium chloride and water-reducing additives were used without noticeable effect on the lightweight concrete, although the effect of $CaCl_2$ in decreasing the setting time was noticeable. The sensitivity of lightweight concrete to the foaming volume and water content was well demonstrated.

EVALUATION

Pumping lightweight concrete through a 2-in-diameter rubber line for distances of about 150 ft with a piston concrete pump was found to be satisfactory, although it took a much longer time than pumping concrete through a 4-in-diameter hose. Little or no degradation of the foaming agent occurred while pumping through this smaller line except for the expected density increase with pumping time. No significant problems developed during placement of 10 loads of lightweight concrete. An air-supported formwork 25 ft long with an 8-ft diameter provided sufficient containment for a wall 1 ft thick and an arch 2 ft thick.

The air-supported formwork proved to be exceptionally well adapted to the underground placement of lightweight concrete, particularly the expanded ends acting as bulkhead seals. The ability of this bulkhead modification to contain wet concrete even against rough and jagged rock surfaces was most remarkable. The time savings for constructing bulkhead containment with underground air-supported concrete formworks alone is significant. The capability of the formwork to wrap around other mine obstructions, such as pipes and wood blocks, yet seal the wet concrete was exceptional (fig. 18). The adhesion of the lightweight concrete was minimal, and the fabric simply fell away from the concrete surface after deflation (fig. 19). Overall, the ease of underground erection and dismantling of the air-supported formwork was an outstanding achievement. The completed section of lightweight concrete has been monitored over the past 3 yr and no structural changes have been noted (fig. 20).

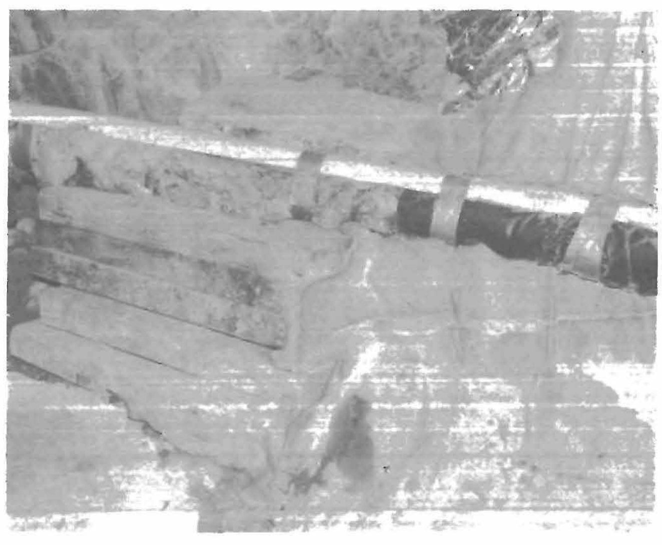

Figure 18.-Completed seal of air-supported formwork with mine utility lines.

Figure 19.–Removing air-supported formwork.

Figure 20.–Completed lightweight concrete section using air-supported formwork.

RAISE PREPARATION STRUCTURE

DESCRIPTION AND OBJECTIVE

In the horizontal cut-and-fill system of mining widely practiced in the Coeur d'Alene Mining District, a substantial structure is required on the main haulage level to handle ore, waste, timbers, and supplies from the stopes above. These are called raise preparation structures (raise prep) and are started at the point where a short crosscut from the main haulageway intersects the vein. In the Lucky Friday Mine, a raise prep is usually about 27 ft long by 20 ft wide by 21 ft high, and contains two chutes and a separate manway and timber slide for miners and material service to the stope. The top 10 ft of the raise prep serves as the beginning of horizontal stope mining along the vein. Stopes are started by making one upward round followed by eight successive, short, horizontal 6-ft rounds. Further mining continues by successive horizontal rounds, each round removing about 9 ft of ore, and is carried outward to the limits of the ore body. As this horizontal mining cycle is completed, the mined-out area is backfilled with mine tailings. The raise prep structures are generally spaced about 200 ft apart along a level, or whatever distance is economical for slushing.

A major portion of the ground support in the timbered raise prep is provided by 14- to 18-in-diameter timber caps 15 ft in length (fig. 21). Each of these large caps is placed perpendicular to the strike of the ore body between the hanging wall and the footwall. The caps are headed in on each end with a minimum of 30 in of headboard blocking to absorb the squeeze and placed so that loading is perpendicular to the wood grain (fig. 22). Obviously, the large amount of timbering and blocking required takes up a great amount of space and necessitates a large opening (fig. 23). Note the large horizontal timber being placed across the opening.

Assuming that 18-in-diameter timber caps have an end area of about 250 in^2 and that allowable load for the timber in compression is at least 1,000 psi, then the working load carried by each cap is approximately 250,000 lb. Because deformation in the blocking over the caps is a controlling factor in crushing and the blocking array is about 2 ft on each side (or approximately 550 in^2), then the load required to crush the blocking without crushing the cap (although crushing of the caps does occur) applied from the rock inward is on the order of $250{,}000/550 = 450$ psi. Further assuming that the blocking array actually restrains an area of surrounding rock equal to 10 times its area, then the average yield stress over the total area is about $450/10 = 45$ psi, or about 50 psi of stress across the total area.

Typically, it is expected that closures of 6 to 12 in will occur within 1 yr after the raise prep area is first mined and that several feet of closure will occur before the level is mined out within 2 to 5 yr. The timber blocking over the caps is usually replaced when squeezing reaches the maximum limit, as can be visually noted. Several sets of blocking must be replaced during the life of the stoping area.

Figure 21.–Large-diameter timber caps used in raise preparation structure.

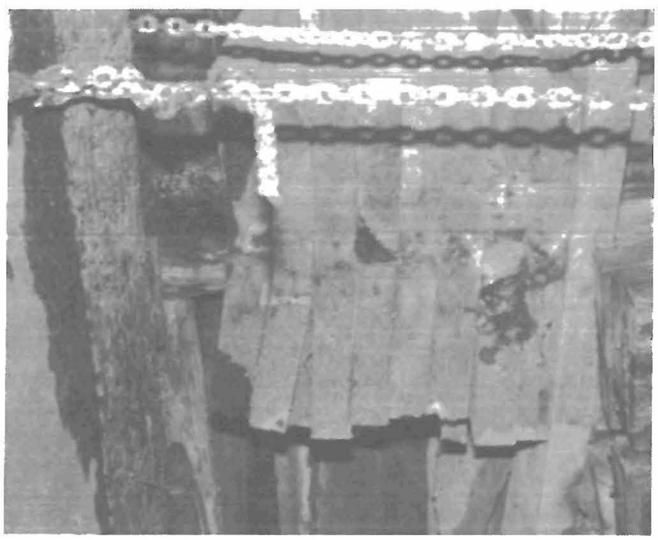

Figure 22.–Typical thickness of blocking used at end of caps.

Samples of the timber caps and headboards used at the Lucky Friday Mine were thoroughly wetted for several weeks to simulate the effects of prolonged exposure in an underground environment.[10] Tests were made with one

Figure 23.–Raise preparation structure under construction.

to six sets of headboards having an 18-in-diameter cap (254 in^2) as the loading follower force to simulate an actual cap and headboard arrangement. The entire assembly was placed in a 400K Tinius-Olsen testing machine. Representative curves are shown in figure 24. Even with a greater thickness of headboard, deformation never attained the ideal shape desired for a constant load material, that is, a condition of no further increase in load with deformation. The plot of load versus deformation shows an increasing load with all thicknesses of headboards.

A new raise prep design using foamed concrete would require considerably less excavation than the design using timber; therefore, the construction time would be shortened. Other advantages would be less repair and maintenance. Some savings were also expected from less ore dilution. No changes would be needed in the drill-and-blast methods used in the mine. However, initial costs of a foamed concrete raise prep were expected to be about the same as those for a timber raise prep.[11] If the concept

[10]It is correctly argued that these tests can only be approximate as the degree of timber wetting and drying in the laboratory can never exactly equal underground mine conditions over a long period of time. However, the general trend of data is suggested to be correct.

[11]Current labor and materials costs were computed by the mining company based on its internal costing methods. Repair and maintenance costs were not broken down by item, but were only available as a total cost for each level, amounting to about $100,000 per month.

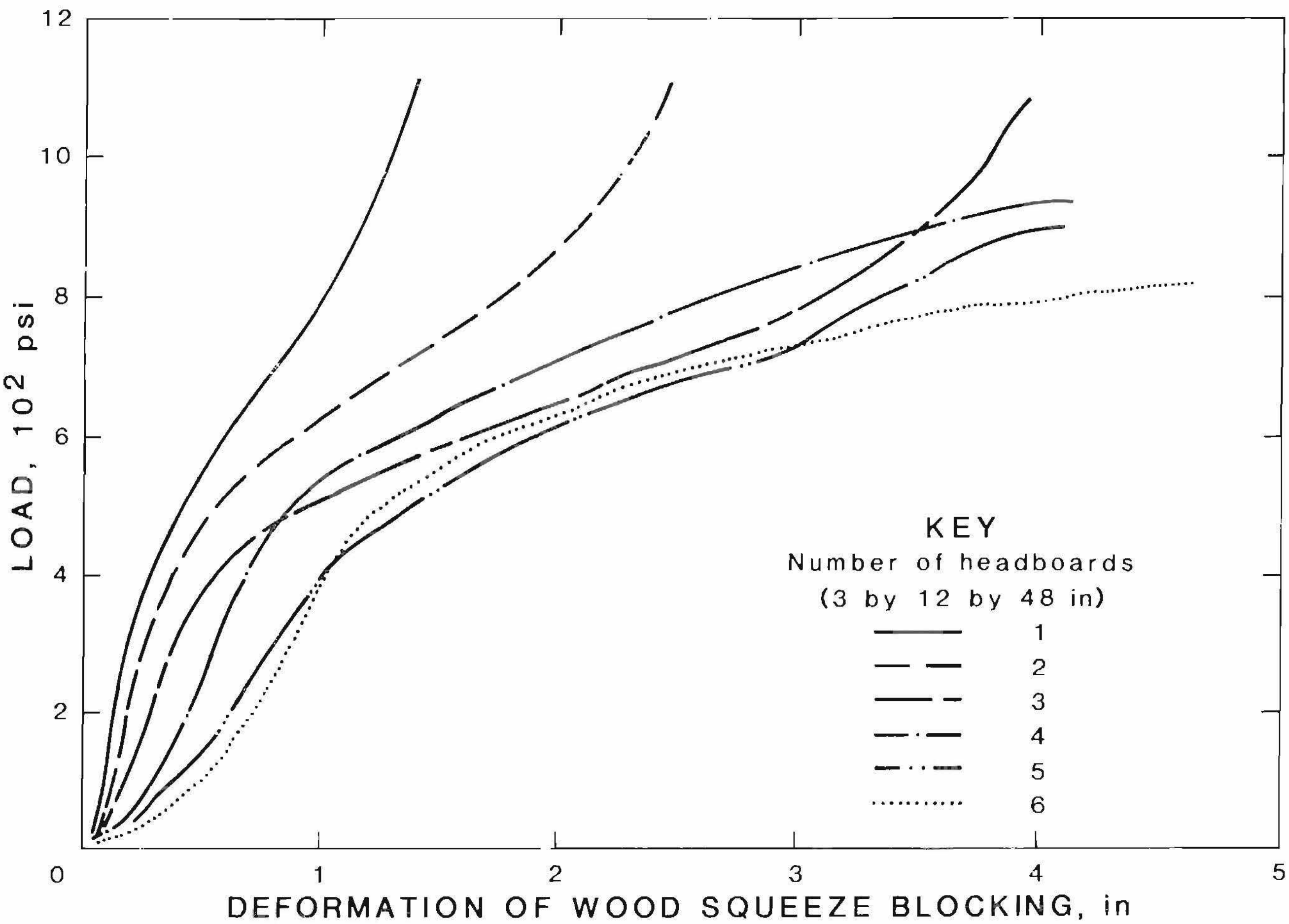

Figure 24.–Representative compression curves of timber blocking, after Werner (25).

should prove successful, raise prep structures using foamed concrete would ultimately be cheaper. Projecting these savings to the end of mining between levels showed that very significant cost savings could be realized. No consideration was given to salvage value, which is a possibility for the more accessible steel members.

CONSTRUCTION

The raise prep was begun after driving the crosscut to completion across the vein. The crosscut was expanded to about 12 by 12 ft through the vein-raise prep distance. An invert sill was started by cleaning the ditch on either side of the drift along the length of the raise prep. This sill pour was necessary to provide a good foundation for the steel columns used later.

The density (about 22 lb/ft^3) and placement details of the 2-1/2-yd^3 sill pour were the same as the later wall and chute pours. The mix for the sill pour, per cubic yard, was as follows:

Cement (Type III, 3 sacks)	lb	282
Water	lb	116
Foam	ft^3	23.7
w-c (by weight)		0.41

After the crosscut excavation and sill pour were completed, a round was made into the vein on each side of the crosscut. This was carried upward another two rounds, followed by erection of the steel columns on the lightweight concrete footings. Drilling and excavation were continued upward for the chute. All exposed rock surfaces were covered with 2-in wire mesh and bolted.

The steel comprising the raise prep structure was specified as A-440 steel in 12 WF 50 beams throughout for design and simplicity of erection. All beams were prefabricated to allow ease of underground construction. A construction schematic is shown in figure 25. Tie members between steel columns were 2-in-diameter steel pipe. For additional structural strength, 3/8-in-thick A-36 steel plate was welded to all inside surfaces. About 250 ft^2 of plate was required. Shear connectors and additional Dywidag rockbolts were placed across the chute bottom in areas having long, flat spans. Access openings to the manway, timber slide, and two 4-ft-diameter timbered chutes on either side were fabricated from rolled 3/8-in plate and field welded. These also served as the concrete formwork up to the height of completion for the raise prep before actual mining began. In essence, the entire formwork area was sealed with steel plate. Annular space around the raise prep for the placement of concrete was about 2 ft. About 100 yd^3 of lightweight concrete was ultimately placed in this annular space.

Overall, the use of steel may appear structurally more demanding than the use of timber. However, both structures carry considerable vertical load from the two ore chutes, the movement of ore passing through the system, and the manway and timber slide chutes. In reality, there is little difference between the two designs, except for the provision for using new materials to take up deformation in the headboard-cap timber squeeze combination.

INSTRUMENTATION

Strain gauges were placed on four column legs, across two caps, and at chute gate members, and weekly readings were taken. The columns instrumented were those in the crosscut resting directly on the sill pour. In the 3 yr since installation, a simple monotonic increasing strain trend has taken place, but no increase in load is apparent. These data suggest the raise prep structure is being loaded slowly and uniformly. At the beginning of April 1986, when mining temporarily ceased, strain readings from the columns stabilized and readings from the chute gate decreased. Total change in strain was on the order of 100 μin.

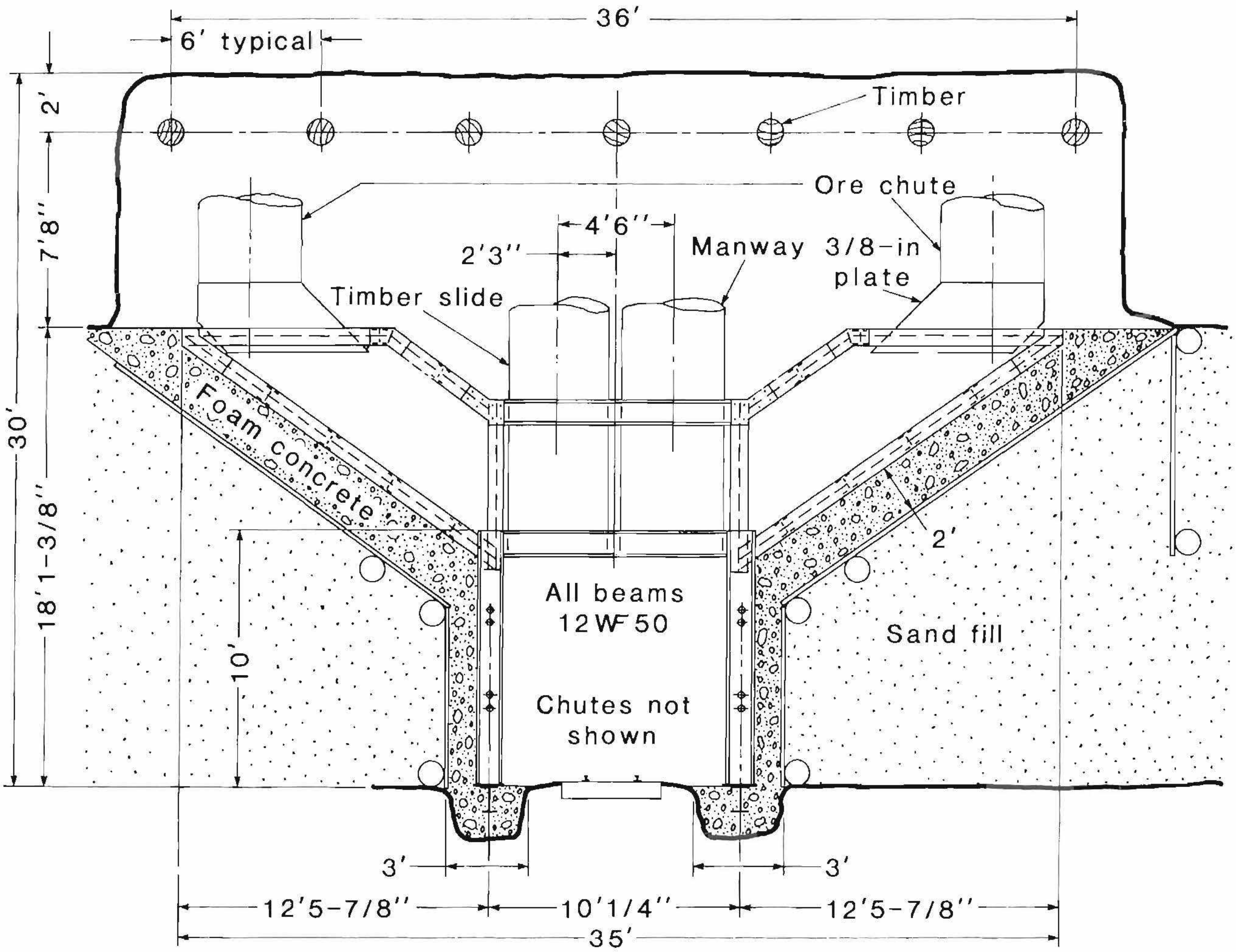

Figure 25.-Construction schematic of raise preparation.

In addition to the strain gauges, two extensometers were placed in the ribs across the chute area and have provided continuous closure data since installation with recording maintained even after mining was discontinued. Total deformation in the first 150 days was about 3 in (fig. 26). This example shows the dependence of deformation upon rate of excavation. Significant closure usually occurs when nearby stopes are expanded.

CONCRETE POURS

The sill pour and subsequent pours up to the first floor of the raise prep at the chute level were all made with concrete mixing, placing, and pumping equipment manufactured by Putzmeister-Neopor, Nürtingen, Federal Republic of Germany. Equipment modification to accommodate underground use was done by removing the trailering and mounting two mixing tanks side by side on a frame suitable for transporting on mine flatcars. Although bulky, the equipment configuration did not inhibit the placement of lightweight concrete.

Each mixing tank held about 1 yd^3 of material. Mixing was by three internal spiral mixing agitator vanes powered by a 220-V, 1,770-rpm motor through a drive box that revolved the vanes at approximately 75 rpm.[12] Each mixing tank could be separately charged with water from a timed circuit. Tanks could be filled with cement and other additives off the conveyor through a flanged silo door at the top of the drum. The advantage of the double mixing tank arrangement was that one drum could be discharging while the other was mixing, thus allowing almost continuous concrete placement. A lever on the side of the mixing tank controlled the amount of mix fed into a Moyno-type pump located below the tanks and driven by the same size of motor as the tanks. Since the placement location was only a few feet away from the mixing equipment, the discharge hose was not over 25 ft long and the vertical lift was not over 10 ft. No difficulties were experienced with the equipment during this experiment (fig. 27).

[12]This equipment was designed for 50-cycle European service, but was run on 60-cycle U.S. service. Thus, the motor speed was slightly increased.

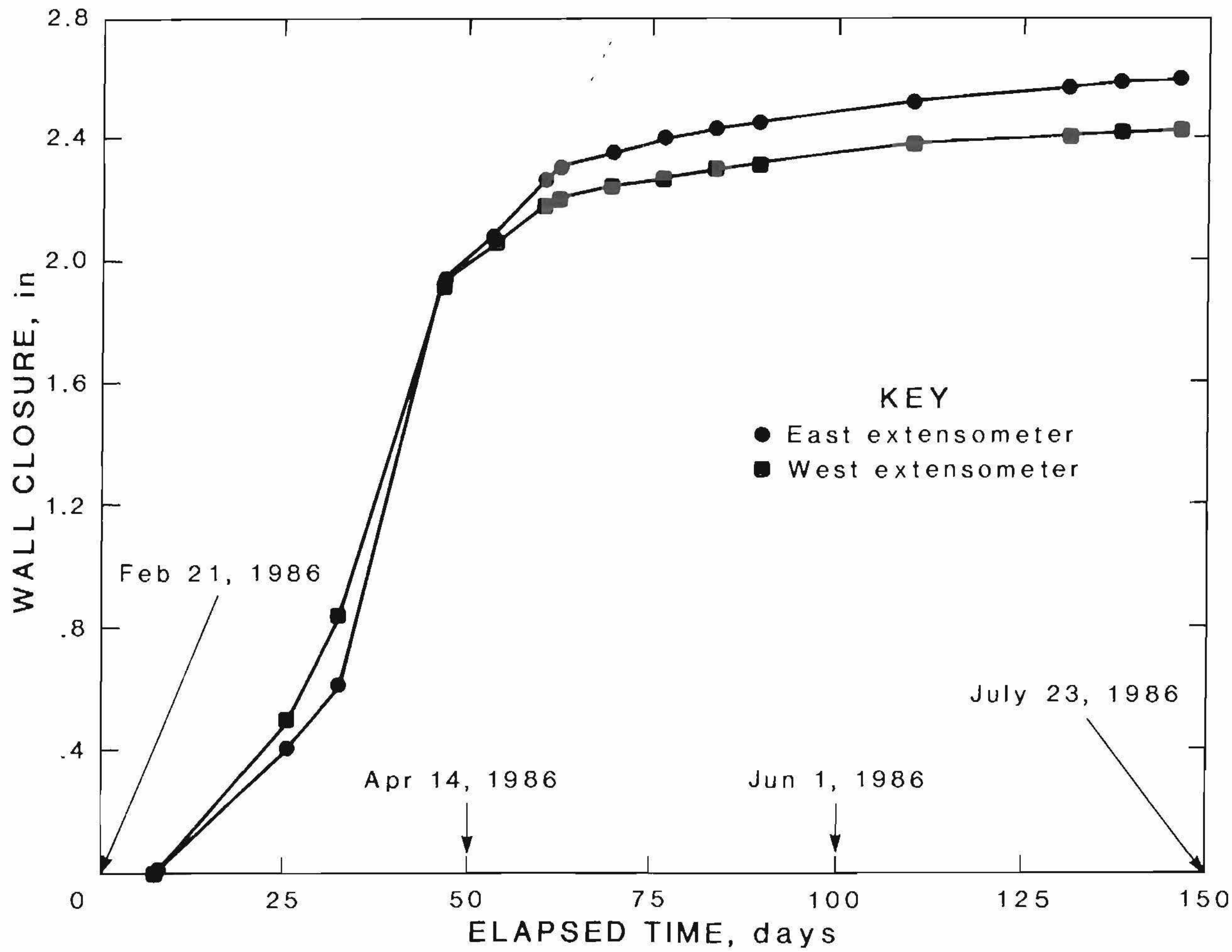

Figure 26.-Extensometer record in raise preparation area.

Figure 27.-Concrete placement equipment at raise preparation area.

The lightweight concrete mix for the pours above the sill was standardized for use by a team of miners, who had received minimal instruction. Each mixing tank was charged with 53 L of water controlled by a timer, followed by three sacks of cement from the conveyor belt. After mixing, foam was added for 1 min 48 s from the foam generator. In addition, a recommended amount of $CaCl_2$ was added to decrease the setting time.

Although no troubles developed, several points of operation should be noted during this experiment. The amount of space occupied by the equipment was excessive, and the volume of water used to clean the equipment presented a drainage problem in the mine as well as when the cement water later entered the pumping system. The dust generated from cement traveling along the conveyor was nearly unbearable, particularly since the crosscut was under direct fan ventilation. Underground moisture tended to cause raw cement to clump around the silo lip on the top of the mixing tank, aggravating the dust problem.

FINAL CONCRETE POUR

Aqualight was used to complete the pour above the chute level of the raise prep structure (*4, 26*). This application was the first underground test at an American metal mine, although it had been used shortly before in an eastern coal mine. Aqualight was developed by the NCB at the Mining Research and Development Establishment at Bretby, England, and first used in an English coal mine in May 1983. The product is one of a family of several similar products developed by the NCB[13] and is an inorganic, cement-based, noncombustible, low-density material with expansive properties reported to be from 1 to 10 times when mechanically mixed with water in a specially developed machine. It is supplied in 25-kg bags and bundled on a pallet for ease of underground handling. Water is precisely proportioned in the machine to make up the correct density. The resulting cement slurry is mixed by a paddle-type mixer and fed into a Moyno pump that draws outside air. The Moyno pumping action, combined with turbulent flow with the entrapped air through the hose, aids the dispersal of entrained air to create a fine bubble structure within the cement mix. The limiting factor on pumping distance is the gel time, which allows a distance of about 750 ft. A standard mix with the machine on slow speed is one 25-kg bag every minute using 3.5 gal/min of water. Four of the 25-kg bags will fill about 1 m^3.

The mixing and placement machine was manufactured in England, but equipped for American practice with a 3-phase, 60-cycle, 220-V, 1,740-rpm electric motor. No other equipment changes were made. An Aqualight pumping machine based on the NCB design is manufactured in the United States by Commercial Coating Services (fig. 28).[14]

Representative compressive strengths of 2-in cubes cut from a test pour made on the surface at the Lucky Friday Mine are shown in figure 29. The density of Aqualight is about 15 lb/ft^3 with compressive strengths of about 10 to 15 psi. The entire pour was completed without problems. The only serious delay was the time to transport the large number of cement-loaded pallets underground and into the crosscut; this operation had to be scheduled with normal mining activities. Aspects of this project have been presented in the technical press (*27-29*).

[13]Rutherford, A. Personal communication, Pozament Co., Leeds, England, July 19, 1985.

[14]John Pfeiffer, Commercial Coating Services, Conroe, TX.

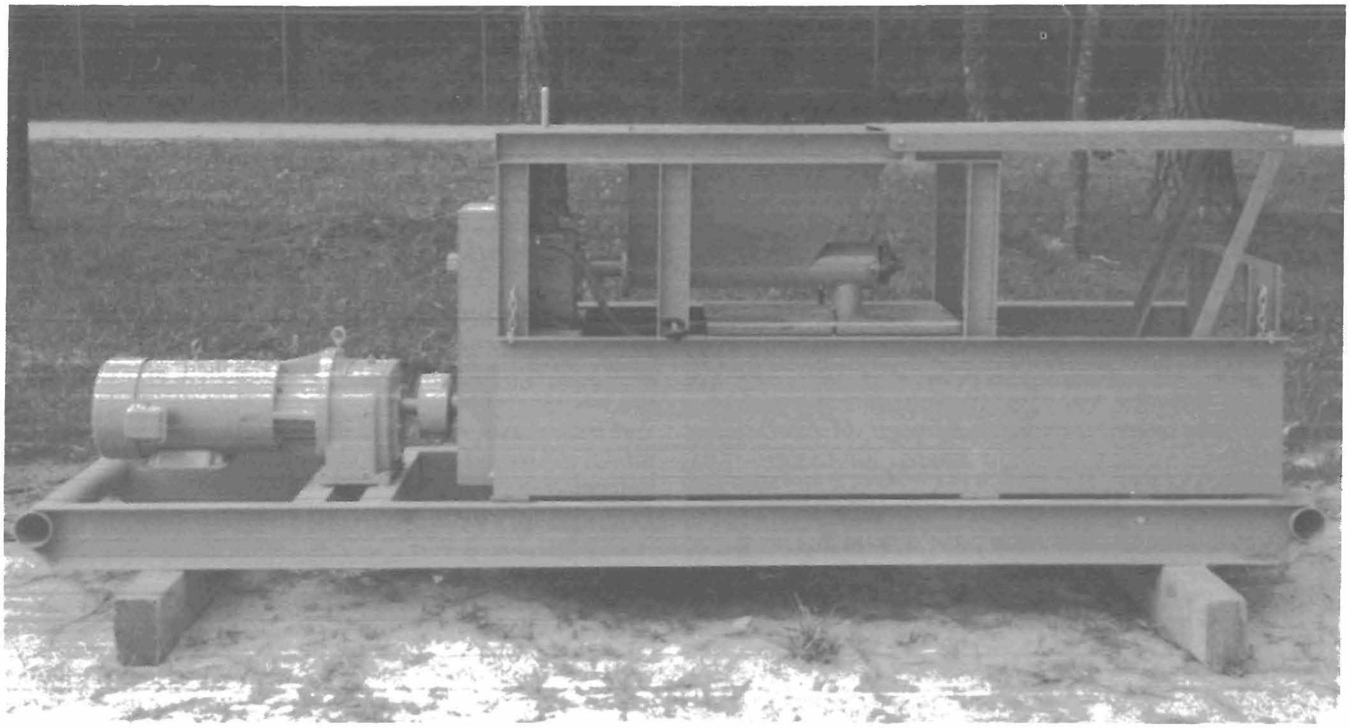

Figure 28.–Modified National Coal Board concrete pumping equipment.

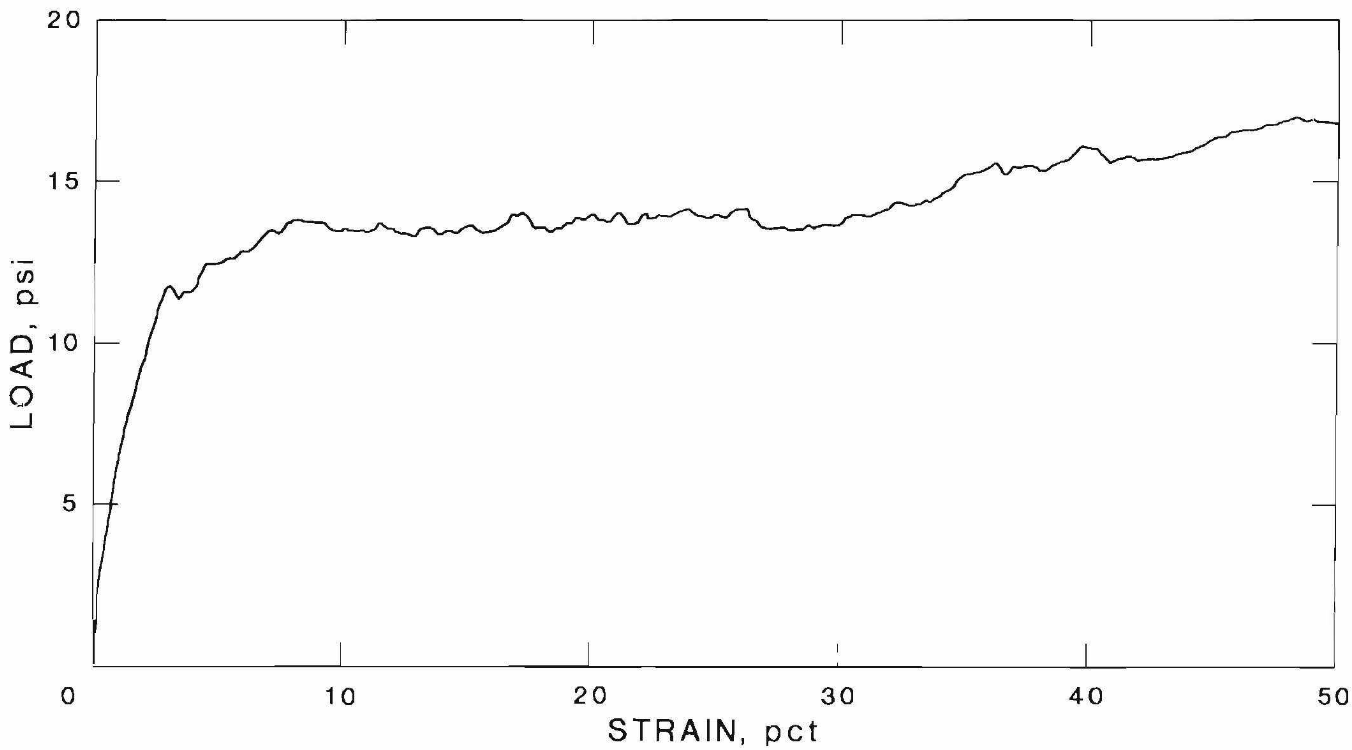

Figure 29.–Typical compression curves for Aqualight at raise preparation. Curve is for samples on 2-in cubes with 1 in of total deflection.

OTHER MINE SUPPORT APPLICATIONS

LIGHTWEIGHT CONCRETE PILLARS

A number of recent commercial formwork products are particularly attractive to mining. Such products used with lightweight concrete in the range of 25 lb/ft^3 are suggested for a frangible, or crushable, pillar.

Cast-in-place concrete mine pillars have been used before, notably in some Missouri lead mines (*30*). In these instances, both cast-in-place and precast circular concrete pillars up to 6 ft in diameter and 35 ft high were used to support mine roofs in open stopes. To provide lateral support the pillars were wrapped with steel bands. It is believed these concrete pillars were some of the largest ever poured in mines and have not been surpassed in the past 25 yr.

Recent developments in circular formwork made from a variety of materials are ideally suited for mining applications. Formwork materials range from paper to fiberglass and are either chemically impregnated or coated with a thin plastic layer for increased water and fire resistance. The paper or fiberglass should be left in place to provide necessary lateral restraint.

These formworks are readily available in sizes up to 4 ft in diameter. Larger sizes can be specially ordered. These forms are especially easy to cut to size and can be erected quickly. Even if filled with lightweight concrete, they are easy to saw with appropriate tools. Out-of-round forms will not affect the intended mining use, as they might in architectural use.

A single thin pillar standing alone will have little resistance to overturning if it is exceptionally high (*31*). For that reason, it is recommended that pillars be placed in packs of three in a triangular configuration with wire strapping to hold them together. A trade-off between the amount of expected rock load and the resisting load of the pillar as well as the potential for overturning must be determined. For example, assuming that material of 100-psi compressive strength is to be used, then a 12-in round pillar will hold about 5 st, a 24-in pillar about 22 st, a 36-in pillar about 50 st, and a 48-in tube about 90 st. If installed in packs of three, three 24-in tubes will hold 66 st, or about 24% more than the 50 st a single 48-in pillar will hold. The three-pack of 24-in-diameter pillars will contain 25% less material. A review of the design alternatives based on this type of analysis may show important material and cost savings in addition to being more stable.

To illustrate this concept, 9-3/4-in-diameter Sonotubes were filled with lightweight concrete of a density averaging about 22 lb/ft^3. At this density, compressive strength is about 100 psi. Steel plates were placed at the top and bottom of the Sonotube, with the top plate 1 in smaller (8 in. in diameter) than the bottom plate (9 in. in diameter) (fig. 30). Using plates exactly the same size as the tube apparently does not allow lateral expansion of the lightweight concrete as it is compressed.

Results from four tests are presented in table 6 and figure 31. The longest tube was about 4 ft (fig. 32). The sustained constant load is noted with pronounced deformation to the point where the lightweight concrete reached absolute compression. In all tests, the concrete was deformed by approximately 66%. Continued loading merely compacted the already compressed lightweight concrete until a final load of 40,000 lb was reached, at which point the test was terminated.

These small-scale tests illustrate the manner in which model pillars deform at a constant load to some range of deformation, which for these tests was 66%. No full-scale field tests in a mine have been conducted.

Table 6.–Simulated pillar tests of lightweight concrete

Test	Initial tube length, in	Total deformation at end test, in	Cake[1] thickness, in	Concrete density, lb/ft^3
1	14-1/2	11	3-1/2	21.77
2	14-5/8	11-7/16	2-3/16	18.81
3	14-7/8	11-3/8	3-1/2	22.15
4	16	12-1/4	3-3/4	21.55

[1]Cake is the thickness of the final, completely crushed lightweight concrete cylinder (which has the appearance of compressed powder). See left-hand side of figure 30.

Figure 30.–Sequence of compression in lightweight concrete pillars. The complete Sonotube assembly is shown on right, but partially stripped away to show steel plates; a fully compressed lightweight concrete section with front cut away is shown in middle; and final compressed lightweight concrete section is on left-hand side. Concrete cylinders on the bottom are for illustration only.

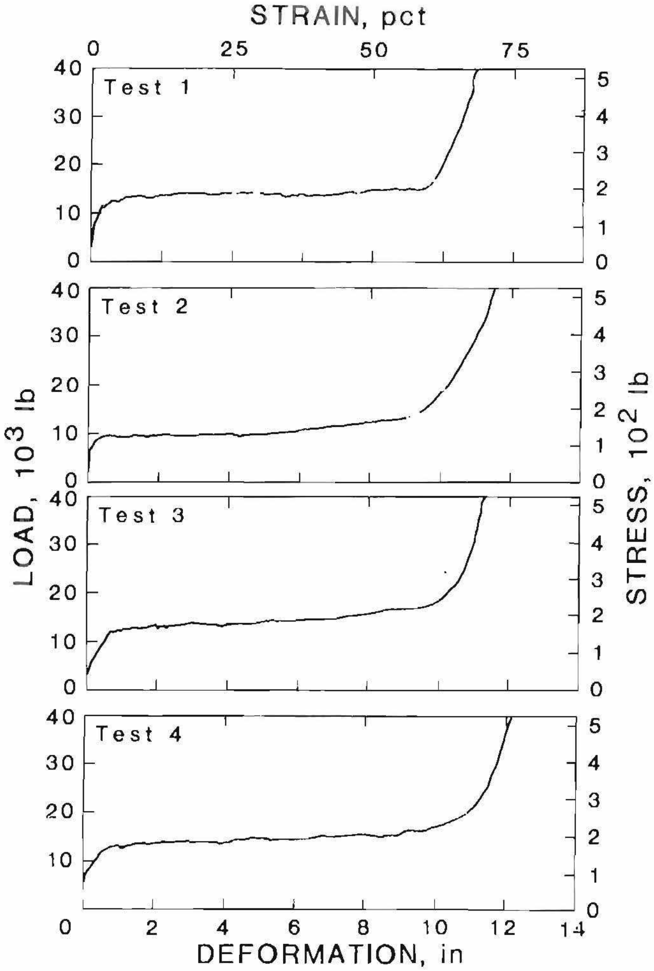

Figure 31.-Compression records for typical lightweight concrete pillar.

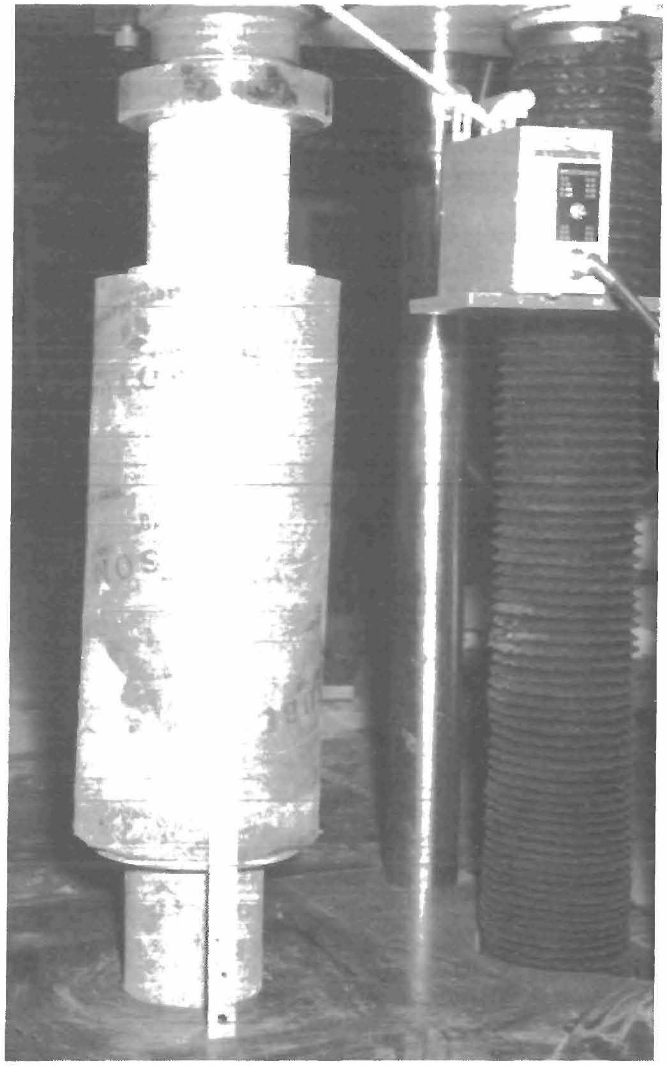

Figure 32.-Typical lightweight concrete pillar in test machine.

CRUSHABLE BEAM MEMBERS

Beam elements strong enough to support a predetermined load and yet absorb energy by deformation within a preset range, say 50%, are another application of lightweight concrete. In a series of laboratory experiments, a plywood beam 18 in long by 6 in wide by 12 in high was fabricated and a 25-lb/ft^3 section of lightweight concrete was placed between two halves of a beam frame designed for 50% deformation (fig. 33). The dimensions of the modeled beam were chosen arbitrarily for the purpose of providing a good load distribution over the surfaces in the limited space available in the test machine. Towards the end of each test, the friction resistance along the sides became noticeable, increasing the final loading. Five tests were run (table 7) to determine the yield load, the peak load at final deformation, and the calculated percent of deformation at the final load. A typical loading curve is shown in figure 34. Continued loading beyond 50% deformation would have destroyed the plywood beam and hence each test was stopped when the top and bottom pieces of

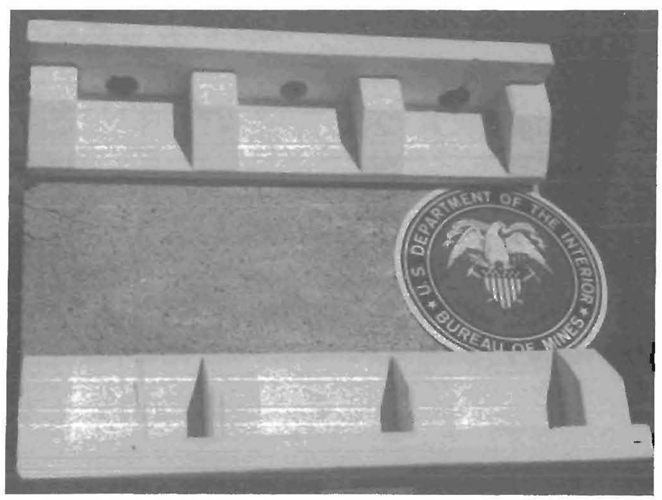

Figure 33.-Model of crushable beam.

the plywood beam converged (fig. 35). The final test load was about 15 st. In summary, this simplified model of an energy-absorbing beam could sustain over 2 st of load at yield and up to 50% deformation.

Table 7.-Results of simulated energy-absorbing beam

Test	Yield load, lb	Final load, lb	Deformation	
			in	pct
1	5,000	30,000	5-7/16	50.7
2	5,000	30,000	6	51.0
3	5,200	27,500	5-1/2	46.6
4	5,800	31,500	5-1/2	46.8
5	6,000	28,000	5-3/4	44.4

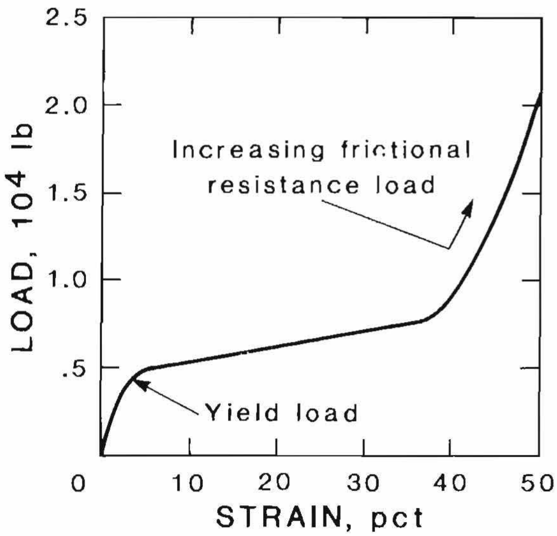

Figure 34.-Loading curve of crushable beam.

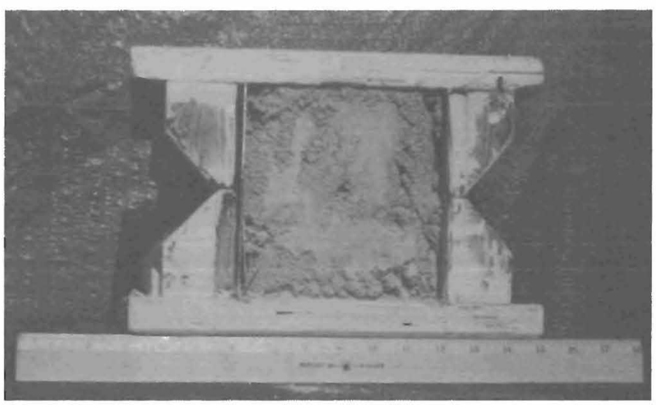

Figure 35.-Beam crushed to 50% total deformation.

An application for an energy-absorbing beam as described above is envisioned in mines where a controlled load is applied on a support. The crushable beam member would take the active load before the support member deformed. Such a situation has been noted where steel sets are blocked directly to the ground. Because the blocking has limited capacity to deform, as shown in the raise prep research, most of the load is transferred directly to the steel support, which then often buckles prematurely. The proposed beam would be specially constructed with crushable sections incorporated as necessary. A disadvantage is that such a crushable beam would have only a finite deformation. Therefore, construction of the beam would have to be carefully planned and engineered.

The example of an energy-absorbing beam illustrates that a similar design logic could be applied to mining structures. Particular emphasis should be given to extending the usefulness of steel arch supports under point loading (*32*). Such a structural combination would fulfill energy-absorbing requirements, but use crushable lightweight concrete materials that are less costly and are fireproof. An advantage of lightweight concrete is that the energy absorbed in the structure is not released with any sudden or explosive force.[15]

PRECAST LIGHTWEIGHT CONCRETE

Since precast concrete products are relatively easy to produce, experiments in forming precast lightweight concrete blocks were conducted. Lightweight concrete could be made in a variety of shapes and sizes and full-scale commercial production would automate the process. A typical 8- by 16-in block of ordinary concrete weighs about 40 lb, whereas a solid cubic foot of lightweight concrete could be cast with a unit weight of 65 lb.

Figure 36 shows a pilot demonstration in which lightweight concrete blocks in the 25-lb/ft^3 range are being formed on 4- by 8-ft sheets of plywood. A useful mine application is shown in figure 37. An experimental divider wall was made of variable sizes of precast blocks; the shear connectors were headless nails. Polypropylene fibers were added as reinforcement and to control shrinkage and increase fluxure resistance. The porous surface of the lightweight concrete readily absorbed the cement slurry used as mortar between the block courses. A simple shear test of this mortar-block bond demonstrated that the cement bond was stronger than the block itself.

[15]Uses of energy-absorbing devices other than for ground support are also proposed, such as conveyance-arresting devices in shafts. Load control by energy absorption in other dynamic mine situations could also be designed.

Bureau investigations (*33*) of underground rigid-wall construction techniques show that many mines are using stopping construction techniques that incorporate compressible materials other than wood. However, many of these materials were used only because they were fire retardant. The Bureau study found that the stronger ventilation stoppings were prone to crack rather than compress under load.

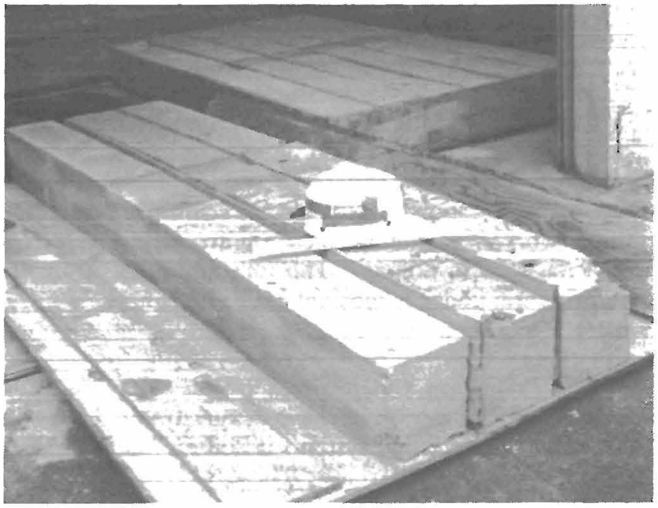

Figure 36.–Precast lightweight concrete blocks.

Precast lightweight concrete blocks would be ideal for fireproof ventilation stoppings, drift sealing, timber crib filling, and framing for airdoors.

Fabric bags are excellent containers for lightweight concrete. For example, discarded fertilizer bags are of a woven plastic fabric and provide exceptional strength while allowing only minor leakage through the fabric. The volume of each bag is approximately 2 ft^3 and a filled, but cured, sack of lightweight concrete in the density range of 25 lb/ft^3 weighs about 50 lb. In figure 38, six of these lightweight concrete-filled sacks are arranged to form a crib. In practice, filled sacks are placed within a timber crib. For cribs with irregular volumes, burlap or plastic cloth can be stapled to the inside and the cribs poured in place using ordinary concrete placement equipment.

Precast lightweight concrete products have the advantage of being less fatiguing for the mine crew to install. Individual blocks can be easily split and cut to fit rock surfaces. Blocks may be placed on pallets for underground transportation.

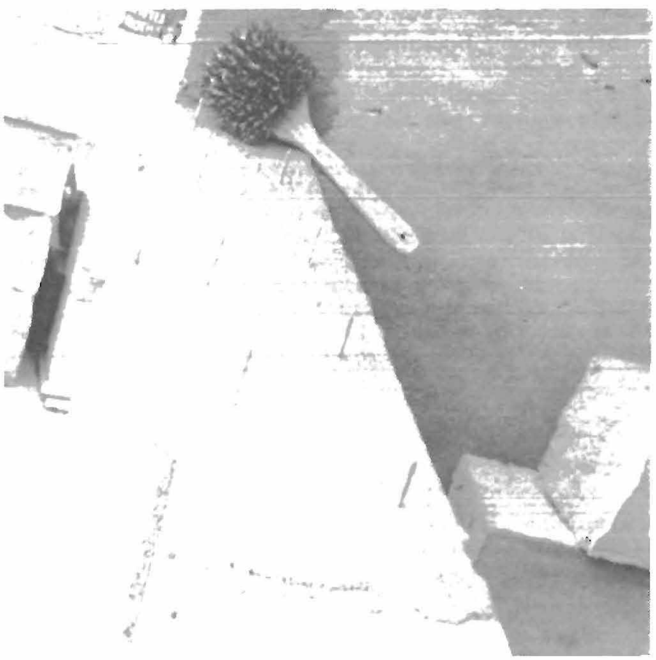

Figure 37.–Wall construction with precast lightweight concrete.

Figure 38.–Plastic fabric sacks filled with lightweight concrete.

SUMMARY AND CONCLUSIONS

The objectives of the research reported here were to develop concepts for new, innovative continuous liners and other support systems for metal and nonmetal underground mines having soft, caving, and squeezing ground conditions.

Drift liners using structural grades of lightweight concrete in the density range of 100 lb/ft^3 and having compressive strengths of 2,000 psi were successfully tested. The first test illustrated a pneumatic placement technique for lightweight concrete. Such a technique would compliment concrete plant and air compressor facilities already existing in many mines.

The second test used a simplified plywood formwork at an underground test site. The time and effort spent in erecting a wooden formwork were shown to be substantial, although lightweight hydraulic jacks developed by the Bureau were found to be exceptionally useful in reinforcing the formwork. The plywood formwork was capable of supporting lightweight concrete reaching depths exceeding 10 ft in the walls and 2 ft across the flat arch.

The third test was an innovation in the use of an air-supported formwork in an underground environment. Practical mining applications were shown by the speed with which the formwork could be erected and dismantled. The modified circular shape of the formwork resembles the double arch shown in previous mine studies to be preferable to reduce wall closure. The air-supported formwork is a particularly useful application of concrete for openings in the size ranges used in mining.

Lightweight concrete in a density range of 25 lb/ft^3 is useful for fabricating crushable support structures where deformations are expected to exceed 50% strain at a constant load. This material property is unique and is best developed with low-density concrete where the concepts of distributed load and flexible liners are important.

Crushable circular pillars of low-density concrete are proposed; such pillars would be easy to install and would be more stable than square or rectangular pillars. The ease of underground placement, as well as less fatigue for mine workers handling these lightweight products, is advantageous in mining. The importance of controlling deformation under a constant load in a squeezing ground control situation can be appreciated in many mining situations.

The evaluation and analyses of these laboratory and full-scale field experiments have demonstrated the feasibility of innovative lining systems based on the use of lightweight concrete materials. These systems have shown effectiveness in materials, placement, formwork, and long-term maintenance. The materials and techniques described for this research are applicable in a wide range of situations encountered in underground mine haulageways where direct cost reductions and decreased future mine maintenance costs are desired. These developments should enhance productivity and increase strategic resource recovery from many deep underground metal and nonmetal mining operations.

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