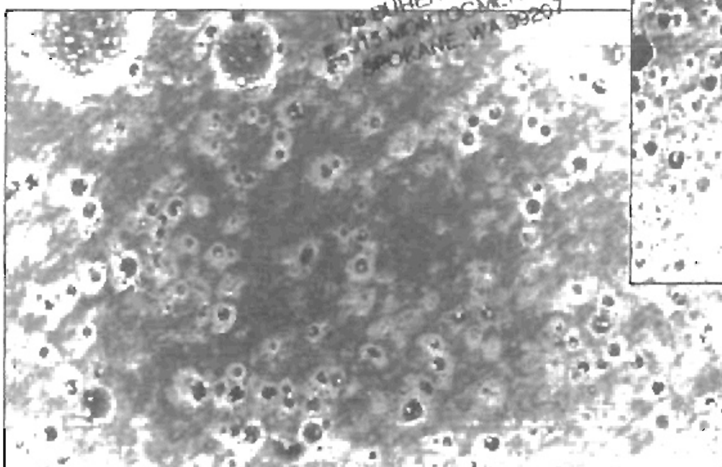
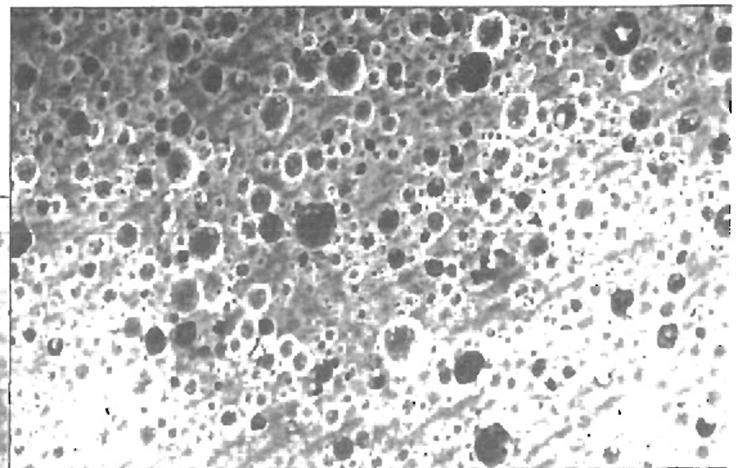
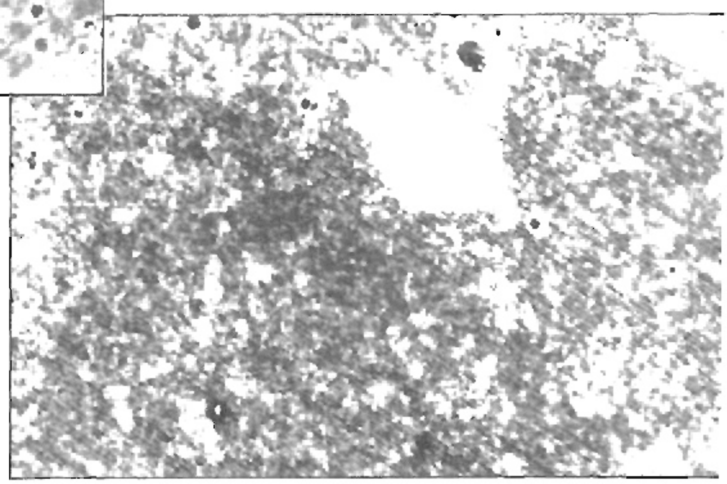
RI 9539

REPORT OF INVESTIGATIONS/1995

Effects of Remote Drop and Pumpdown Placement on Cellular Concrete







UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

U.S. Department of the Interior Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

Cover: Scanning electron microscope images of surfaces of representative samples from large forms (× 10). Top, G—bubble structure of cellular concrete; center, 18P—after pumping up to 18-m level and down 18 m to large form; bottom, 37P—after pumping up to 37-m level and down 37 m to large form.

Report of Investigations 9539

Effects of Remote Drop and Pumpdown Placement on Cellular Concrete

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UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	m	meter
g/cm³	gram per cubic centimeter	m³	cubic meter
h	hour	m³/h	cubic meter per hour
kg/m³	kilogram per cubic meter	mm	millimeter
kPa	kilopascal	μm	micrometer

EFFECTS OF REMOTE DROP AND PUMPDOWN PLACEMENT ON CELLULAR CONCRETE

By D. L. Boreck[1] and R. E. Miller[2]

ABSTRACT

The hazards to the public posed by abandoned mine shafts are well documented. As private development encroaches on previously mined areas, the potential for fatalities and serious injuries from abandoned mine shafts increases. The U.S. Bureau of Mines has conducted research into cellular concrete as a material for sealing these openings. The current work involves testing the characteristics of cellular concrete before and after it had been pumped or dropped from different heights into a simulated mine shaft. Cellular concrete was pumped vertically up to and subsequently dropped from heights of 18 and 37 m into concrete forms. Wet density measurements were made at multiple sampling points in the test circuit. Air content determinations and uniaxial compressive strength testing were conducted. Research results showed significant loss in air content and changes in the characteristics of cellular concrete during pumping or dropping from various heights. Recommendations on effective use of cellular concrete for sealing abandoned mine shafts are made.

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INTRODUCTION

Restoring abandoned mine lands to usefulness is one of the most critical land issues facing the United States today. The issue is one of future use. It is also one of health and safety for present and future generations. The U.S. Bureau of Mines (USBM) has conducted and continues to conduct research in remediating abandoned mine lands and, as a result, restoring those lands to usefulness. The work on sealing abandoned mine shafts described in this report is a part of the USBM's abandoned mine land's research effort.

In the past, mines were often located in areas that were remote and visited by few people. With time, the main population centers have expanded into previously unoccupied areas. In other cases, abandoned mines are located in what is now national forest or recreational land. The scenic beauty brings an influx of people into the area. Interaction of people with open and unreclaimed mines may potentially result in injuries or deaths.

Through history, many techniques have been used to isolate or close abandoned mine shafts. Often, a fence was installed around the site or wooden planks were used to cover the shaft. Both of these seals proved insufficient in preventing trespass by intruders. Trespassers would go over, through, or under the seals.

The National Coal Board (London) (*1*)[3] summarized the state-of-the-art methods for sealing abandoned mine shafts as (1) complete backfilling of the shaft, (2) installation of a concrete plug keyed into a shaft at some depth within the opening, and (3) installation of a reinforced concrete cap over the shaft that completely covers the area around the opening. Each of these methods has its drawbacks.

When a shaft is backfilled with material, settlement often occurs over time, leaving subsidence features on the land. With shafts that are deep, trying to backfill the opening with sufficient aggregate material may be difficult. In addition, exposure of some untreated fill materials to percolating water may pollute groundwater resources.

Installation of a keyed or wedged concrete plug at some depth within the shaft is an option. An internal plug is usually more expensive relative to other options, but it is less likely to result in subsidence features over time, and it provides internal support to the shaft walls. Installation of a keyed plug requires that personnel and equipment work inside the shaft, exposing the labor crew to explosive or toxic gases such as methane and hydrogen sulfide. If the shaft walls are unstable, the walls may also fail during installation of the plug.

A reinforced concrete cap installed over a shaft can be effective in deterring vandals and carrying heavy loads around the opening only if the walls of the shaft are competent. Otherwise, the wall rock or soil supporting the cap may degrade and collapse, leaving openings around the base of the cap where people can enter, either intentionally or accidentally. Capping a large, irregularly shaped, or elongated opening is difficult to accomplish efficiently.

Another method used in Western U.S. hard-rock mines is to form a plug within an upper portion of the shaft using polyurethane foam. Polyurethane foam is most often used to seal unstable timber-lined shafts. Form work required to place the foam is minimal. The use of polyurethane foam has significant advantages over simply capping or backfilling the shaft. The equipment and materials required to mix and place the foam are portable and can be taken into remote locations. The foam, as it expands, can work its way into tight corners and around pipes or wood planks. Because of the extremely light weight of the material, the tendency for the plug to settle because of the effects of gravity is low. Major disadvantages of using polyurethane foam are as follows: (1) It has a compressive strength less than 689 kPa, providing limited load-carrying capacity; (2) the material is not as fire resistant as concrete; (3) upon loading, the foam plug tends to yield in the center, pulling away from the walls of the shaft (*2*); and (4) depending on the mix design, the material cost of polyurethane foam can be expensive when compared with other sealing materials.

An alternate method tested by the USBM is to use cellular or "foam" concrete for a combination plug-cap. A cellular concrete plug in conjunction with a cap of conventional concrete (2,242 to 2,402 kg/m^3) was utilized to seal a shaft in West Virginia (*3*). Wet cellular concrete has a low viscosity and, like polyurethane foam, can work into tight corners and around objects within an opening.

Cellular concrete can be foamed to a very low density, yet durable material. The ingredients of cellular concrete will vary depending on the end-use requirements. In general, the mixture is cement, water, air, and additives. The overall density will vary. Air is entrained in the concrete by either a chemical reaction, whipping air into the mix, or mixing a nontoxic foam into the concrete as in this research. At 721 kg/m^3, cellular concrete can exceed 2,069 kPa in compressive strength tests, giving it greater strength than polyurethane foam. It is also nonflammable. Knowledge of the stability of cellular concrete when it is pumped or dropped from different heights will be critical in determining the overall effectiveness of cellular concrete seals.

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

BACKGROUND

Cellular concrete has been used in the construction industry for a number of applications: walls or roofs in buildings, roof repair, and fill material. It has been utilized by the oil well industry (*4*) for oil well cementing. Cellular concrete, with a minimum density of 961 kg/m^3, is employed when there is lost circulation and long lifts of concrete are required to cement the casing.

Cellular concrete, also called foaming mud cement or foamed concrete, has also been used in the mining industry. It has been used as filler where open voids adversely affected mining. The USBM (*5*) has tested light cellular concrete of various densities for making liners and other support systems for underground mine openings with soft, caving, and squeezing ground conditions. Lightweight concrete with a density of 400 kg/m^3 was tested for fabricating support structures.

Besides the benefits already noted, the bubble structure of cellular concrete functions to prevent cracking of the surrounding concrete during freezing of water in the concrete (*6*). Therefore, air loss, i.e., stability of the bubble structure in the wet concrete during placement, is an important concern. Loss of the air bubbles in the concrete during placement translates into a decrease in the volume of in-place concrete and a general change in the properties of the material. Yingling and others (*7*) measured the loss of air for pumped conventional concrete containing 5.6% to 16% air. A total of 14 batches were placed under differing conditions, including variable pumping rates, a vertical downward pumping distance of 15 m, and the inclusion of four 90° elbows at the end of the line to increase resistance in the line. A batch of concrete was also pumped horizontally to verify that very little air is usually lost during horizontal pumping. One test involved dropping concrete of a known air content 4.3 m into mortar boats and measuring the air content of the resultant mixture. Observations made from the tests revealed that (1) a significant proportion of initial entrained air is removed by the concrete pump, (2) losses do not usually occur when the concrete is pumped horizontally or presumably at low boom angles, (3) the impact of rapidly moving concrete on a surface results in a significant loss of air, and (4) although more research needs to be done in this area, air loss increases with an increase in initial slump. (Slump is a measure of the ability of fresh concrete to flow.) Although this study was done on conventional concrete, the authors feel that these observations provide viable input in analyzing placement requirements for lighter weight cellular concrete.

DESIGN OF SIMULATED MINE SHAFT

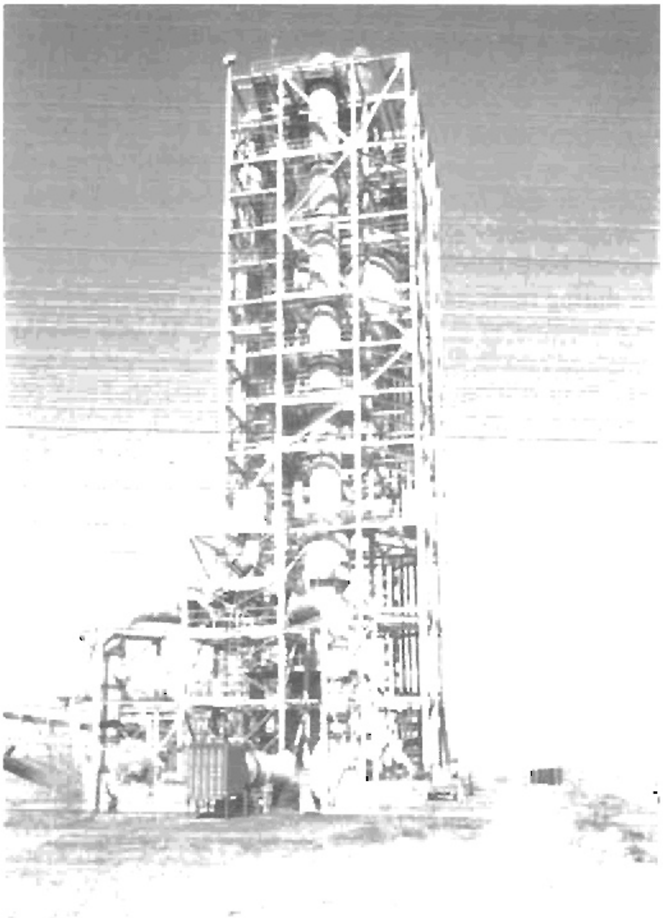
The simulated mine shaft (SMS) was constructed on a 61-m-high tower located north of Denver, CO (figure 1). Cellular concrete was pumped vertically up the tower, as may occur when a mine shaft is on the side of a steep hill and vehicle access to the shaft is limited. The cellular concrete was then dropped or pumped down from different levels to large forms located at ground level of the tower. In an effort to simulate free-fall of cellular concrete while protecting the surrounding area from wind-carried concrete, a tubular windscreen was included in the design.

This tower, previously used for oil shale research in the late 1970's, was accessible at the 18-, 37-, 43-, and 49-m levels. The SMS was constructed using these accessible levels of the tower (figure 2). The design included four major parts: (1) a piping system to transport the cellular concrete up to the different levels and also to convey the concrete back down to the large forms, (2) the windscreen, (3) a cantilever-hoist system to lift and hold the windscreen in place, and (4) large forms to simulate the shaft.

PIPING SYSTEM TO TOWER

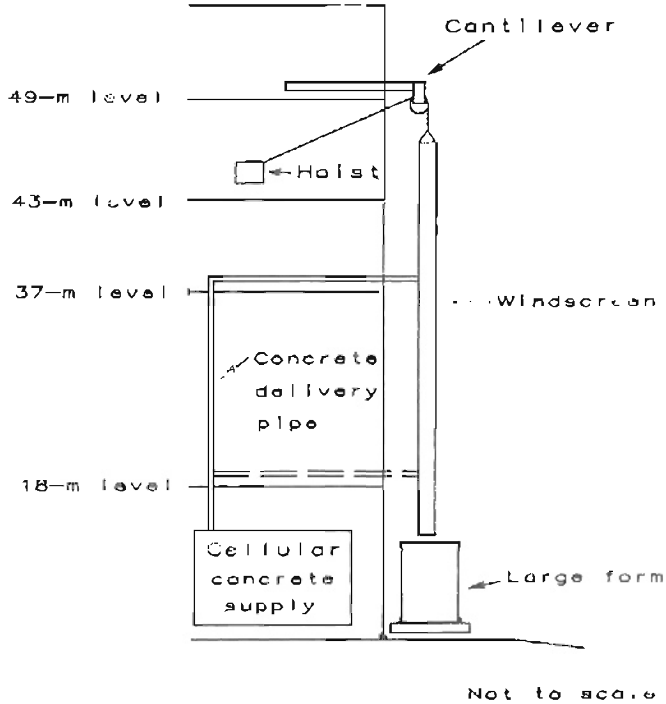
Once the tubular windscreen was raised using the hand-operated hoist, it was secured to the cantilever beam and the tower. The hoist was then used to raise the contractor's concrete delivery system. The contractor used hoses and polyvinyl chloride (PVC) pipe. A 7.6-m length of 7.6-cm-diam concrete hose was attached to the concrete pump. For the 18-m tests, two 7.6-m sections of 5.1-cm-diam concrete hose were added to the 7.6-cm-diam hose. For the 37-m tests, a 15.2-m long section of 6.4-cm-diam flexible fire hose was added to the string of concrete hose. Victaulic couplings and reducers were used on all hoses. These hoses brought the cellular concrete from the pump at ground level to the test levels on the tower. At the test levels, the respective hose was connected to a 6-m horizontal section of 5.1-cm, schedule 40, PVC pipe. A 5.1-cm-diam section of PVC pipe was also used for the pumpdown pipe.

Figure 1



Tower northwest of Denver, CO, with parts of SMS installed.

Figure 2



General design of SMS.

Three valves were installed to regulate flow of concrete for the different tests (figure 3). The first valve was used to direct concrete to the windscreen for the free-fall tests. The second valve was used to open the end of the tee for the pumpdown tests. The third valve, at the bottom of the pumpdown pipe, allowed the line to fill with concrete before dumping it into the large forms. A fourth valve was installed at the 18-m level. This valve ("T" in figure 3) was used only at the 18-m level for limited sampling of the concrete. At the 37-m level, a tremie (a drop chute or plastic hose placed in deep forms to pump concrete into the forms) was used. The horizontal section of pipe was raised as testing proceeded from ground level to the 18-m level and finally the 37-m level. The 61-m-long concrete delivery hose went up at approximately a 30° angle from vertical during the 18-m tests. It hung from the tower vertically during the 37-m tests.

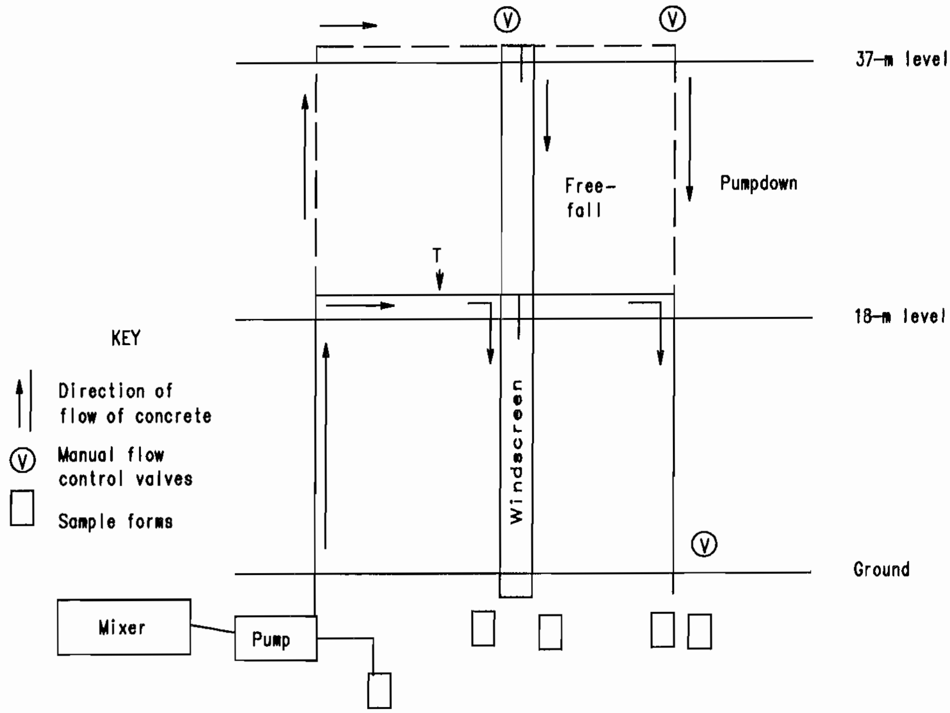
CONCRETE PUMP

The pump used for the testing was a Morgan Mustang, air-driven 31-m^3/h, double-piston, positive-displacement pump. During operation, one piston sucks concrete into the pump while the other forces it out through the discharge hose. The pistons in this particular pump were 15.2 cm in diameter. Therefore, by calculating the volume in the concrete hoses used in these tests and assuming the entire column of concrete had the same density as the material exiting at the top, it was calculated that the pressure exerted on the concrete by the pistons of the pump during the 18-m tests was at least 51 kPa, and it was at least 113 kPa for the 37-m tests. This pump is capable of 5,171 kPa maximum face pressure on the pistons, although pressures this high were never reached during testing.

WINDSCREEN DESIGN AND INSTALLATION

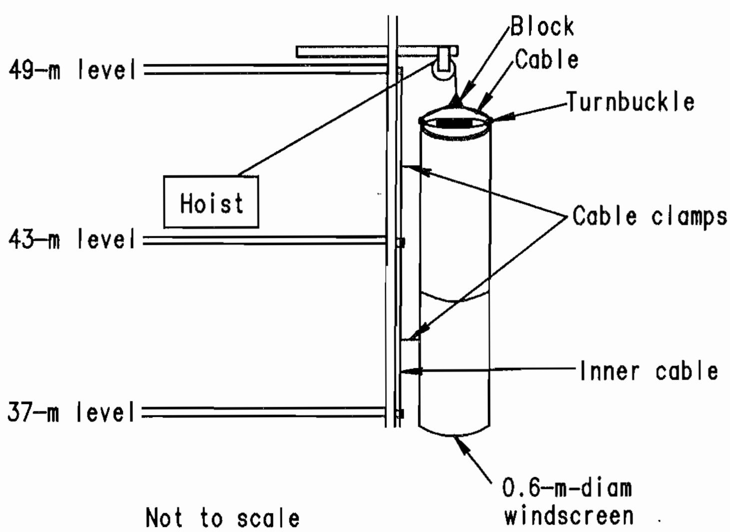
Mineduct vinyl ventilation tubing was used to prevent splatter of the cellular concrete onto the grounds surrounding the test site. It was chosen because of its flexibility and because the concrete would not readily stick to the vinyl interior of the tubing. The tubing was 0.61 m in diameter and assembled by clamping a string of eight 6.1-m sections together (figure 4). Hooks were used to support the windscreen along 0.61-m intervals over the entire length. These hooks were bolted to 0.95-cm-diam steel cables using standard cable clamps. At the top of the tubing, a 2.5-cm-diam turnbuckle was used to keep the two cables apart and prevent collapse of the windscreen during testing. The two cables terminated at the turnbuckle.

Figure 3



Piping system for delivering cellular concrete to test forms. (T = samples taken from "T" valve at 18-m level.)

Figure 4



Design of windscreen.

From the turnbuckle, a 1.3-cm cable was run up and over a block with a 30.5-cm sheave. The block had an eyelet on the top end that was connected to the hoisting rope, suspended from the cantilevered beam attached to the tower. At the 18-, 37-, and 43-m levels, the inner support cable was anchored to large brackets attached to the tower.

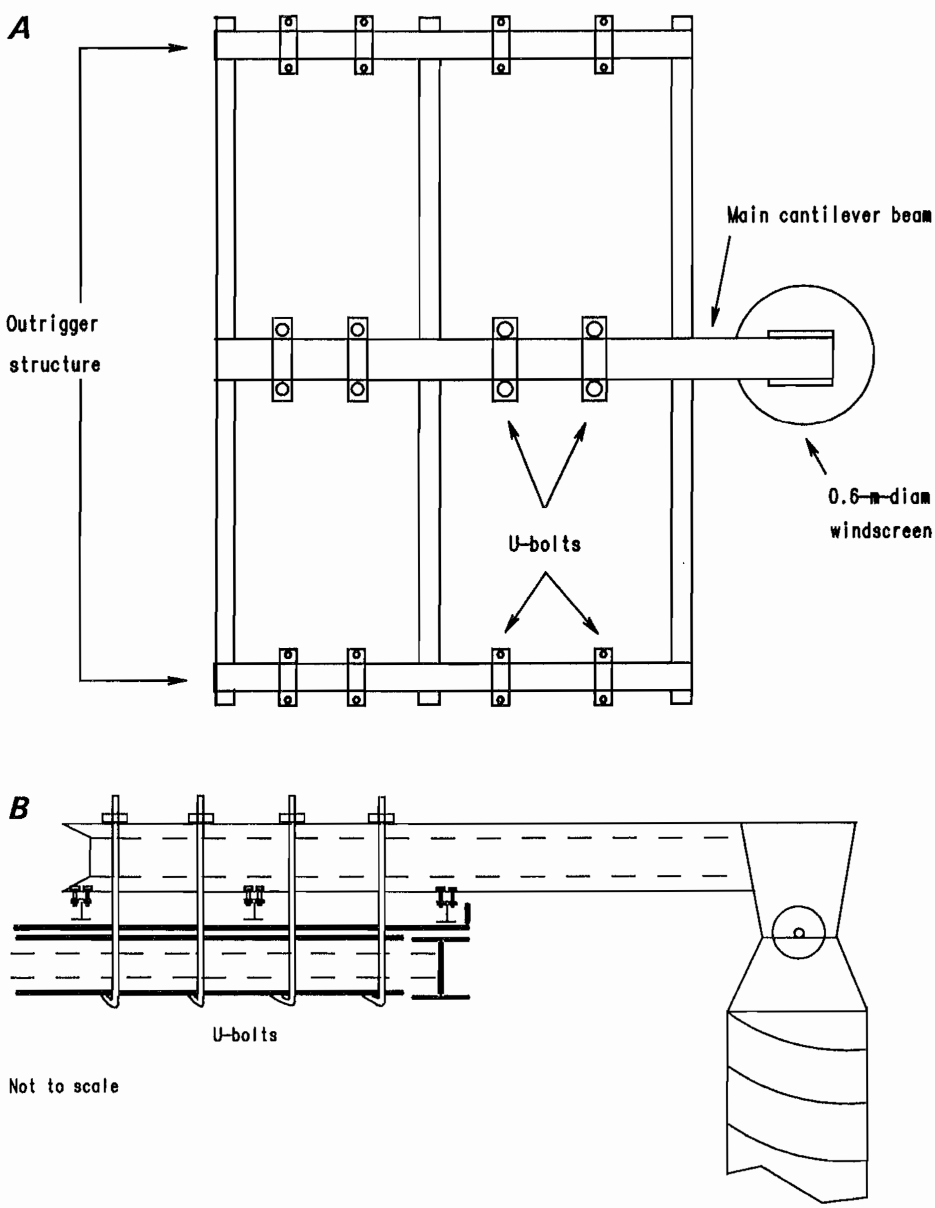
CANTILEVER-HOIST DESIGN AND INSTALLATION

The cantilever that supported the hoisting mechanism for the windscreen and concrete hose was designed by USBM personnel with input from U.S. Mine Safety and Health Administration (MSHA) civil engineers. It was designed to bolt onto the tower for later removal with little permanent alteration to the existing structure. To support the cantilevered beam for wind loads against the hanging windscreen, a main beam was attached to a framework of smaller I-beams. Both the framework and the cantilevered beam were bolted to the tower using U-bolts (figure 5). The hoist was mounted at the 43-m level, 6.1 m below the beam.

LARGE FORMS

An important part of the SMS was the basal collection point for the dropped or pumped cellular concrete. The large forms placed at the base of the SMS represent the location in an actual mine shaft that would be in contact with the concrete plug.

Figure 5



Design of cantilever beam. A, Top view; B, side view.

The large forms were made from 0.91-m-diam cardboard cylinders sold under the brand name of Sonatube. Sonatube sections were cut to 1.5-m lengths and upended onto pallets covered with 5.1-cm-thick, large-bubble polystyrene foam sheets. The lower end of the Sonatube form was then pressed into the polystyrene foam sheet and secured with adjustable packing straps. Cellular concrete was collected in these forms from the drop and pumpdown tests. After curing, the cardboard was stripped from the samples to map the surface of the samples for voids or discontinuities.

Cellular concrete has a high slump and flows easily. As such, a form within a shaft must be relatively watertight to prevent loss of the concrete down the shaft. To test sealing materials, a thick layer of straw was tested as a mat that could be remotely set to seal around forms within an actual shaft. Approximately 10 cm of straw was placed inside each Sonatube form. After curing, the effectiveness of using straw or similar loose plant material was evaluated.

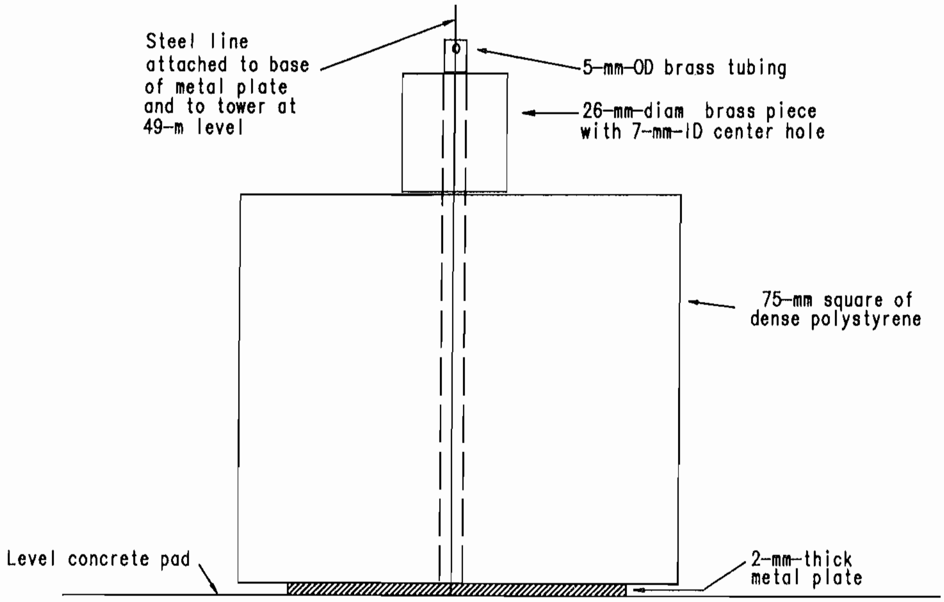
The large forms were moved to the side after the pour. It was felt that moving the forms immediately after the pour, while minimizing agitation, would not adversely affect quality. After the initial move, one form had to be moved; it was not moved until 24 h after the pour.

PRELIMINARY FREE-FALL TESTS USING POLYSTYRENE FOAM

Little information was available to the authors on the effects of drop height on cellular concrete. It was felt that at some height, the effects of dropping the cellular concrete would reach a maximum. The cellular concrete did not contain aggregate that would segregate during free-fall. Therefore, a test, using another air-filled material, was designed to qualitatively determine from what height maximum deformation of that material would be achieved. This height is the height from which a mass of cellular concrete reaches terminal velocity (the velocity at which air resistance offsets acceleration due to gravity). Every falling object reaches a terminal velocity. For example, rain droplets 3 mm in diameter reach their terminal velocity within approximately 1 meter of free-fall from a cloud.

The material chosen was Styrofoam Blueboard insulation. Styrofoam blocks were dropped from different levels of the tower onto a brass plate (figure 6). All blocks had equal weights and were cut into 7.6-cm square cubes. The material had a density of 0.48 g/cm^3. During testing, the blocks traveled down a thin wire attached to the tower at the 49-m level. A brass weight was placed on top of each of the blocks. The combined mass of each block and the brass weight was the same as if the block consisted of 0.72-g/cm^3 cellular concrete (based on wet density). Not taking into account the shape of the blocks versus the shape of wet free-falling cellular concrete and the frictional resistance of the wire, this test would give some indication of the height that terminal velocity would be achieved for

Figure 6



Polystyrene foam block design for free-fall tests. (OD = outside diameter; ID = inside diameter.)

the falling cellular concrete. When the blocks hit the brass plate at the bottom, the weight made an indentation into the blocks. The depths of these indentations were measured and plotted to determine impact force versus drop height (figure 7).

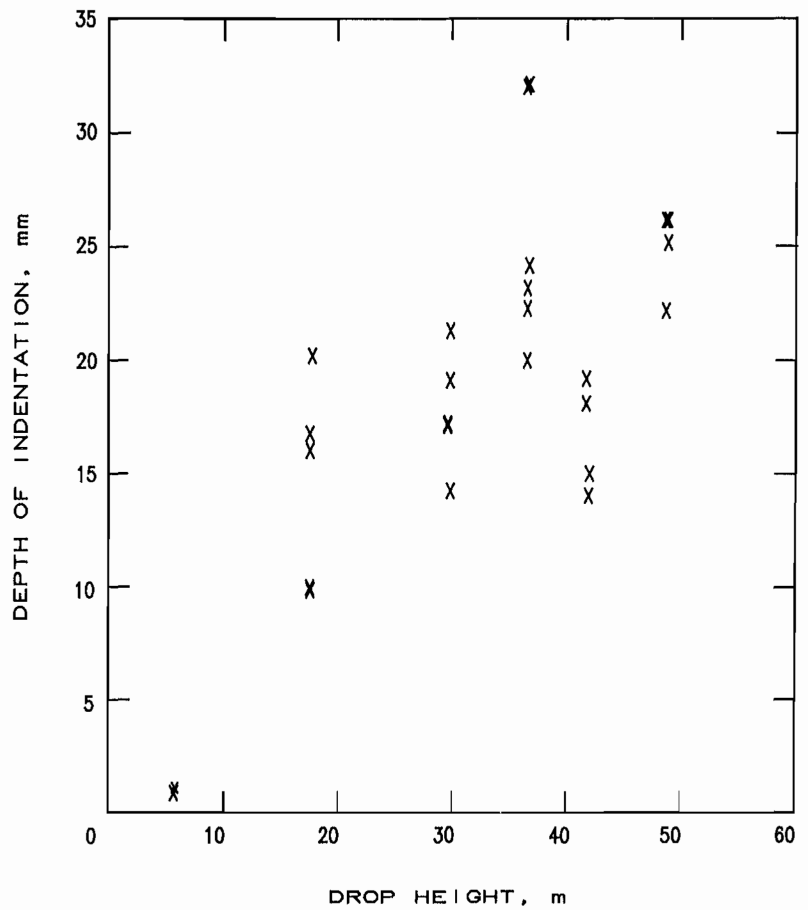
The depth of indentation from impact started leveling off between the 18- and 37-m levels. Dropping from higher than 37 m did not significantly increase the impact force when the block hit the brass plate. Therefore, it was concluded that dropping from higher than 37 m would not make a difference in the final properties of the cellular concrete because of the terminal velocity effect.

CELLULAR CONCRETE SPECIFICATIONS

The equipment utilized to regulate the foaming agent-air mixture to make the foam was designed and built by the contractor (figure 8). The foaming agent was a mixture of cationic and anionic protein-based surfactants. Mixing the foam into the concrete was done in a standard size readi-mix truck that was used to transport the concrete mix to the site.

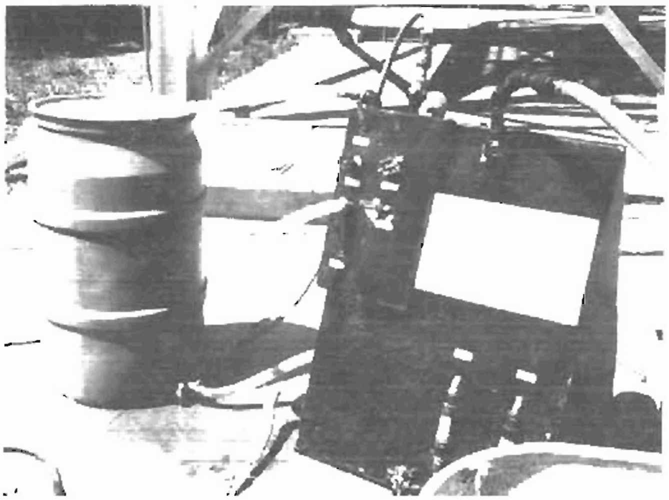
As with standard concrete, the final mix will vary, depending on the percentage of the main constituents and additives. Often this is dependent on job requirements and the intended use of the concrete. For this study, it was decided to minimize the use of additives. The mix design agreed upon for the tests is shown in table 1.

Figure 7



Impact force versus drop height for polystyrene foam block free-fall tests.

Figure 8



Equipment used to regulate foaming agent and air during mixing of cellular concrete.

Table 1.—Mix design for cellular concrete used in tests

Ingredient	Amount, kg/m³
Cement	1,205
Fly ash	464
Water	401

The initial wet density[4] requirements were set at 0.72 g/cm³ from the mixer. This was the wet density used in a recent shaft seal by USBM personnel (3). The actual density was increased significantly to 0.91 g/cm³, based on consultation with experts in the field of cellular concrete. The logic for the increase was a concern that a lighter cellular concrete would not withstand the rigors of testing and analyses. To ensure that the testing would be successful, the target wet density of the cellular concrete was increased to 0.91 g/cm³.

EXPERIMENTAL PROCEDURES

To test the effects of dropping or pumpdown placement on cellular concrete, the experimental procedures were designed to analyze as many different variables as possible. It was not known from what height a significant loss of air would occur because of pumping the cellular concrete to the ground level. Based on results of the polystyrene foam block drop tests, drop tests were conducted at the 18- and 37-m levels. For comparison, pumpdown tests were also conducted from the same levels (figure 9 and table 2).

Table 2.—Average wet density and average air content for cylinder samples collected at different sampling points

Location	Sampling point	Average wet density, g/cm³	Average air content, %
Mixer, unfoamed	Truck	1.96	23
Mixer, foamed ..	S	0.95	69
Ground	G	ND	55
18 m	18I	1.45	49
	18P	1.63	43
	18D	1.82	35
37 m	37I	1.84	33
	37P	1.91	29
	37D	1.97	27

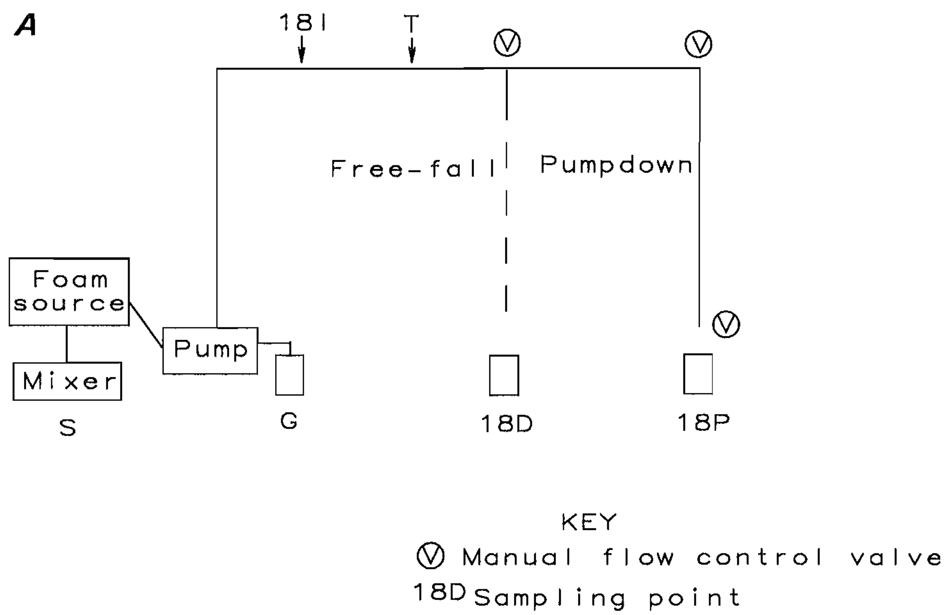
ND No data.

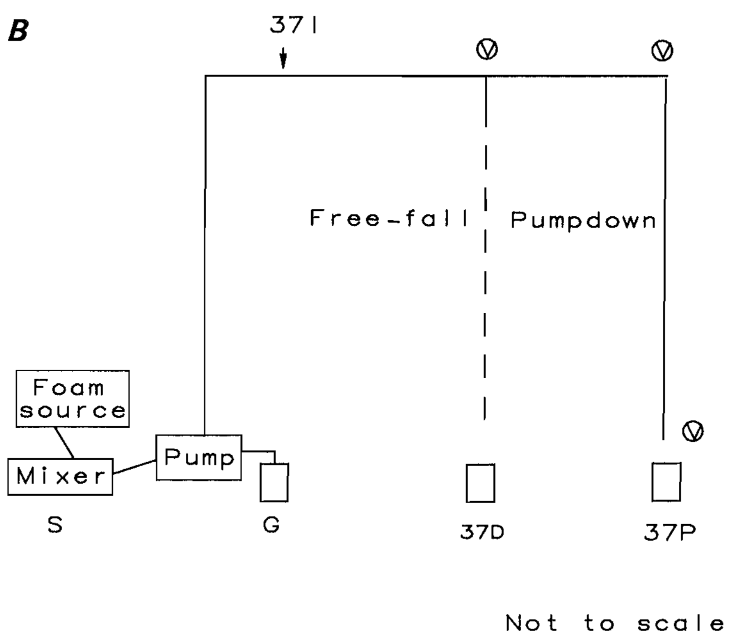
The cellular concrete drop testing was completed over a 3-day interval from May 11 through May 13, 1993. A total of 23 m³ of cellular concrete were poured. The concrete was foamed to a wet density between 0.89 and 0.97 g/cm³ ("S" in figure 9). A total of five large forms were filled (figure 9): Large form G was the baseline sample from the ground level; large form 18P was the 18-m pumpdown test; 18D was the 18-m drop test; 37P was the 37-m pumpdown test; and 37D was the 37-m drop test. Large form G remained in-place until 24 h after the pour and was then moved to the storage area adjacent to the tower. The other large forms were moved immediately after pouring to the side using a forklift. All forms were covered with tarps or plastic sheeting and allowed to cure for 28 days.

Wet density measurements were taken by collecting cellular concrete samples in standard 7.6-cm-diam by 15.2-cm-long plastic sample cylinders. Wet density values were determined for each cylinder using standard weighing techniques (figure 9 and table 2). Between 1 and 12 cylinders were taken at each of the sampling sites shown in figure 9. Cellular concrete was taken directly from the mixer (sampling point S). Cylinders were also collected at the 18-m level (sampling point 18I) and the 37-m level (sampling point 37I) prior to drop or pumpdown. These samples were taken by disconnecting the delivery hose from the horizontal section of PVC pipe. Samples were

[4]Densities for the remainder of the text are given in g/cm³ to show the differences in density more clearly (1 g/cm³ equals 1,000 kg/m³).

Figure 9



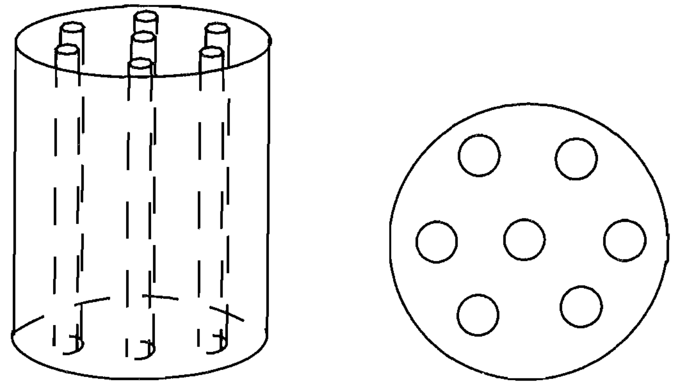


Changes in wet density and air content. (T = samples taken from "T" valve at 18-m level.) For comparison, average values are given for wet density and air content of concrete prior to addition of foaming agent (see table 2). A, From 18-m level; B, from 37-m level.

also collected from large forms 37P and 37D, and at other points along the circuit. Cylinder samples were collected by the contractor at 18P and 18D. Wet density measurements were reported to USBM researchers by the contractors. A total of 55 sample cylinders were collected for analysis. The samples were capped, boxed, transported to the office (post 24 h), and allowed to cure. Compressive strength was determined for 12 of the 55 sample cylinders. Three of these samples were tested at 7 days, six were tested at 28 days per American Society for Testing and Materials (ASTM) Standard C495-91a, and three were tested at 90 days (appendix A, figure A-1). Compressive strength results from these 12 samples make up data set WDC. Fourteen of the remaining samples were selected for air content determination per ASTM Standards C495-91a, Section 9—Oven Dry Weight, and C138-81. Air content results from these 14 samples make up data set WDA. For a specific breakdown on sample selection and analysis, see appendix A, figure A-1.

In late July, seven vertical 5.1-cm-diam cores were collected from each of the large forms (see appendix A, figure A-2 for details of sampling). The coring pattern is shown in figure 10. Cores taken from G, 18P, 18D, 37P, and 37D were described using a binocular microscope with 10X, 20X, and 30X powers. General sample descriptions are given in appendix B. As many 11-cm-long segments as possible were cut from each core. The number of core segments usually totaled from 26 to over 40 segments. Nine core segments from each large form were randomly selected and prepared for post 28-day compressive strength testing (data set LFC, appendix A, figure A-2*B*). A maximum of 20 of the core segments were randomly selected from each large form for air content determination (data set LFA, appendix A, figure A-2*A*).

Figure 10



Pattern for obtaining cores from large forms.

WET DENSITY MEASUREMENT RESULTS

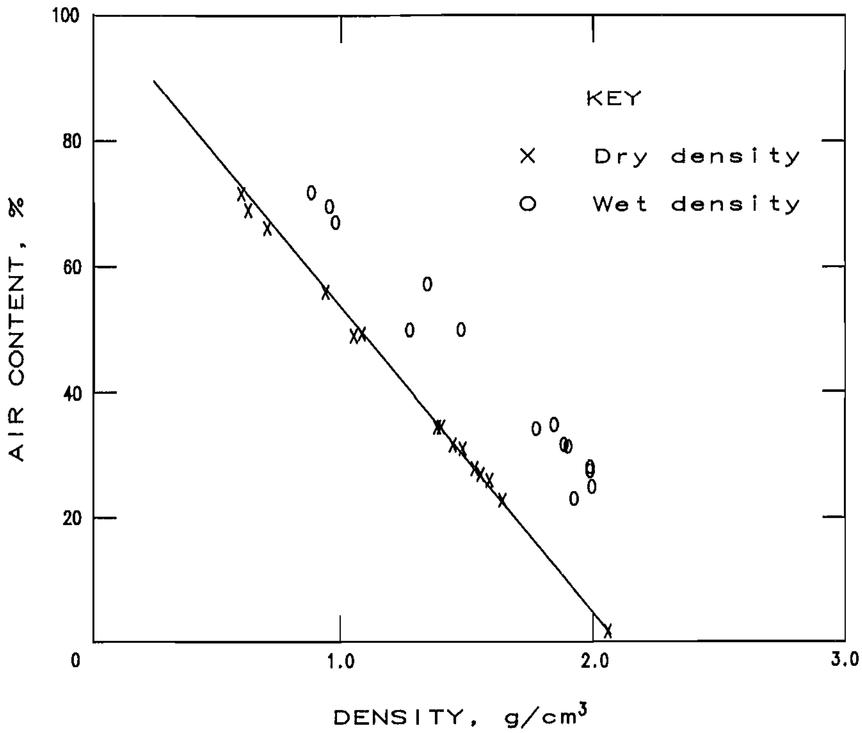
The wet density of the initial unfoamed concrete mix was 1.96 g/cm³ (figure 9 and table 2). The concrete was foamed to wet densities between 0.89 and 0.97 g/cm³, with an average wet density of 0.95 g/cm³. Wet density of the mixture at 18I had increased to an average of 1.45 g/cm³. The wet density of the foam concrete increased from 1.45 to 1.63 g/cm³ when the concrete was pumped vertically down 18 m into 18P. The density increased from 1.45 to 1.82 g/cm³ when the mixture was dropped through the windscreen into 18D.

For the second phase of the testing, cellular concrete with an average starting wet density of 0.95 g/cm³ was pumped 37 m vertically upward (figure 9 and table 2). Wet density measurements taken at the top (37I) increased to 1.84 g/cm³. After pumping the concrete down into form 37P, the wet density increased from 1.84 to 1.91 g/cm³. Dropping the foam concrete through the windscreen into 37D increased the wet density from 1.84 to 1.97 g/cm³.

AIR CONTENT TEST RESULTS

The air content was determined for 14 cylinder samples of varying densities. The results comprising data set WDA (appendix A, figure A-1) include wet density, oven-dried density, and air content (table 2). Data from WDA were plotted as density versus air content in figure 11. A line was manually fitted to the oven-dried density data points. The inverse relationship between density and air content is not only evident for the oven-dried density values (X) from which the air content values were calculated, but also when comparing wet density values (O) with the air content.

Figure 11



Air content versus density for 7.6-cm-diam cylinder samples.

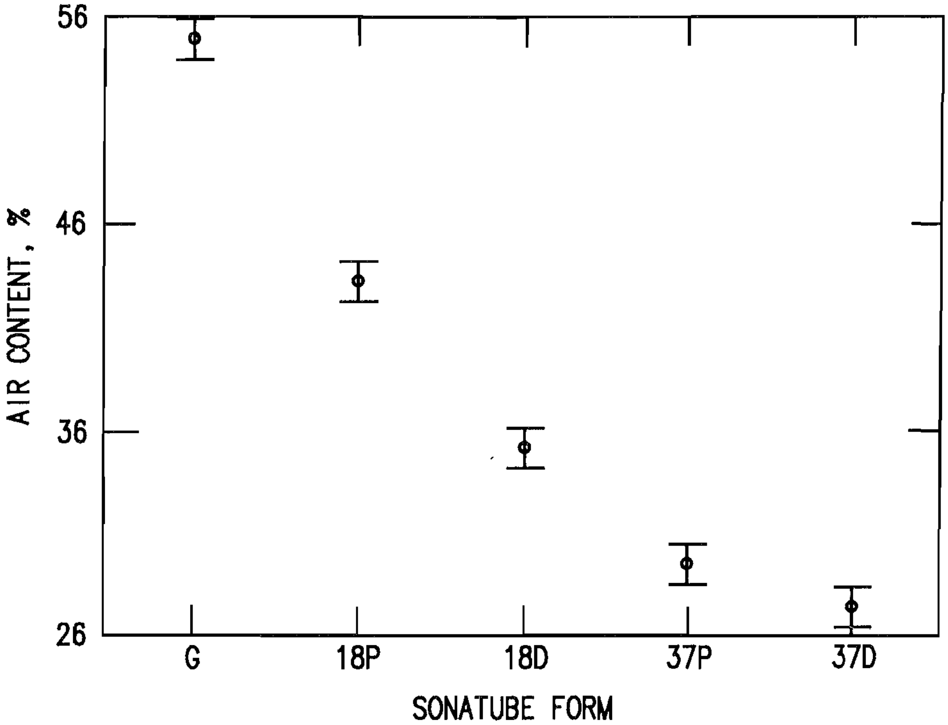
Air content measurements (based on dry density) made on core segments from the large forms make up data set LFA (appendix A, figure A-2). To compare values within LFA, a multiple-range analysis (95% confidence interval for factor means) was done (figure 12). The standard deviations varied from 4.7% to 9.3% of the mean values. As can be noted, the air content decreases significantly between G, 18P, and 18D. Similar differences are noted for 37P and 37D. The analysis results showed statistically significant differences between the large forms, except between 37D and 37P. From both testing and visual inspection, the cellular concrete in the different large forms was homogeneous, i.e., no significant differences in air content or no discontinuities that may affect the general competency of the plug (appendix B).

A comparison was made between LFA and WDA (figure 13). Figure 13 is figure 11 with a plot of the mean and standard deviation of the densities (horizontal bar) and air contents (vertical bar) of the different large forms (LFA). Although there is some variation between the parent line derived from WDA and the values from LFA, the range of values from the large forms closely approximate those from WDA.

COMPRESSIVE STRENGTH TEST RESULTS

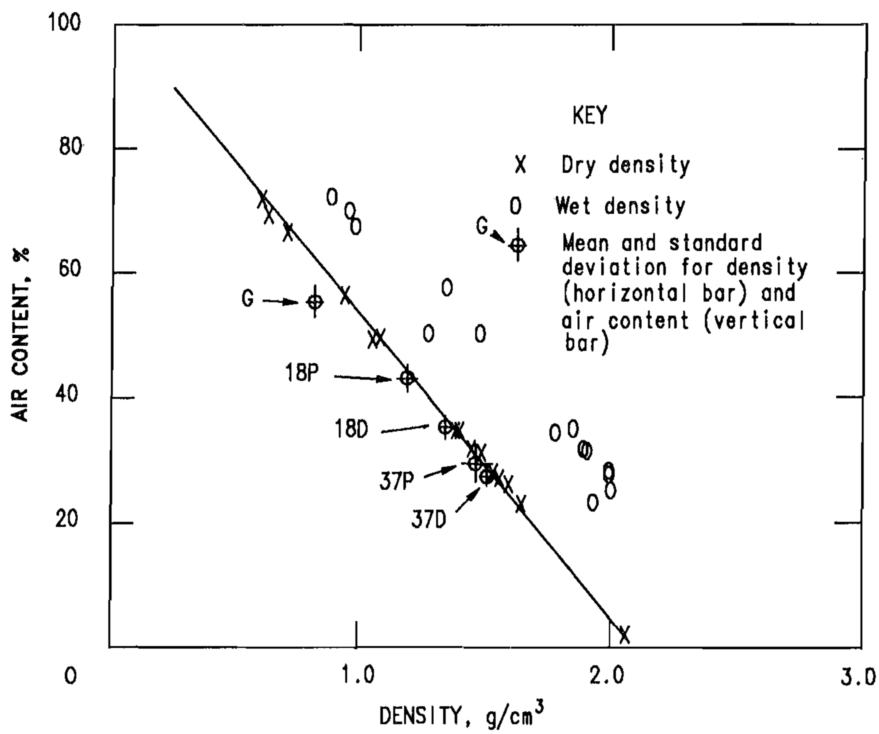
Figure 14 shows results for the compressive strength testing of cylinder samples. Data set WDC is made up of 28- and 90-day compressive strength and dry-density data for a suite of samples of varying densities (appendix A, figure A-1). The compressive strength changes dramatically with increase in density of the material. The compressive strength data for core segments from the large forms (data set LFC, appendix A, figure A-2) were compared using multiple-range statistical analysis (figure 15). The standard deviations varied from 18% to 23% of the mean values. The differences between the large forms from the 18- and 37-m tests were statistically

Figure 12



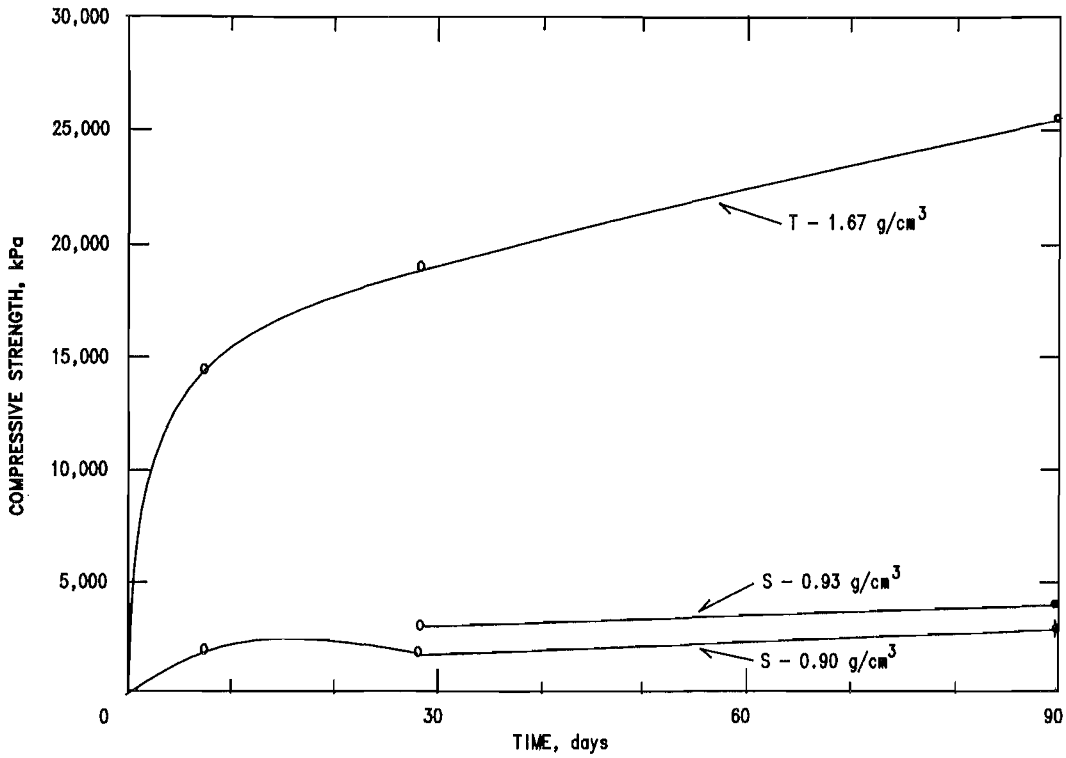
Multiple-range analysis for percentage of air by level.

Figure 13



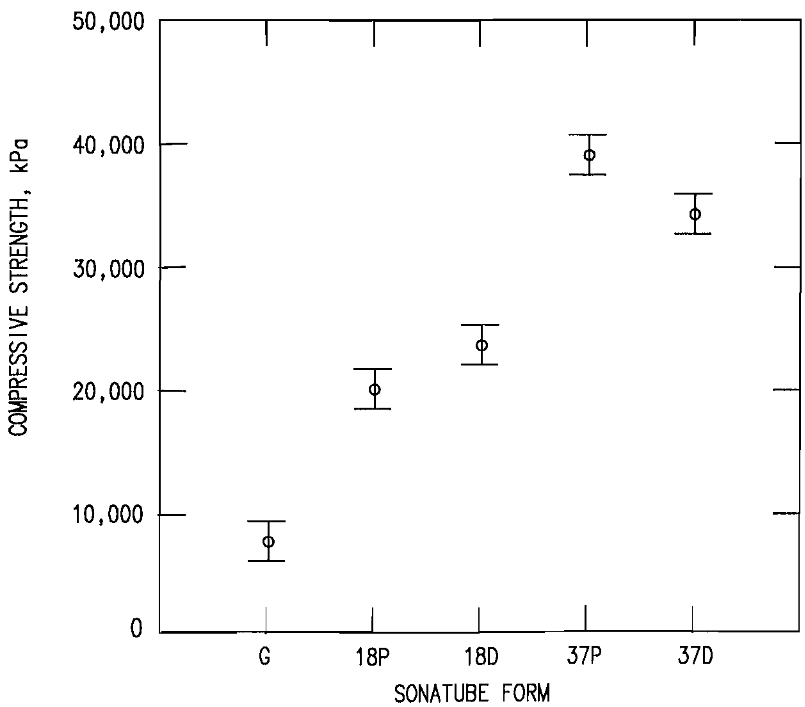
Comparison of air content and density results from large forms with those of 7.6-cm-diam cylinder samples.

Figure 14



Density and uniaxial compressive strength test results for 7.6-cm-diam cylinder samples. (S = samples taken from mixer after addition of foam; T = samples taken from "T" valve at 18-m level.)

Figure 15



Multiple-range analysis of post-28-day compressive strength test results for large forms.

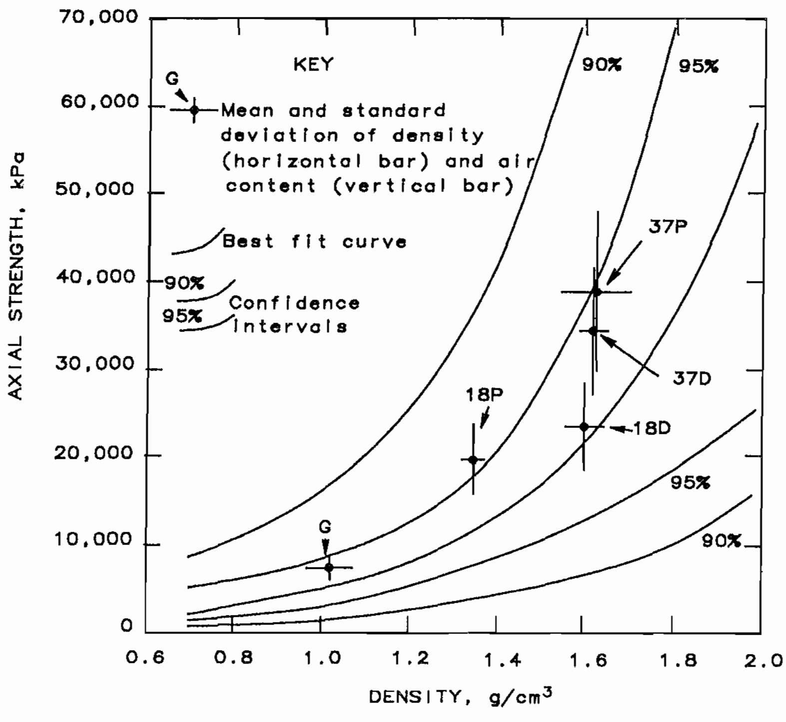
significant. However, the compressive strength values for the drop and pumpdown tests at both levels overlapped. The differences were not statistically significant for both the 18- and 37-m levels.

The 28- and 90-day densities and compressive strength data from WDC were compiled and analyzed using regression analysis to determine the best fit line or curve for the data. Given the small number of data points of different densities, the R-squared value for a linear fit was 82%. An exponential curve was also attempted with a resulting R-squared value of 92% (figure 16). The reason why an exponential curve is a better fit than a line may be due to the small data set size. Yet, it may also be due to the degree of air loss and increase in matrix in the samples caused by dropping or pumping the cellular concrete.

MODE OF CORE FAILURE DURING COMPRESSIVE STRENGTH TESTING

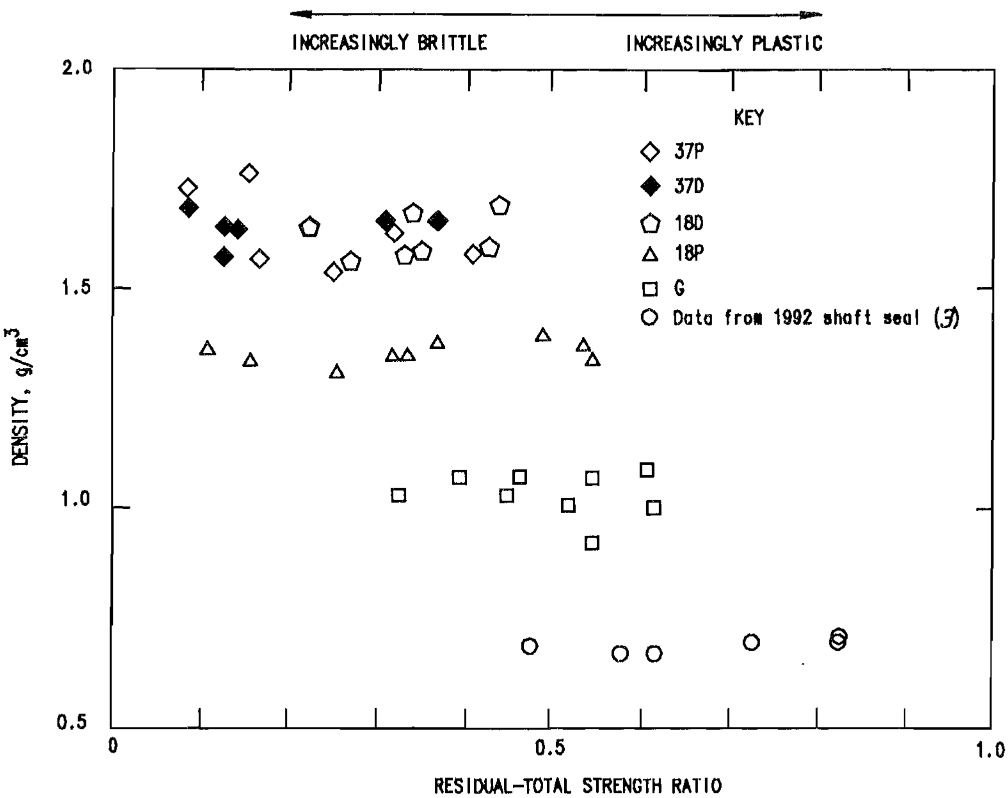
An analysis was done on the failure curves of the 44 large form core samples to determine the ratio of residual strength (remaining strength or ability of the core to support load after failure) to the total breaking strength. The ratios for samples from the different Sonatube forms were plotted versus density of the sample to determine trends in ductile versus brittle failure with increasing density (figure 17). From figure 17, the less dense, higher air content concrete from G showed a higher ratio and more ductile failure than the concrete subjected to pumping or dropping. The failure curves for these samples showed predominately ductile behavior (see appendix B, figure B-2). The cores, after testing, showed little change in volume and did not break apart as did higher density samples. These characteristics changed relatively quickly with 18P with a wide variation in the ratios. Core failure, for the most part, was more characteristic of a brittle solid than a ductile material (appendix B, figure B-4). Sample failure from 18D, 37P, and 37D was predominately brittle (appendix B, figures B-6, B-8, and B-9). The ratios for cores from these three large forms were similar. For comparison, ratios were determined from failure curves from

Figure 16



Regression analysis of compressive strength on density with data sets for five large forms superimposed.

Figure 17



Ratio of residual strength to total breaking strength versus density for 44 core segments from large forms.

cores of lower density foam concrete (0.72 g/cm³ wet density) poured during the USBM shaft sealing project in West Virginia (*3*). The ratios for these samples are also shown in figure 17. These less dense samples had an equal to higher ratio than the samples from G. From the above, it is evident that, with increasing transport and subsequent loss of entrained air, significant changes occur to the concrete, making the material more brittle. This can be problematic when the design specifications call for a lightweight, more plastic material.

DISCUSSION OF RESULTS

The data show that cellular concrete, to retain the bubble structure and therefore lightweight and associated characteristics, should be placed carefully and near the point of mixing. Air loss during emplacement can be associated with pumping, the delivery system, the vertical distance the concrete is pumped, and whether the cellular concrete is dropped or pumped (tremied) into the shaft.

Loss of air from cellular concrete, especially the lighter weight concrete, can result from pumping. A 14% air loss was noted between the mixer (S) and G on the ground level (figure 9). Depending on the type of pump used and the conditions, some loss of air from cellular concrete due to pumping may be unavoidable. If the concrete is foamed near the shaft opening, the need to pump concrete long distances will be minimized. If cellular concrete must be pumped uphill, it is essential that the distance be lessened to keep air losses low.

Significant air loss occurred due to pumping up to the 18- and 37-m levels. A total of 6% more air was lost between G and 18I and 22% between G and 37I.

Pumping cellular concrete back down from the 18-m level resulted in a decrease in air content from 49% to 43%. The effects of air loss can be visually seen in scanning electron microscope images taken of samples from G and 18P (appendix B, figures B-1 and B-3). Dropping the concrete from the 18-m level (35% air) and pumping or dropping from the 37-m level (29% and 27% air, respectively) resulted in a nearly total loss of the air content. The air contents in 37P and 37D were near those of the unfoamed concrete mix (23%).

Comparisons of air contents from the large forms and those determined from sample cylinders (figure 13) show relatively good agreement between the two sets of data. For this research, the linear trend derived from WDA gave a relatively close approximation of air contents for the individual large forms (LFA).

For cellular concrete, an increase in density of the concrete (and the subsequent decrease in air within the sample) resulted in an increase in the compressive strength. Figures 14 and 15 show this increase. Each large form was relatively homogeneous for air content (4.7% to 9.3% standard deviation from the mean). However, the variation of compressive strength within the concrete plug was larger (18% to 23% standard deviation from the mean).

As cellular concrete is pumped to a site, air loss and subsequent loss of the cell structure occur. These changes result in both significant changes in the characteristics of the concrete and an increase in the weight and cost of in-place cellular concrete. A decrease in air in the samples tested resulted in a decrease in the ratio of the residual-total breaking strength (ductility) of the samples (figure 17). Samples that were transported were stronger, but failure during loading was more brittle and less ductile. It is felt that the ductility of the material is an important characteristic for long-term performance of the shaft plug. Minimizing pumping and handling of the wet cellular concrete is critical to the permanence and durability of a shaft plug.

CONCLUSIONS AND RECOMMENDATIONS

Cellular concrete is a highly versatile material that is used in many areas of construction. It was used by the USBM to seal one abandoned mine shaft. Cellular concrete, after curing, is stable, with low permeability and sufficient strength to form an effective plug for abandoned mine shafts. It is also considered to be relatively benign to the environment. Cellular concrete, during emplacement, is highly susceptible to air loss.

Air loss results in an increase in density and a subsequent increase in compressive strength. Yet, in sealing abandoned mine shafts, high strength may not be as important as other features, such as a lighter weight and a well-developed cellular structure. Homogeneity of the plug and how the plug fails under applied stress can also play an important role in the long-term competency of the shaft plug.

It is recommended that the concrete be foamed as near to the shaft as possible to minimize air loss from transportation. The cellular concrete should not be allowed to free-fall. From this research, 18 m was considered the absolute maximum height of free-fall for drop placement. At 18 m, the effects of foaming the concrete were nullified. It is not known at what level below this point loss of entrained air could be minimized. Therefore, cellular concrete should be placed using a hose or tubing if possible. Use of a tremie or other methods to minimize air loss from the concrete may be considered if the downward vertical distance is significant. Care must be taken here as well. For the cellular concrete tested, the difference between the concrete dropped and that pumped down from the 37-m level was minimal. The differences between drop and pumpdown at the 18-m level were more significant (appendix B, figures B-3 and B-5). It is felt that the depth of placement must also be limited to a value below 18 m for a similar mix of cellular concrete. Lastly, care must be taken to minimize pumping or limit pumping pressures after the cellular concrete has been generated. Equipment necessary to foam cellular concrete may be portable enough to take to the site. Unfoamed concrete can first be pumped to and subsequently foamed at the shaft prior to emplacement. In-line methods of foaming the concrete, such as in-line foam injectors and static mixers, may also be considered.

ACKNOWLEDGMENTS

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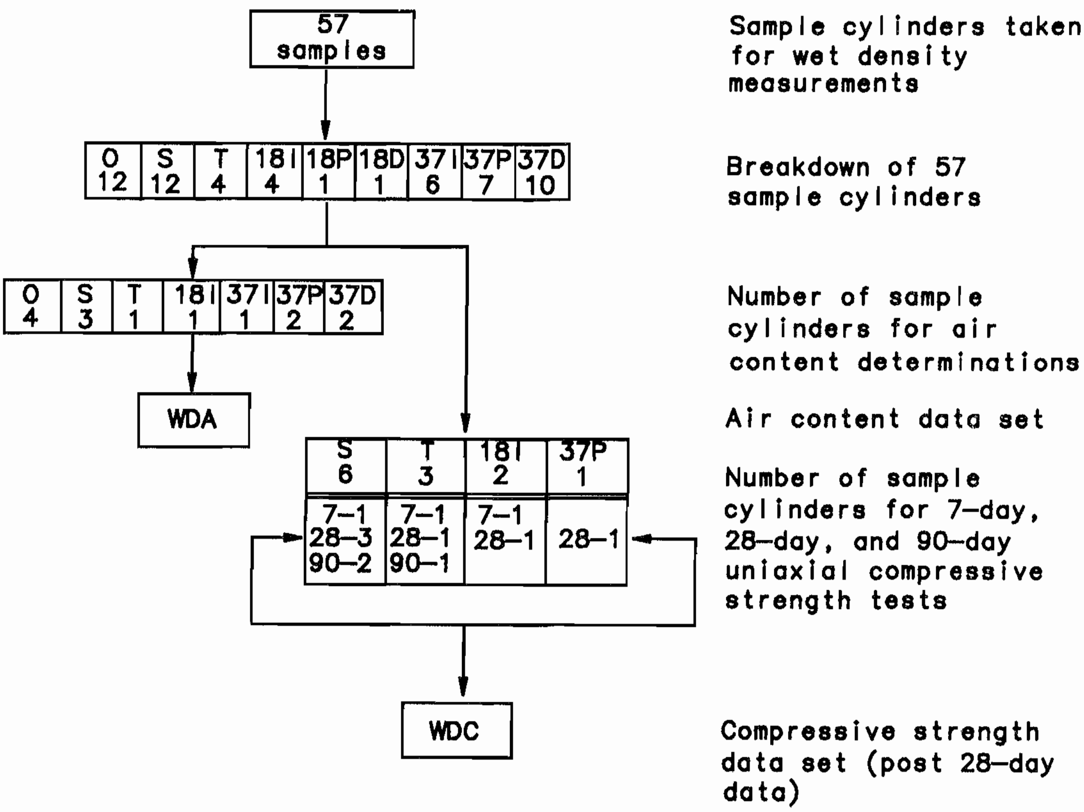
APPENDIX A.—SAMPLING PROCEDURES FOR TESTING SAMPLE CYLINDERS AND LARGE FORMS

Both cylinders for wet density measurements and cores from large forms were collected. A total of 57 wet density measurements were obtained (figure A-1). Of that, a total of fifty-five 7.6-cm-diam plastic sample cylinders were collected. Cylinders were not taken at points 18P and 18D. Wet density measurements were determined by the contractors and reported to USBM researchers. Samples of different densities were selected from the 55 cylinders, prepared, and tested for air content (data set WDA) and uniaxial compressive strength (data set WDC).

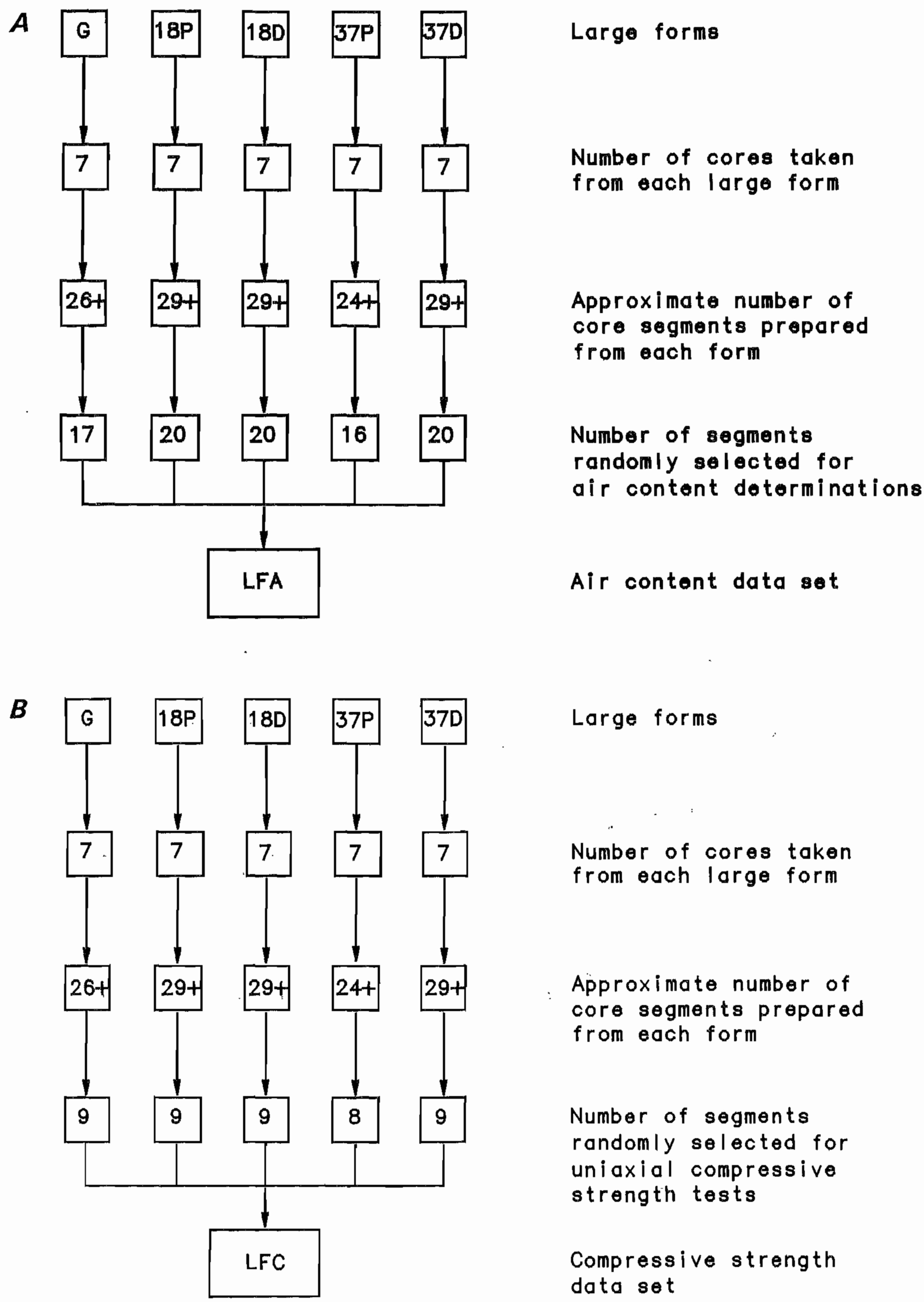
As noted in the main text, seven cores were taken from each large form. Core segments were randomly selected, prepared, and tested for air content (data set LFA) and uniaxial compressive strength (data set LFC). Figure A-2 contains flowcharts of specific sample sizes for each large form, analyses, and resulting data sets LFA and LFC.

Figure A-1



Flowchart of breakdown of samples, types of analysis, and resulting data sets from 7.6-cm-diam cylinders taken for wet density measurements. [O = samples of different densities taken at other points in test circuit; S = samples taken from mixer after addition of foam; T = samples taken from "T" valve at 18-m level (see figure 9A).]

Figure A-2



Flowcharts of numeric breakdown of cores, core segments, and data set size. A, Air content determinations and data set LFA; B, compressive strength determinations and data set LFC.

APPENDIX B.—CHARACTERISTICS AND ANALYTICAL RESULTS OF CORES FROM LARGE FORMS

Seven cores were taken from each form. As noted previously, sections were prepared for uniaxial compressive strength testing and air content determinations. Nominally, four slices of concrete from the upper, middle, and lower sections of each core were cut and the surfaces examined using 10X and 30X power under a binocular microscope. A grain-size chart developed by American Stratigraphic Co. for analysis of sandstones in sedimentologic studies was used to determine bubble size. Percentage matrix, where applicable, and shape of the bubbles were noted. The presence of vugs, straw used to seal the base of the forms, and impurities (fine aggregate and unmixed cement) were also noted. The descriptions that follow were based on generalized visual estimates. No quantitative point-count or analytical techniques were used to further describe the samples.

G—GROUND LEVEL

The cellular concrete from G (baseline) drilled easily and core retrieval was good. There were no large vugs or breaks in the pour that would have affected the strength of the plug. Because of the lighter density of the cellular concrete, straw that was to be used as a seal at the bottom of the form floated and mixed with the concrete. Upon microscopic analysis, the cellular concrete bubble structure was well developed (figure B-1). Actual visual estimates of matrix between bubbles could not be made. The bubbles were spherical with a wide range of sizes. The predominate bubble size that could be detailed using the binocular scope varied from 88 to 710 μm in diameter, although some bubble diameters reached 1.4 mm. The percentage of air as determined for 17 samples from G was 55.1%, with a standard deviation of 2.73%. Three cylinder samples taken from the mixer had an average air content of 68.7%. Approximately 14% of the air was lost going through the pump. A total of nine randomly selected samples tested for uniaxial compressive strength gave a mean value of 7,378 kPa, with a standard deviation of 1,336 kPa, given an average dry density of 1.02 g/cm^3 with a standard deviation of 0.052 g/cm^3. All samples, when tested for compressive strength, showed ductile behavior and had a relatively high residual strength after failure (figure B-2).

18P—PUMPDOWN FROM 18-m LEVEL

The cellular concrete in 18P was expanded in the mixer (0.89 to 0.97 g/cm^3), pumped to the 18-m level (1.45 g/cm^3), pumped horizontally approximately 6 m, and pumped back down into the Sonatube form through a 5.1-cm-diam PVC pipe. A valve at the base of the tubing remained closed until the tubing was filled with cellular concrete. At that point, the valve was opened, and the Sonatube form was filled with cellular concrete. A tremie was not used to place concrete in this form. The wet cellular concrete was allowed to fall approximately 1.5 m from the end of the PVC pipe to the base of the form. The wet density of the material after placement in 18P was 1.63 g/cm^3. During assessment of the sides of the samples after stripping off the form, the straw became mobile during the pour. Small amounts of straw were found throughout the section with significant volume of the material found in the basal 37 cm of an 87-cm-high sample. Vugs to 10 cm in diameter were also noted. From microscopic analysis of sawed slabs of the cores, the concrete surface had a white, mottled appearance (figure B-3). Matrix made up from 50% to 80% of the exposed surfaces. The percentage matrix varied vertically through the cores with no pattern noted (i.e., more matrix at the base or top of the sample) in the seven different cores. The majority of the smaller bubbles were spherical, although some larger bubbles were elliptical in shape. The bubble size ranged from 125 μm to 6 mm in diameter, although some of the bubbles were 88 μm or smaller. The mean air content, based on analysis of 20 samples, was 43.2%, with a standard deviation of 2.05%.

The mean compressive strength, based on analysis of nine samples, was 19,713 kPa, with a standard deviation of 3,903 kPa. The mean density for these samples was 1.345 g/cm^3, with a standard deviation of 0.025 g/cm^3. The failure curves for a representative sample from 18P are given in figure B-4. The mode of failure was more brittle than samples from G and less brittle than samples from 18D.

18D—18-m DROP TEST

The cellular concrete in 18D was expanded in the mixer (initial wet density of 0.91 to 0.94 g/cm^3), pumped up 18 m to the 18-m level (wet density of 1.45 g/cm^3), and then allowed to drop 18 m through the windscreen into the Sonatube form (wet density reported at 1.82 g/cm^3). From core analysis, the concrete looked homogeneous, with few large vugs and discontinuities. Because of the heavier weight of the material, straw was found predominately in the base of the sample plug. Visual estimates from microscopic analysis of cut sections of the core were that 90% or more of the sample was matrix, with 10% or less of the exposed surfaces occurring as bubbles (figure B-5). The bubble sizes ranged from 62 μm to 6 mm in diameter. Yet, the size of the majority of the bubbles ranged from 88 to 710 μm. The fabric of the material varied significantly from that of G, the ground-level sample. The cellular structure was not evident. Bubbles, for the most part, looked more like entrapped air and less like air that had been originally generated during mixing. As the cellular concrete fell, it began to disperse and separate almost immediately. When the cellular concrete came from the end of the windscreen, it came out as a fine mist. It is felt that most of the bubbles remaining within the concrete were due to air trapped during placement.

Air content was determined for 20 samples. The mean air content was 35.3% for 18D, with a standard deviation of 1.69%. A total of nine samples were successfully tested for uniaxial compressive strength. The mean compressive strength was 23,443 kPa, with a standard deviation of 4,881 kPa, based on a density of 1.596 g/cm^3, with a standard deviation of 0.044 g/cm^3. Upon failure, the sample showed brittle behavior with a lower residual strength relative to its compressive strength (figure B-6).

37P—PUMPDOWN FROM 37-m LEVEL

The wet density of the concrete was determined prior to expansion. The average value based on four samples was 2.01 g/cm^3. The initial density from the mixer was 0.94 g/cm^3. The wet density after pumping the expanded mixture up to the 37-m level, horizontally across the floor, and down 37 m into 37P was 1.91 g/cm^3. The form was filled using a tremie in an attempt to minimize the loss of air from the sample. With the use of the tremie, the straw at the base of the form was pushed out and away from the pipe. Straw was mapped on the outside of the form up to 50 cm of the 94-cm-high plug. Yet, little straw was encountered in any of the seven cores taken from the plug except for in the lower 5 to 15 cm of the cores. Microscopic analysis under 30X power revealed that the matrix made up from 90% to 99% of the cut sections analyzed. In these cores, a trend existed where the amount of air bubbles in the upper sections of the cores was higher than near the base of the concrete plug. The bubble size ranged from 62 μm to 2.0+ mm. As with other samples, the majority of all bubbles observed were spherical (figure B-7). Yet, a minority of the larger bubbles demonstrated an elliptical shape. This feature was not common, with isolated pockets of elliptical bubbles noted. The average percentage of air based on 19 samples was 29.48%, with a standard deviation of 2.75%.

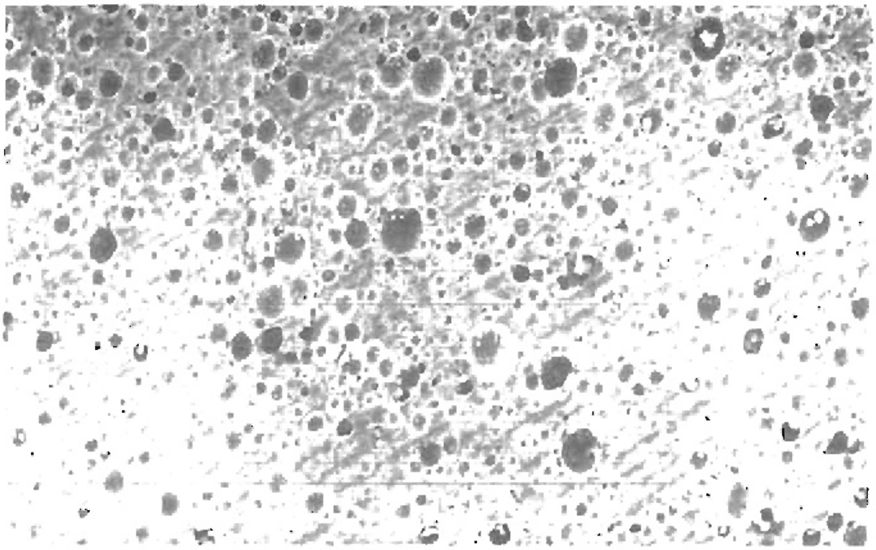
The mean uniaxial compressive strength for eight samples tested (a ninth sample broke during sample preparation) was 38,839 kPa, with a standard deviation of 9,016 kPa. The samples, upon breaking, showed a brittle character with a low residual strength (figure B-8). These samples were similar to those from 18D.

37D—FOAM CONCRETE DROP FROM 37-m LEVEL

The concrete in 37D was foamed to a wet density of 0.94 g/cm^3 in the mixer, pumped to the 37-m level (wet density of 1.84 g/cm^3), moved horizontally, and dropped through the windscreen into 37D (wet density of 1.97 g/cm^3). In the cores, straw was confined to the lower 20 cm of the form. Microscopic analysis of representative cores revealed a homogeneous material similar to what was noted in 37P. The matrix made up from 90% to 98% of the sample with no gradational pattern noted in the cores. Bubble size varied from 88 μm to 5 mm in diameter, yet the majority of bubbles were larger than 177 to 250 μm in diameter. In this concrete, elongation of the bubbles was noted, even in the smaller sized bubbles. The mean air percentage, based on analysis of 20 samples, was 27.5%, with a standard deviation of 1.67%.

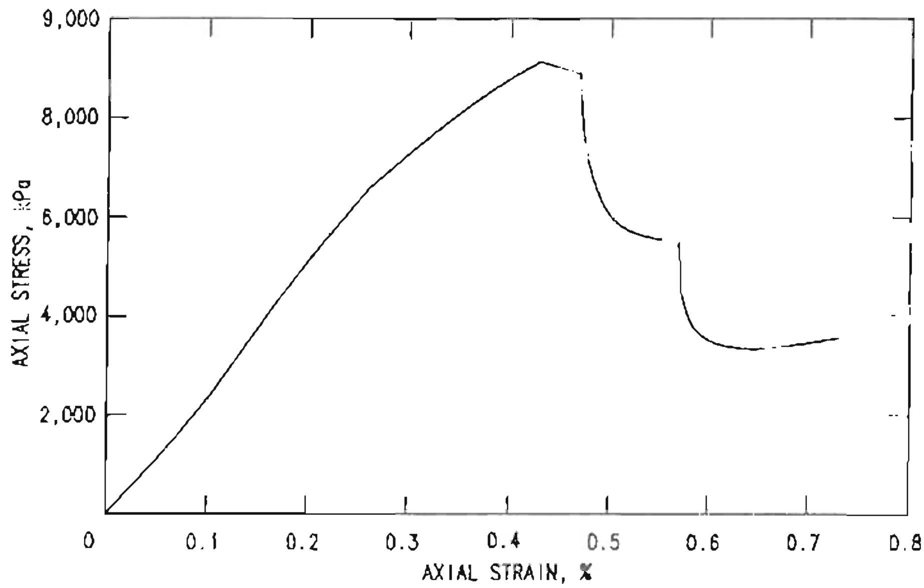
The mean compressive strength, based on testing nine samples, was 34,385 kPa, with a standard deviation of 7,127 kPa. The mean dry density for these samples was 1.62 g/cm^3, with a standard deviation of 0.031 g/cm^3. The samples, similar to those from 18D and 37P, showed more brittle characteristics than samples of lower density, i.e., G and 18P (figure B-9).

Figure B-1



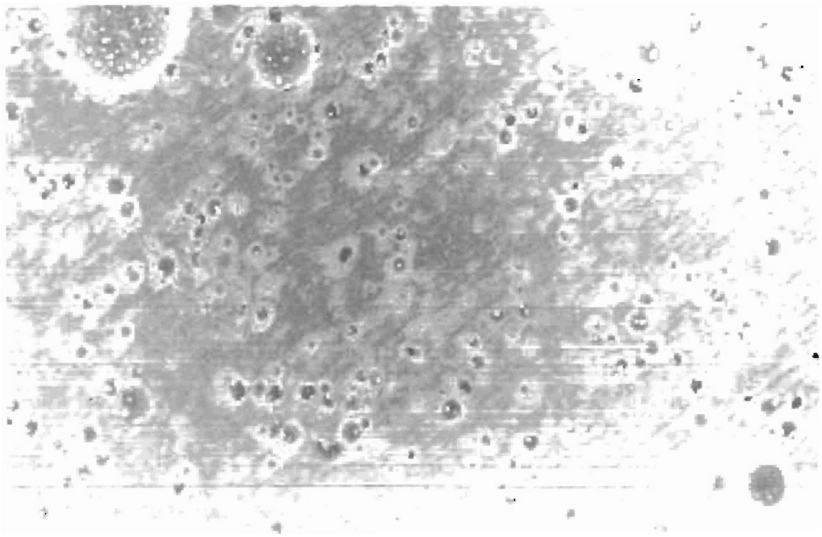
Scanning electron microscope image of surface of representative sample from large form G (× 10).

Figure B-2



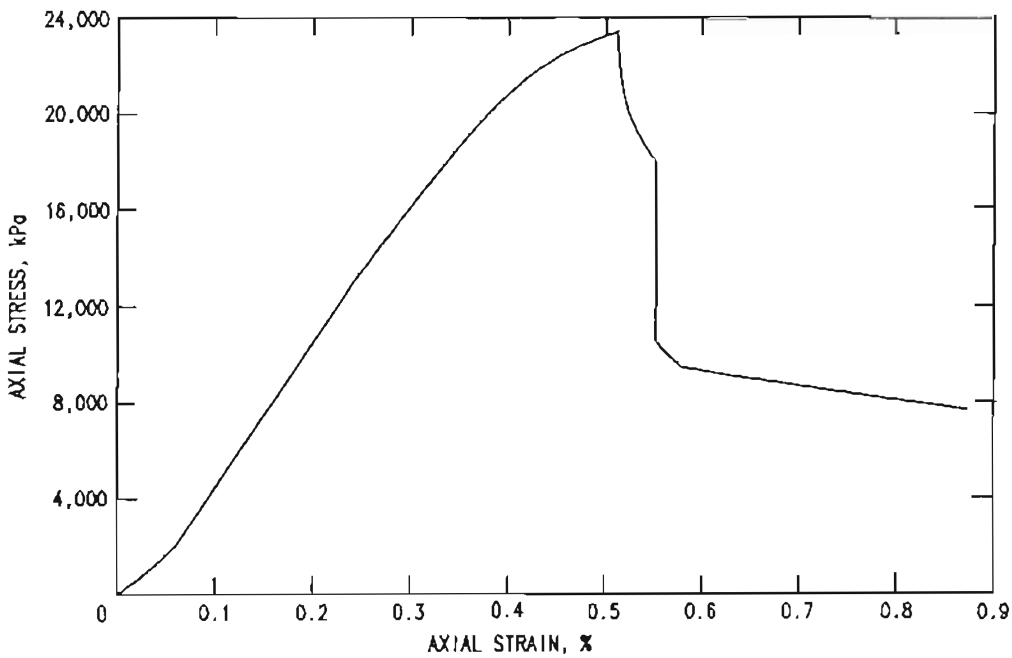
Failure curve for representative sample from large form G.

Figure B-3



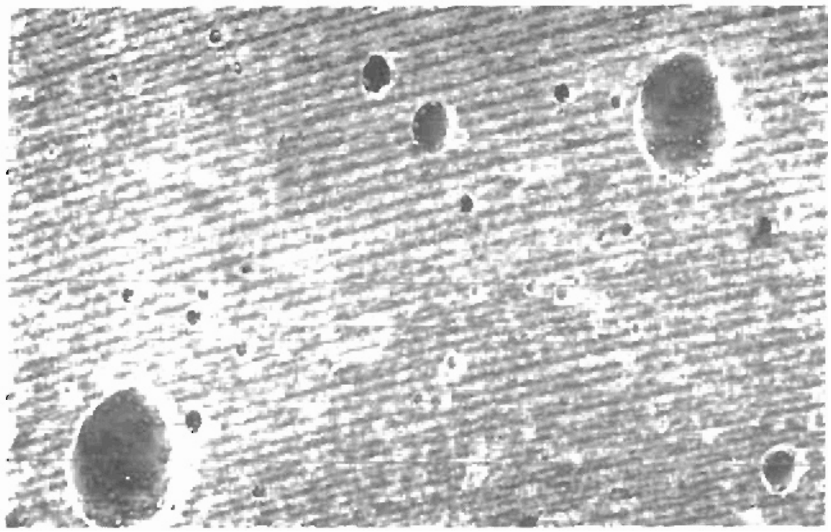
Scanning electron microscope image of surface of representative sample from large form 18P (× 10).

Figure B-4



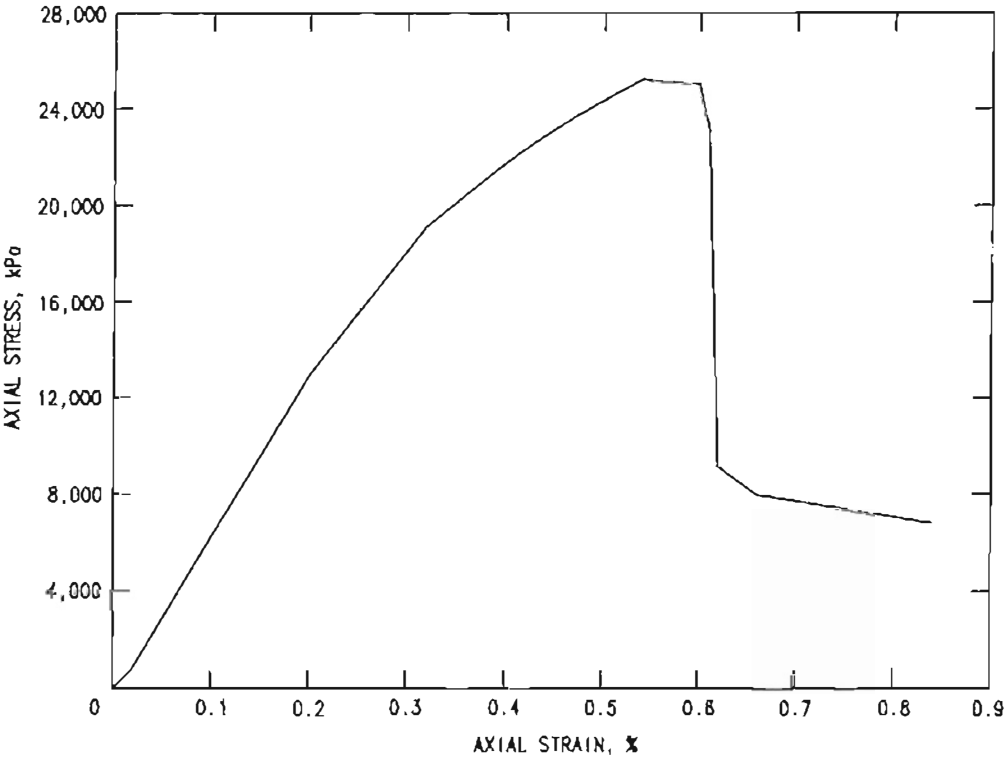
Failure curve for representative sample from large form 18P.

Figure B-5



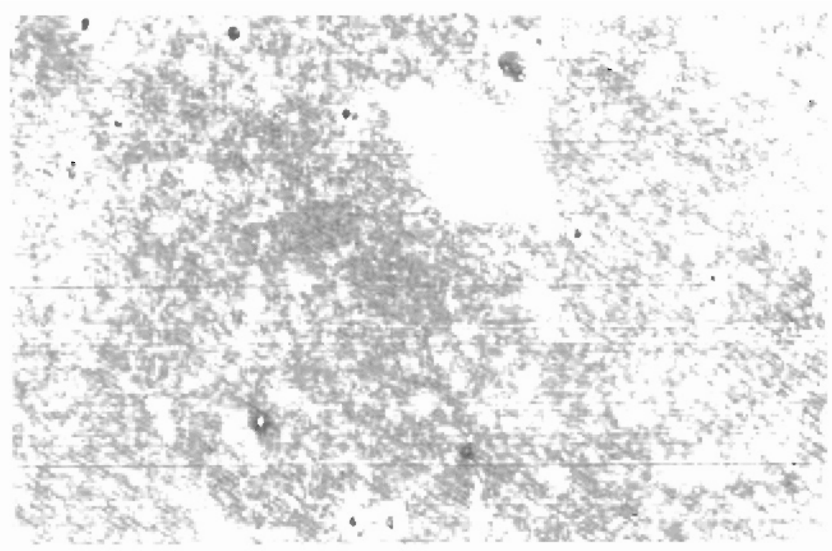
Scanning electron microscope image of surface of representative sample from large form 18D (× 10).

Figure B-6



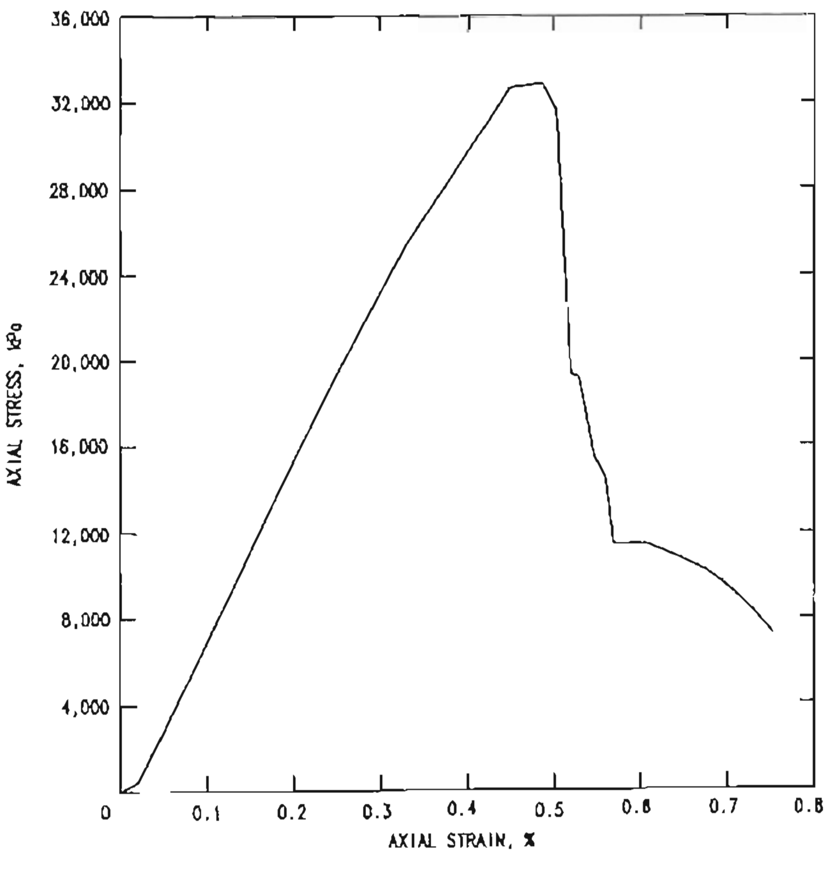
Failure curve for representative sample from large form 18D.

Figure B-7



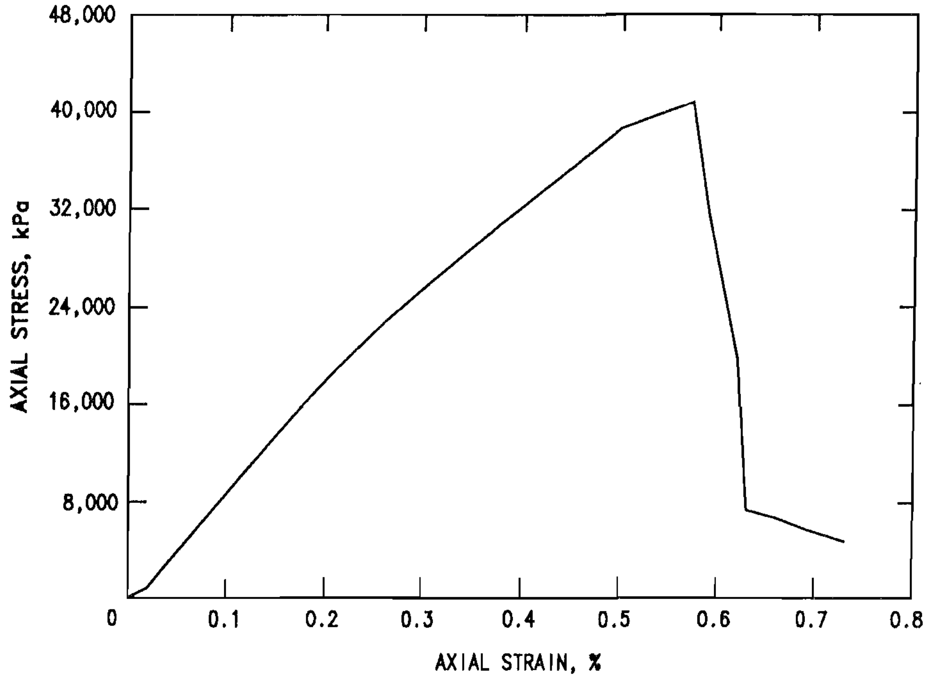
Scanning electron microscope image of surface of representative sample from large form 37P (× 10).

Figure B-8



Failure curve for representative sample from large form 37P.

Figure B-9



Failure curve for representative sample from large form 37D.

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