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**State-of-the-Art Techniques
for Backfilling Abandoned
Mine Voids**

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm cubic foot per minute

in inch

fps foot per second

pct percent

ft foot

psi pound per square inch

gpm gallon per minute

STATE-OF-THE-ART TECHNIQUES FOR BACKFILLING ABANDONED MINE VOIDS

By Jeffrey S. Walker¹

ABSTRACT

Abandoned underground mine openings are susceptible to collapse because of the mining methods used, the character of the overburden, and the typically large, wide entries with minimal roof support. The final effect of the collapse of the underground workings is surface subsidence. To reduce the probability of subsidence, methods to backfill the mine void with various types of materials have been developed. This U.S. Bureau of Mines report describes the available technologies for subsidence abatement and discusses their operation and application. The basis of these abatement methods is the replacement of the mined material with mine waste. Backfilling of mine voids is the most common method of stabilization used to abate subsidence and protect surface structures. Hydraulic flushing and grouting, using remote methods from single or multiple boreholes, are the most often-used methods for the placement of backfill material. Other subsidence abatement techniques are available and may be more appropriate under different conditions. These other techniques include pneumatic stowing, either by in-mine or remote methods, and various point support methods that do not completely fill the mine void and are used for the protection of small areas of the land surface and surface structures.

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INTRODUCTION

Subsidence from abandoned underground coal mines has become an everyday concern of many citizens living in coal-producing regions of the United States. Because subsidence causes direct damage to property, with significant financial loss, and more importantly presents an extreme danger to public health, safety, and general welfare, subsidence and subsidence-related problems are considered by the Office of Surface Mining Reclamation and Enforcement (OSMRE) and affected States to be the highest priority issues relating to reclamation of abandoned mine lands (AML).

The development and improvement of methods to abate subsidence from the collapse of abandoned underground

mines has been more or less neglected for the last 10 to 15 years. The same methods and procedures used in the late seventies are still used today. The objectives of the U.S. Bureau of Mines Abandoned Mined Land Subsidence Abatement Research Program are to improve subsidence abatement practices through the evaluation of current backfilling methods, to increase the use of sound geotechnical engineering principles in site investigation and remedial design, and to develop state-of-the-art tools and procedures for subsidence abatement. This work will provide a source of documented information describing the mechanism of subsidence development, applicable abatement methods, and remediation procedures.

BACKGROUND

The principal application of mine backfilling in the United States today is different from that of 100 years ago. Backfilling was first used in the anthracite coalfields of northeastern Pennsylvania to support the surface in active mining operations, to arrest the development of progressive pillar failure, to aid in the recovery of pillars, and to dispose of mine waste (1).² Today, backfilling is primarily used as a method to abate subsidence from the collapse of abandoned underground coal mines. There have been a few instances in which this technique was applied in active mines. However, with the increased use of high-extraction mining methods, backfilling during the mining operation may be a future option for subsidence control.

There are a number of differences between backfilling methods used in active mines to prevent surface subsidence and those used in abandoned mines. The greatest difference is the lack of access to abandoned mine voids. In active mines it is possible to directly observe the backfilling operation and control the location and amount of the fill material deposited. Whereas, in abandoned mines, often there is no access to the mine void. All work must be done from the surface in a remote fashion. It is this difference that separates the techniques used for in-mine backfilling and remote backfilling of abandoned mine voids. The primary concerns of in-mine backfilling programs are the logistics of material transportation through the mine and the capacity of the system. Remote backfilling operations require consideration of these factors, and also installation of equipment through boreholes, contending with unknown mine configurations and collapsed zones and blind monitoring of the fill.

There has been little change in the backfilling technology used during the past 100 years, and technical information to support the design of artificial pillars is almost wholly lacking in the literature. The most recent discussion of state-of-the-art methods for subsidence control was written in 1974 by the Appalachian Regional Commission (2). Since that time, progress has been made in the design of point support methods and delivery equipment, but the basic concepts and limitations remain the same.

There are two options available for the abatement of subsidence: point support and area-wide techniques. Point support techniques are used for situations in which subsidence is occurring in a relatively small area as a result of individual pillar failure. These methods provide additional support at a single location, such as at the center of a large mine opening or beneath a single surface structure of interest (fig. 1). Area-wide techniques are used where a large portion of the mine is at risk of collapse. The area-wide techniques fill large portions of the mine with fill material from multiple injection boreholes.

In general, there are four methods for the construction of artificial supports used in subsidence abatement: hydraulic, pneumatic, mechanical, and hand. Only hydraulic and pneumatic methods have widespread application to subsidence control in AML, because these methods can be implemented from the surface without the need for personnel to enter the mine. This type of backfilling operation is termed "blind" or "remote." It differs from in-mine backfilling techniques in that the remote method is typically performed through a borehole without placing any equipment into the mine except for the material injection pipe and nozzles. In-mine techniques utilize operators inside the mine to direct and control the flow of material into the void. Hand and mechanical methods, such as belt

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

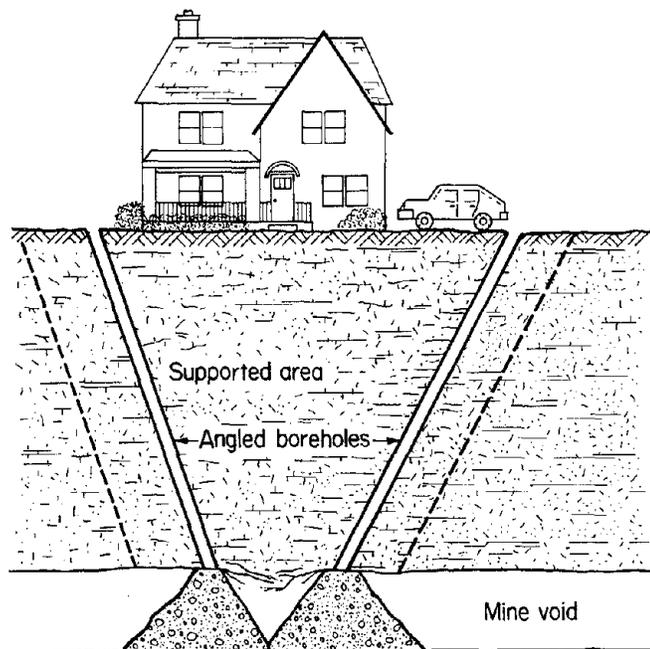


Figure 1.—Idealized example of point support method.

or sling packing machines, are restricted to construction of the support from within the mine. These methods have become obsolete or uneconomical for large-scale subsidence control and have been replaced with the use of pumped concrete for in-mine construction. Cribbing made from timber or concrete blocks remains the only type of hand-constructed support used today.

Inherent to remote backfill systems is the problem of tracking the placement of the backfill. It is difficult to monitor the size of the fill area and to determine the direction in which the fill area is growing (3). This problem is relevant to both pneumatic and hydraulic methods. However, because larger areas can be backfilled using the hydraulic method, the need to determine the growth of the fill becomes much more important.

Simply stated, hydraulic flushing consists of washing backfill material into a mine void using large quantities of water. The hydraulic flushing method is believed to have originated in the anthracite coalfields of Pennsylvania in 1864 in an effort to prevent the destruction of a church

from mine subsidence (1). The practice of hydraulic flushing was further developed during the late 1800's and early 1900's and was used on a regular basis in the anthracite coalfields to extinguish fires and support areas of extremely high extraction. In 1901 hydraulic flushing was introduced into Europe, where it has been used extensively to dispose of mine waste into the abandoned sections of deep room-and-pillar mines. The practice of hydraulic flushing in the United States decreased with the decline of the anthracite industry in the 1940's. Currently, use of hydraulic flushing in the coal industry is limited to subsidence abatement in abandoned underground mines. However, in the metal mines of this country, hydraulic methods are commonly used to remedy ground control problems.

Pneumatic stowing was first applied in Germany in 1924, and it has become the favored backfilling method, replacing hand packing and hydraulic methods. Pneumatic stowing consists of the transportation of backfill material into the mine through a pipeline by flowing air. In Europe the general use of pneumatic stowing is to place mine refuse in the gob areas behind advancing longwall faces. This practice not only provides roof support, but reduces or eliminates the disposal of mine waste on the surface. Pneumatic stowing is not used widely in the United States, and is typically limited to small-scale use for building mine seals or filling behind tunnel liners. In recent years, however, pneumatic stowing has been used in ground control applications in the Western United States where there is a lack of abundant water supplies or the mine workings cannot tolerate excessive moisture conditions (4).

"Hand packing" and "mechanical packing" typically refer to backfilling of very small mine areas for specific purposes, such as permanent support of unstable roof areas or replacement of barrier pillars during second and third mining operations. However, the term "packing" has been used as general term to describe any type of mine backfilling operation.

The type of abatement method to be used for each situation is not easily determined. Each method has its pros and cons. It is safe to say, however, that all of the subsidence abatement methods need to be further investigated to fully document their capabilities and to improve their application.

AREA-WIDE TECHNIQUES

HYDRAULIC FLUSHING

Hydraulic flushing is the practice of filling the mine void with various types of material (i.e., crushed stone, mine refuse, sand, or fly ash) by washing or pumping the

material into the mine with water (fig. 2). The fill material is transported into the mine as a slurry and deposited in the void until the void is completely filled or there is a blockage of the injection pipe. Bulkheads and mine pillars are often used to limit the flow of the material to

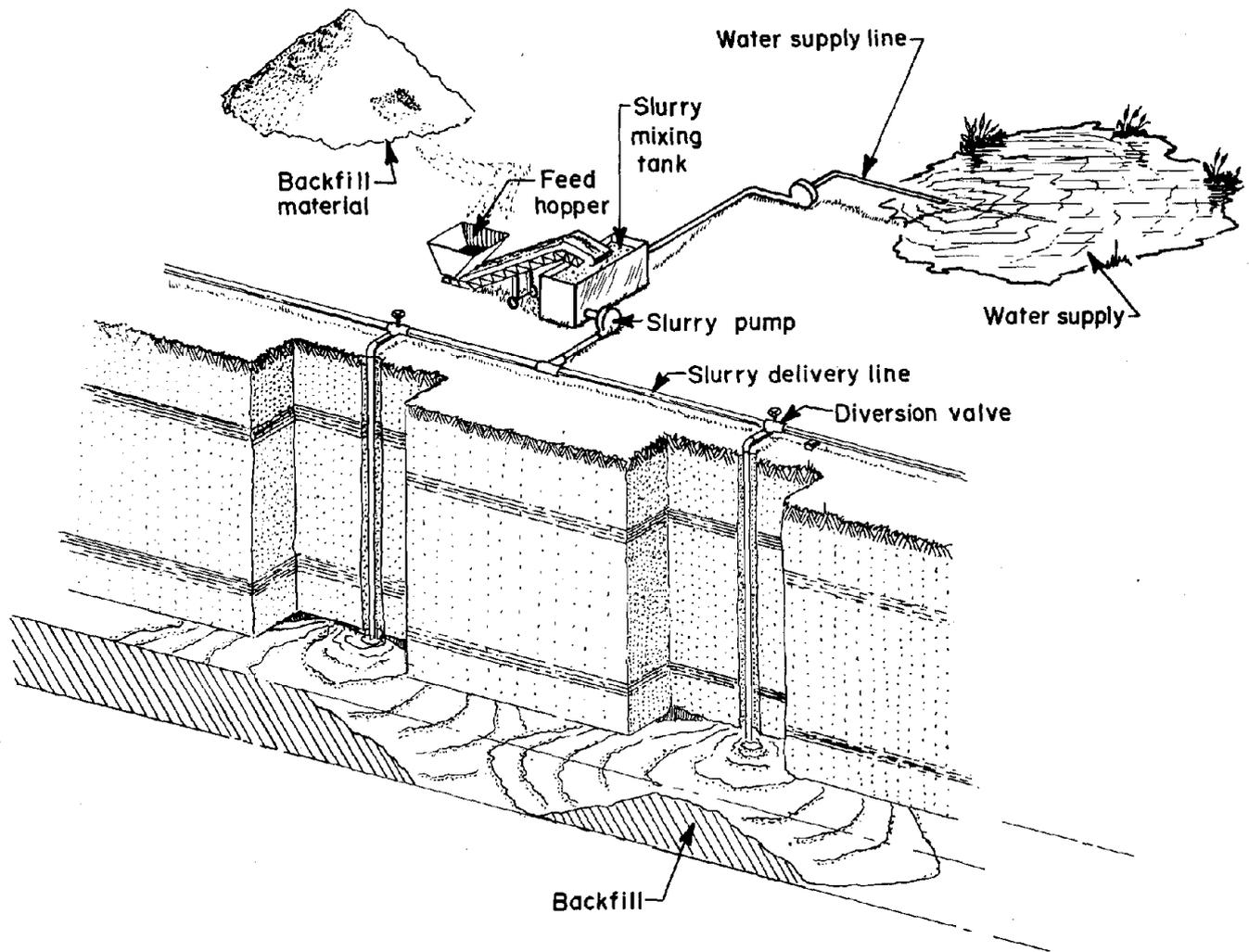


Figure 2.—Hydraulic backfilling.

a specific section of the mine. Current flushing methods require pumping of large amounts of water and material with little control over the direction and compaction of the resultant backfill. The available hydraulic flushing techniques include high-volume pumping, low-volume pumping, and gravity feed (5).

In the high- and low-volume pumping methods, granular material is blended with water in a large mixing tank at a processing plant (typically located some distance from the injection borehole) and is then pumped to a series of injection boreholes through pipelines (6). The energy provided from the pump and the static head of the borehole gives the backfill material the velocity required to keep the fill material in suspension and determines the size of the area that can be flushed from a single borehole. Normally, many boreholes spaced close to each other are required to backfill a large area.

The efficiency of the backfilling process within the mine is a function of the slurry velocity. When the slurry first enters the open mine void from the borehole, its velocity drops rapidly, and the solid particles drop out to form a donut-shaped mound on the mine floor (7). As the height of the mound approaches the mine roof, the velocity of the slurry is maintained by the narrowing of the opening between the roof and the fill material (fig. 3). When the slurry reaches the outer limit of the mound, the velocity decreases abruptly and solids are deposited in a process that is similar to the development of an alluvial fan. In an open void without obstacles, such as pillars or stoppings, the filling occurs in a circular fashion (7). However, in actual conditions, large mine openings are not usually encountered; the honeycomb pattern of room-and-pillar sections is more often typical. In a table-sized mine model simulating a typical arrangement of rooms, it was shown

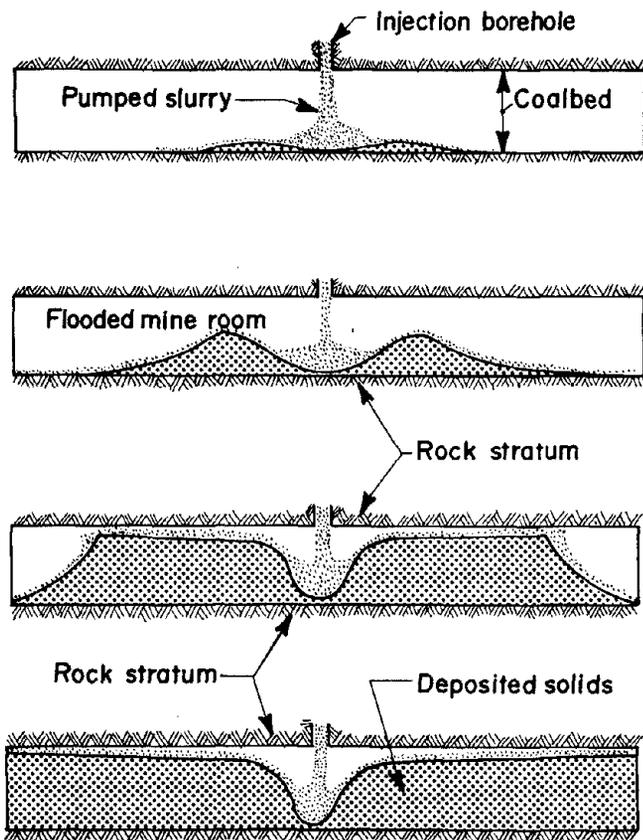


Figure 3.—Idealized hydraulic backfilling process (7).

that the flow of the slurry usually develops in one direction until the resistance to the flow becomes so great that another flow path is developed (8). This process is repeated until nearly all of the mine openings are filled or the slurry cannot be pumped any farther. Figure 4 represents the deposition pattern of hydraulic backfill in a model mine (8).

The lateral extent of the fill is determined by the energy of the pumped slurry and the condition of the mine. As the mound of fill builds outward into the mine, the flow channels between the mound and the mine roof become longer and more serpentine; therefore, the resistance to flow is increased. When this resistance becomes so great that the slurry can no longer transport the material beyond the fill, "refusal" or the limit of the backfilling is reached. In practice, it is extremely difficult to estimate the volume of fill needed for a specific area because of the uncertainty concerning the configuration of the mine and the tendency of the slurry to cut a channel through the existing fill and flow unrestricted into other parts of the mine (9).

The particle size distribution is variable throughout the fill; this is due to the changing velocity of the slurry. As the velocity of the slurry is decreased, the heavier particles

fall out of suspension. The smaller and lighter pieces of fill material are then carried farther from the injection point and deposited. The resultant fill is therefore stratified based on the velocity of the slurry.

Where the dip of the coalbed exceeds 40° , a barrier or bulkhead may be needed to prevent large-scale movement of the slurry down-dip away from the planned flushing area (5). This technique is often called controlled flushing. The barriers, bulkheads, or cutoff walls constructed across the mine openings are permanent obstructions designed to limit the flow of backfill material or to contain the material within a specific area. These obstructions are made from grout or gravel and can be installed remotely or from within the mine if access is available. The construction of these items is similar to the construction of several of the point supports, which will be discussed later in this report.

High-volume pumping is normally used on very large backfilling projects to place mine refuse or other available material into the mine void and spread it over a large area. It is typically used in mine areas that are known to be open and have few obstructions. The high volume of water and its velocity at the injection point ensure a wider spread of material than in any of the other methods since the energy of the slurry is much greater. High-volume pumping requires a large quantity of water and fill material. A minimum of 500 gpm is necessary, and as much as 8,000 gpm may be required depending on the size of the boreholes and the type of material (5). Fill materials with higher densities require a greater amount of flow to keep the solids in suspension in the slurry mixture.

The advantages of high-volume pumping are that a large amount of material can be placed in a short period of time and that low-cost, locally available backfill material can be used. The disadvantages of the system are the costs of establishing a central slurry mixing plant, a pipeline network, and a high-volume water supply. Furthermore, the addition of water to a formerly dry mine may cause sloughing and weakening of the pillars, floor, and roof.

In low-volume pumping, a combination of slurry and low-volume pumps is used to carry the material to the injection point. The water requirements are 100 to 500 gpm, about 10 times lower than for high-volume pumping (5). The advantage of the system is the typically small, portable, construction-type pumping equipment, which causes little congestion within the project area. The disadvantages are longer material placement times; the need for additional water, leading to adverse effects in the mine; and the need for additional boreholes, because the material spreads a limited distance from the injection point.

Gravity feed systems do not use mechanical pumps to transport material. The solids are dumped into a hopper, which feeds to a stream of water entering the mine. The

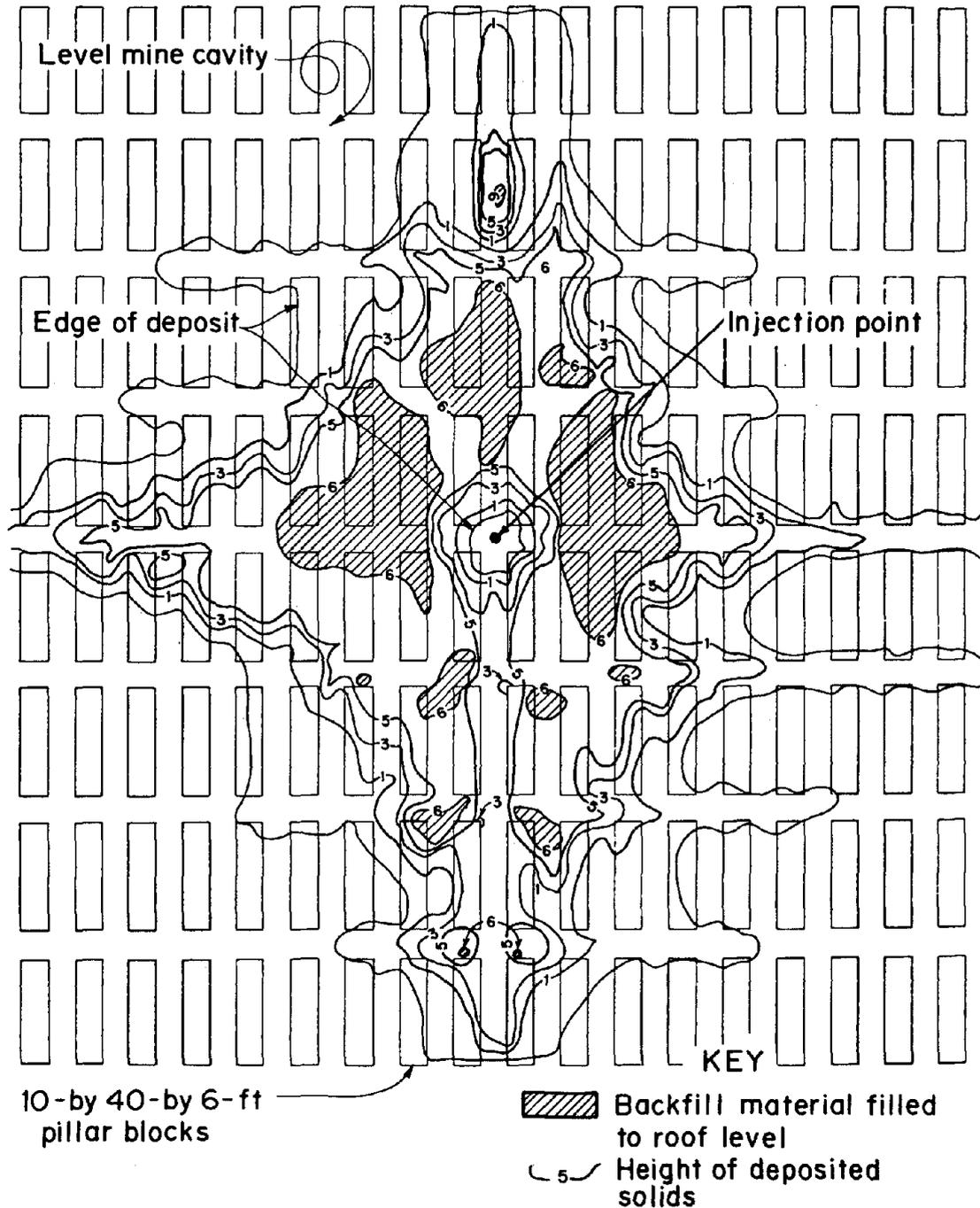


Figure 4.—Hydraulic backfill placement in model mine (8).

capacity of this type of system is very low and is limited by the type of material and the size of the borehole. The advantages of this system are the low operating cost and the small amount of required equipment. The disadvantages of this system include the following: material is not transported laterally beyond the injection point, injection rates are very slow, and filling the void without blocking the injection pipe is difficult.

An extensive amount of equipment is needed when pumping methods are used. In addition to a large supply of water and fill material, a screening and mixing plant and a network of pumps and pipelines to transport the slurry to the injection borehole or supply water to the mixing plant are required (fig. 5). All of this equipment should be sized in accordance with the rate of backfilling desired.

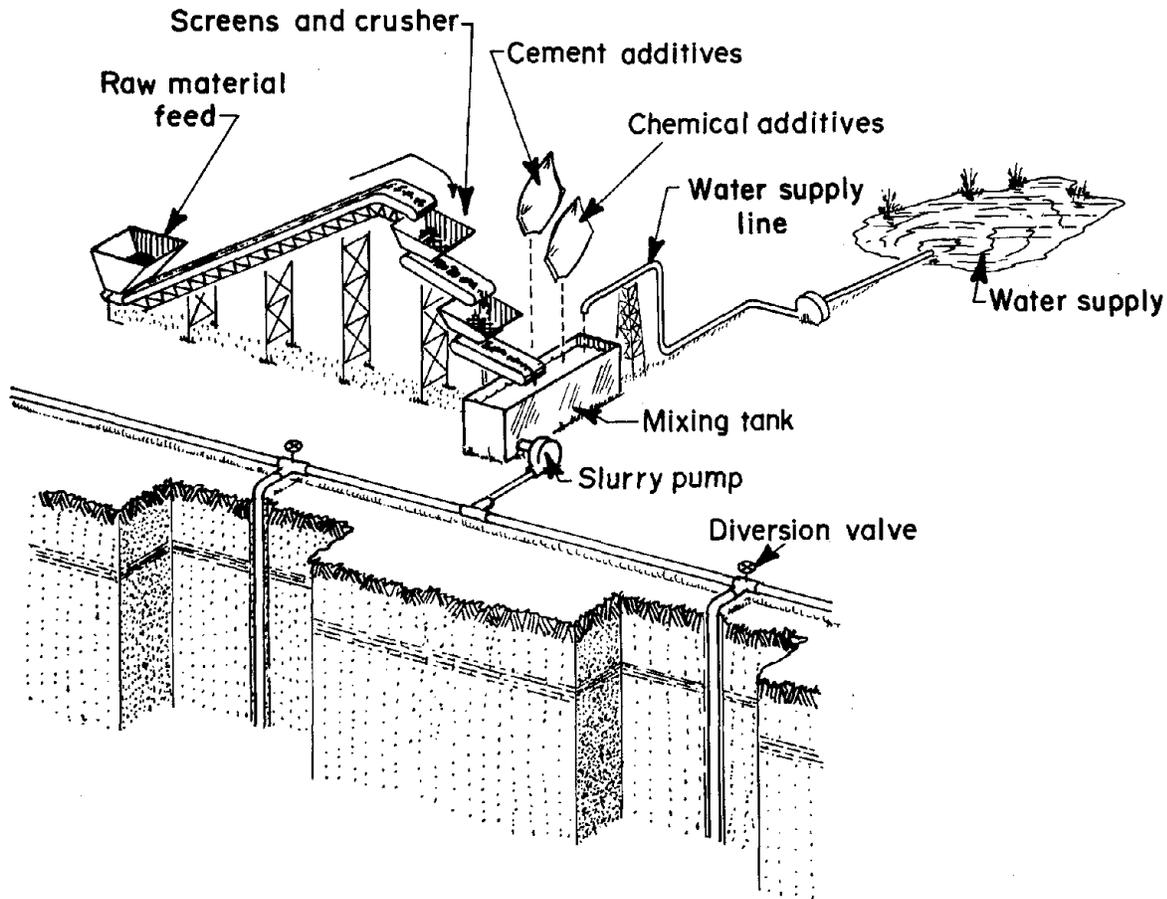


Figure 5.—Hydraulic backfilling equipment.

The greatest difficulty with hydraulic flushing is the control of the material in the mine. Boreholes are typically used to monitor the flow of the backfill during the flushing process. Downhole video cameras and/or observation wells are used to determine the extent of the backfill and the head pressure of the backfill at various locations during backfilling operations. However, because the configuration of the mine void is typically unknown and the opening is often blocked by fallen debris or abandoned equipment, the backfill material frequently flows in unexpected directions. Without knowing where the material has been transported in the mine it is impossible to determine the support capacity of the backfill.

In several cases, an amount of fill material that exceeds the estimated volume of the mine void has been pumped into a borehole without a pressure increase that would indicate filling of the void (5, 9-11). A recent study found that at some sites where the flushing operation was considered a success the backfill material did not completely fill the void (12).

PNEUMATIC STOWING

"Pneumatic stowing" refers to a specialized form of pneumatic conveying in which mine backfill material is transported into a mine and "stowed" or placed into the void. At the present time, the technology has not been developed to the point where pneumatic stowing is generally accepted as a viable method of subsidence control. However, the problems are being overcome as its use becomes more common. The advantage of pneumatic stowing over hydraulic techniques is the elimination of water-related control problems. However, the fill material, with current technology, cannot be carried a great distance from the nozzle. This limitation prevents pneumatic stowing from being used as a truly area-wide technique. Furthermore, this method can only be used in dry mines.

The pneumatic stowing system is a more recent development than hydraulic flushing. Recent research indicates that it may be possible to pneumatically project material up to 80 ft beyond the injection site (4). Material placed

using pneumatic methods can achieve a fairly high degree of compaction and good contact with the mine roof. The drawback to the system is the potential for excessive abrasion of the injection nozzle and elbows, which causes failure of the equipment after only a relatively small amount of material has been stowed.

There are two methods for pneumatic conveying (3). One is dense phase, in which the pipeline is nearly filled with material that is moved as a fluid with low-velocity air pressure in slugs. The other method is dilute phase, in which there is less than 5 pct fill material in the pipeline and it is moved at relatively high velocity as a fluid.

In general, the mining industry uses dilute phase conveying. However, some mines use rock dust systems, which utilize dense phase transport. The two major applications of pneumatics in the U.S. mining industry have historically been hoisting cuttings from shaft and tunnel boring operations and stowing.

There are few published cases of remote pneumatic stowing operations. No personnel are present at the discharge end of the pipeline during remote stowing

operations, and all equipment used in the mine must be installed through a borehole (fig. 6). The available information indicates that the majority of remote pneumatic stowing operations were unsuccessful either because of a lack of site-specific information or from the inability to direct the trajectory of fill material (3, 13).

Research is progressing at the Bureau to improve the capabilities of pneumatic stowing systems. The problems with the systems include excessive wear on the injection pipeline, especially at the elbows and transition points, and inability to project the material into the mine void once it is injected down the borehole. Various configurations of collapsible elbows with nozzles are under development to redirect the material from the vertical injection pipe out into the mine void in a nearly horizontal fashion (fig. 7). The function of these elbow-nozzle assemblies is not only to redirect the material into the mine but to reentrain the material into the airstream. Reentrainment ensures maximum trajectory by placing the fill material above the airstream exiting the nozzle rather than below the airstream. It is calculated that if the research is successful

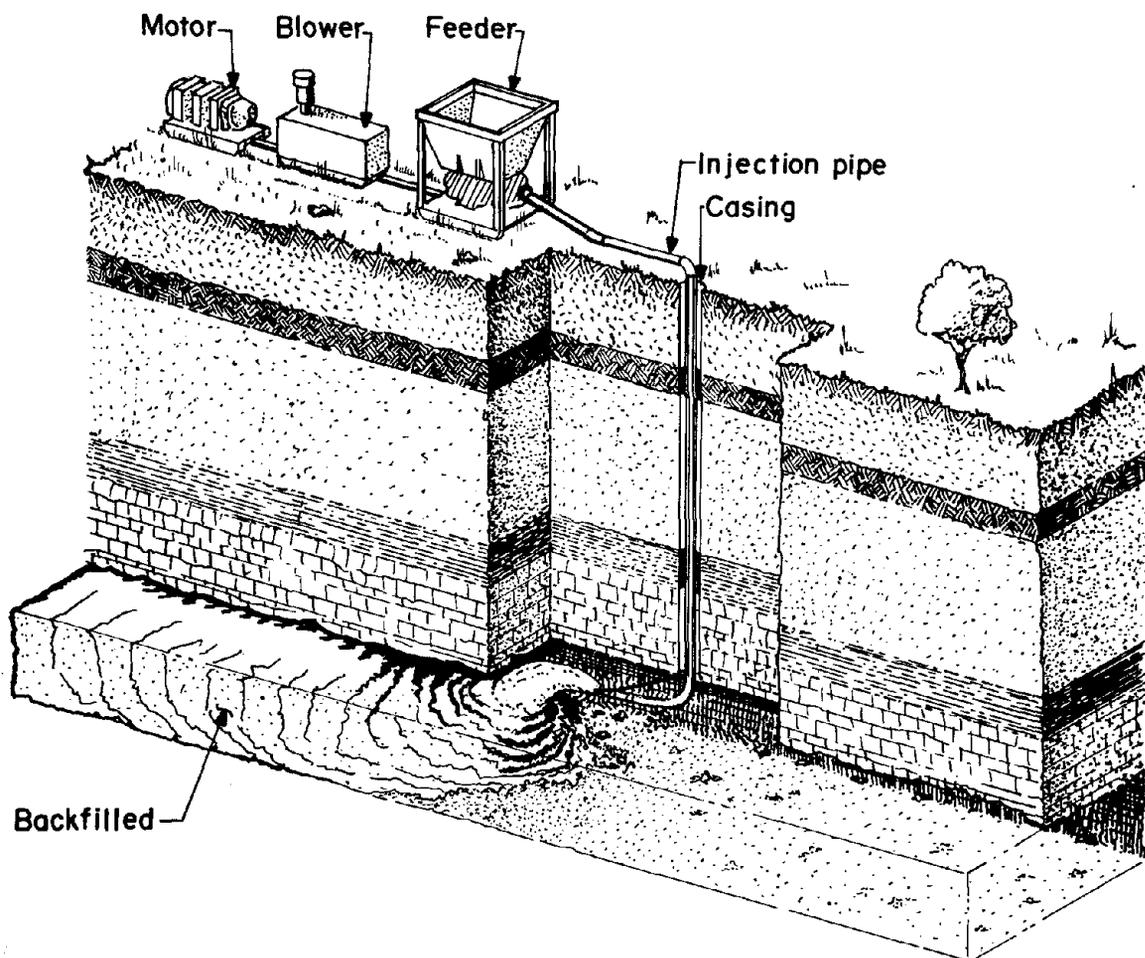


Figure 6.—Idealized pneumatic stowing process.

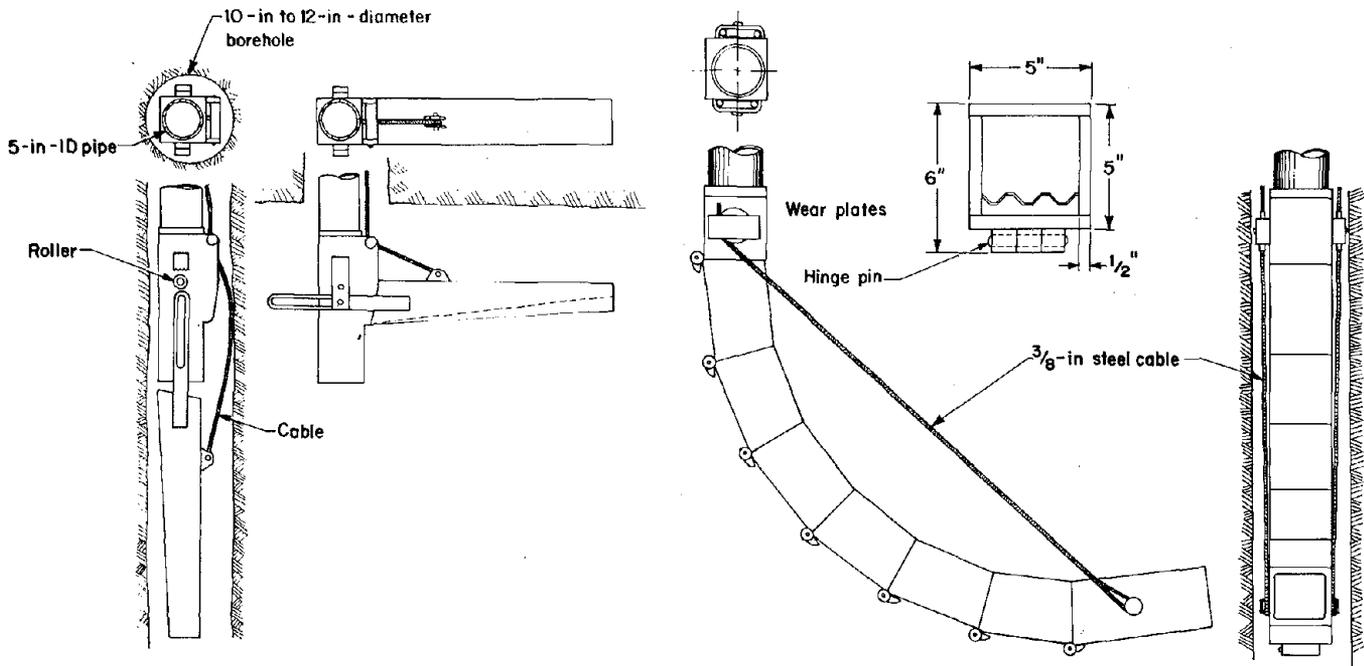


Figure 7.—Remote stowing elbows. Left, Short-radius elbow with blind T; right, segmented wide-radius elbow (4). (ID = Inside diameter.)

elbow-nozzle assemblies of this type may be capable of projecting the fill material as far as 100 ft in a 6-ft-high mine entry (4).

A different type of elbow-nozzle assembly is also being researched. This type is called the pneumatic ejector (14). The pneumatic ejector consists of a high-pressure air nozzle fitted to an elbow at the end of the injection pipe (fig. 8). The high-pressure nozzle in the elbow creates a supersonic airstream (in excess of 1,600 fps) across the bottom of the injection pipe. As the backfill material falls through the injection pipe into the mine, a transfer of momentum occurs. The result is a combined stream of fill material and air moving horizontally at a velocity of 100 to 500 fps. This system was tested by the OSMRE and was found to be capable of projecting the material as far as 50 ft horizontally depending on the height of the mine opening (15). Theoretically, a 2,000-cfm airstream at 100 psi will project sand material as far as 90 ft in a mine void 7.5 ft high. The advantage of this system is that air velocity turns the fill material, thereby eliminating the abrasion on the injection equipment. Research is continuing, and it is expected that several different types of elbow-nozzle combinations will be developed.

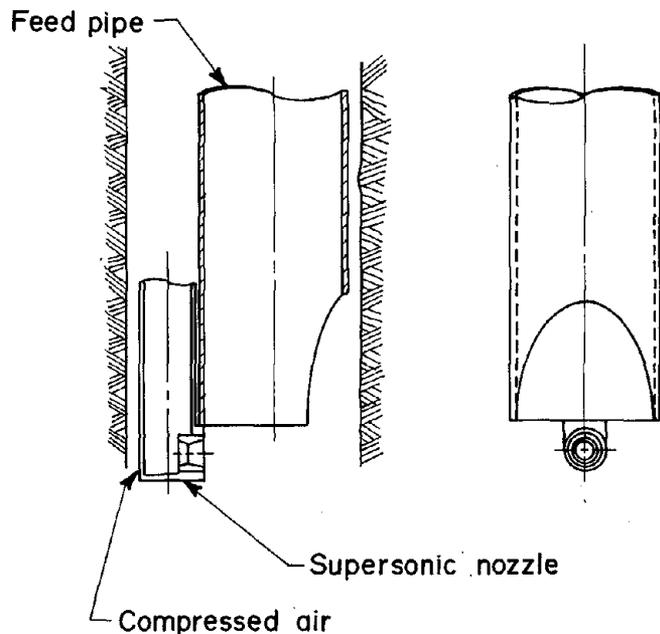


Figure 8.—Pneumatic ejector.

The principal equipment needed to perform pneumatic stowing is the same as for any other pneumatic conveying activity: a power pack, a compressor or blower, and an air-lock feeder (fig. 9). The differences between various applications are the quantity of air required, the pipe size, and the air pressure. These are all functions of the weight of the material to be conveyed and the length and elevation of the delivery pipeline.

The air supply for pneumatic stowing operations is provided by either a positive displacement blower or compressor. The majority of the pneumatic backfill equipment in the United States use rotary lobe positive displacement blowers, usually capable of supplying 3,000 to 5,000 cfm at 14 to 18 psi. Pneumatic stowing machines that are powered by compressed air are available and have been used extensively in European mines where up to 100 psi of air at large volumes is readily available.

The chamber air lock, screw feeders, and rotary air lock are three types of air-lock feeders that can be used to introduce the backfill material into the airstream without excessive loss of air. The rotary air-lock feeder is by far

the most popular feeder. The size of the chamber air lock and the lack of positive sealing capability of the screw feeder make them less desirable. The rotary air-lock feeder is essentially a drum with screw-shaped pockets around the outside. Material is fed into one pocket at a time. As the drum rotates, the pocket is sealed in the housing and dumps its load into the airstream while another pocket is being filled. The rotary air lock is a high-maintenance item because of the abrasiveness of the backfill material.

The pipelines, elbows, and nozzles for pneumatic stowing are also high-wear items. In horizontal pipelines, pipe wear is fairly rapid and is most often found on the bottom of the pipe. Because of the excessive wear, the pipelines are made of hardened steel pipe. The pipe is rotated regularly to achieve longer life. Ramps are sometimes built into the pipeline to lift the material from the bottom of the pipe and reentrain it into the airstream rather than letting it slide along the bottom of the pipe. The wear on vertical pipelines is much less, usually only 10 pct of the wear found on horizontal piping.

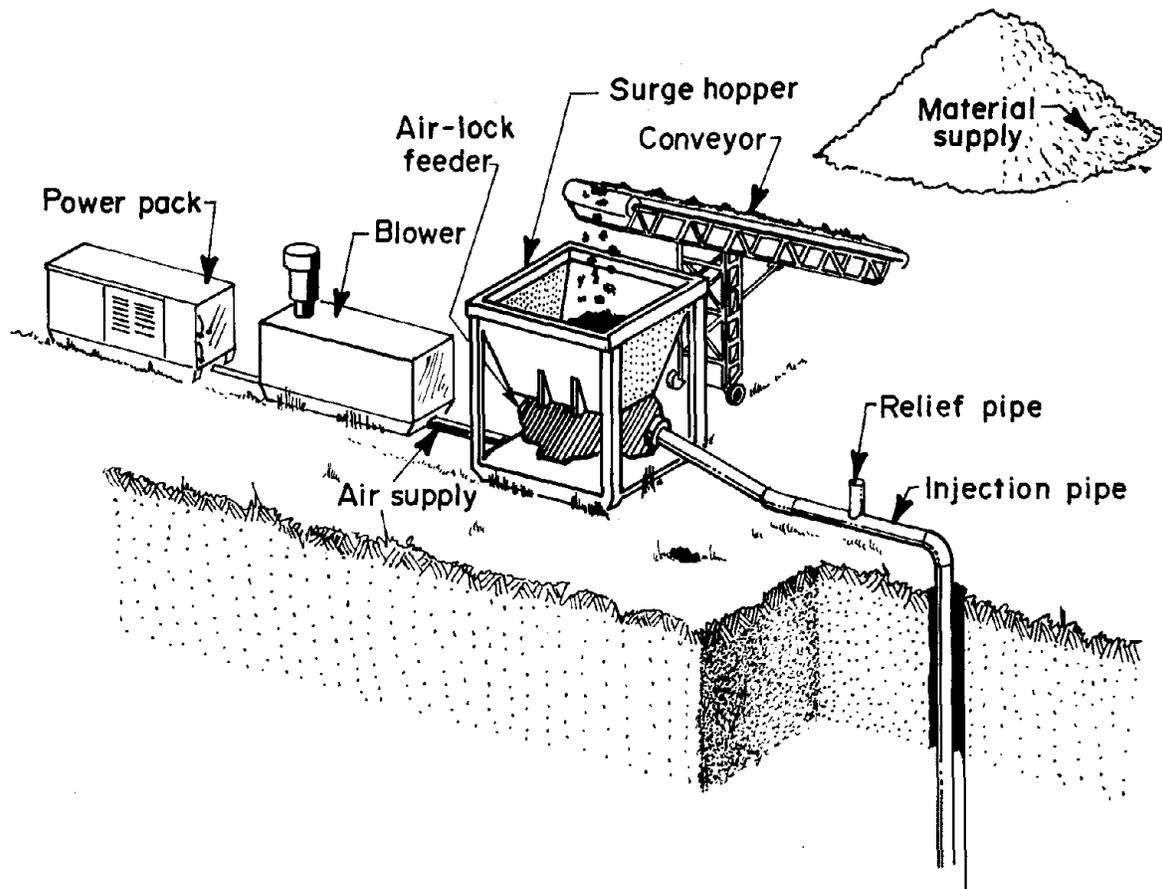


Figure 9.—Support equipment for conventional pneumatic stowing.

Elbows are required at places where the pipeline changes direction. The elbows must be specially designed to maintain the material entrained in the airstream and must include replaceable wearing portions. In a well-designed elbow, there is an impact section at the entry and a transition piece to accelerate the flow at the discharge. The liners of the elbows are typically manufactured from tool steel of at least 650 Brinell hardness and sometimes have a W-shaped cross section to maintain airflow beneath the entrained material and to reduce the wearing surface (4).

At the discharge end of the pipeline, a nozzle or deflector plate is usually used to direct the fill material. The deflector plate is usually a steel plate or a section of a pipe cut lengthwise. Nozzles have been used to concentrate the stream of material coming from the pipeline and direct the trajectory without moving the pipeline. It has been suggested that the nozzles would increase the degree of compaction achieved by directing all of the force to a smaller target area (16).

EXCAVATION

Excavation or daylighting of the mine void is a technique that can be used for shallow mines. This type of remedial action is similar to a surface mining operation. The area affected by subsidence is excavated to mine level, the remaining coal is removed, and the area is then back-filled to the original grade. This technique is suitable only for areas where little surface activity is present and where the surface topography would require extensive regrading because of the effects of subsidence. The cost of this method is extremely high, especially in areas that are not accessible to heavy surface equipment and are limited by environmental constraints.

POINT SUPPORT TECHNIQUES

Point support methods are used in areas where an analysis of the subsurface conditions indicates that the in situ support would not be sufficient for long-term stability. These methods are typically used with the intent of supporting only a small area such as a structure or a specific surface feature. These methods are extremely cost effective when applied correctly. However, the ability to accurately locate the artificial supports is limited by a lack of knowledge of the mine void and overburden characteristics.

GROUTING

"Grouting" is a general term that typically refers to the use of a fly ash-cement mixture as the backfill material.

BLASTING

Blasting to reduce the overburden to rubble and to collapse the mine roof in a controlled manner has been used as an area-wide subsidence abatement technique in one demonstration project. This project was located at the Urlacker Mine site near Dickerson, ND. This demonstration project was performed at a shallow mine site (30 to 50 ft of depth) and was considered a success. The blast did induce caving that extended to the surface, and the area has had no reported additional settlement or subsidence since 1983, when the project was concluded (17).

The concept of blasting to prevent subsidence is based on the fact that as a rock mass is reduced to rubble, it swells to fill a larger volume. Theoretically, the magnitude of the swelled volume is calculated to be equal to or slightly larger than the volume of the mine void. In deeper mines the rubble zone is formed just above the coal seam, similar to a longwall operation; however, in a shallow mine the rubble zone extends to the surface. The relationships among the open mine voids; the depth to the coalbed; and blast design considerations, such as charge weight, spacing, and delay times, are not well understood. In addition, the swell factors and the crater formation process are not well known for coal measure rocks.

The concerns with this type of reclamation include problems with blast vibrations in urban areas and environmental concerns such as damage to ground or surface water sources. Additional research is underway to address these concerns and to provide additional technical information.

Generally grout is placed as grout columns, which consist of small cones of cemented backfill material extending from the mine floor to the roof directly beneath the injection borehole. The addition of cement to the backfill increases the strength of the material. The support capacity of grout-stabilized backfill is considered to be very good, and grouting is used regularly as a backfill method in small areas.

Historically, grout columns have been constructed from 6-in-diameter boreholes filled with crushed rock or gravel from the mine floor to the surface, which has been pressure grouted to form a permanent support. Newer methods utilize quick-setting, low-slump grout pumped through 2- to 6-in-diameter boreholes to completely fill small areas of open mine voids or to form self-supporting grout columns (fig. 10).

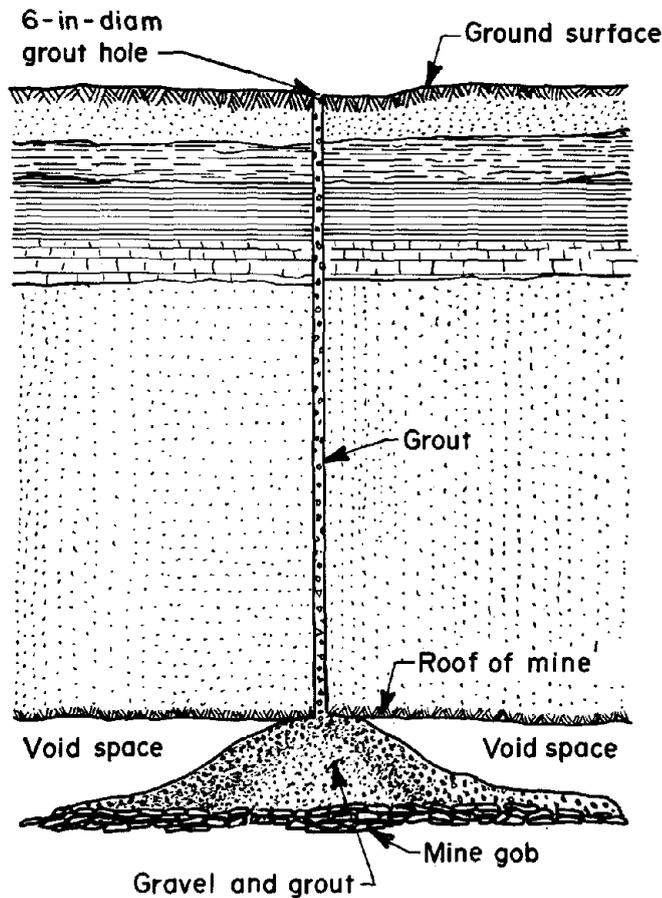


Figure 10.—Typical grout column.

Grout can also be used in areas where caving has already occurred. In pressure grouting, grout is forced into the voids at a pressure on the order of 1/2 psi per foot of depth. This method not only fills the mine void but penetrates and stabilizes the fractures in the overburden that occurred as a result of subsidence (5). Figure 11 shows an idealized use of pressure grouting to stabilize the rubble material resulting from a roof collapse and the resulting fractures in the overlying rock mass.

Grout mixtures vary according to the requirements of an individual project. For most applications, mixtures of portland cement and fly ash are sufficient, and these mixtures provide inexpensive and reliable fill material. Mixtures of 1 part cement to 3 to 9 parts sand or fly ash are typical (18). Chemical additives are available to modify the penetration and setting abilities of the grout mixtures. Chemical grouts are typically several times more expensive than cement grouts.

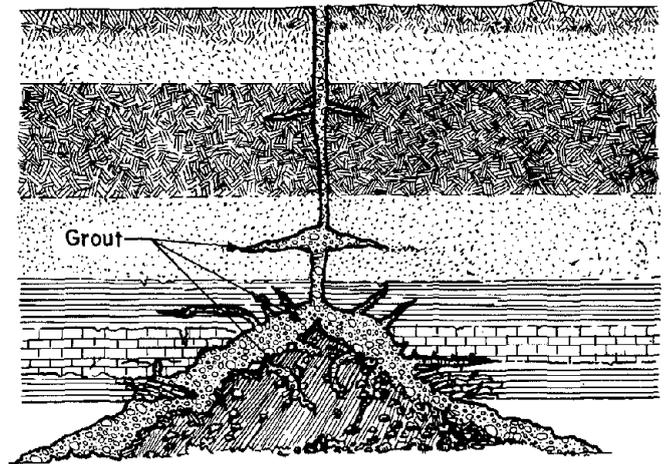


Figure 11.—Pressure grouting to stabilize collapsed overburden.

As with hydraulic flushing, the drawback to grouting is an inability to monitor placement and to determine areal distribution and percentage of mine roof contact.

A new technique for the construction of grout columns is the use of sodium silicate additive to the grout mixture (19). In this technique a chemical additive is applied to the outside of the grout as it is discharged. The sodium silicate reacts with the surface of the grout stream, forming a skin of calcium silicate that acts as a barrier. This allows the grout to form a self-supporting column. Figure 12 illustrates the device for applying the sodium silicate to grout as it is entering the mine. The sodium silicate technology can be used in both dry and flooded conditions. In dry conditions the calcium silicate skin contains the high-slump concrete, and in wet conditions the skin prevents water from penetrating the grout mass and diluting the mix. An example of the shape of a grout column using sodium silicate technology compared with an average grout column is shown in figure 13.

The strength and capability of grout columns made by this method have been tested by the OSMRE, and the columns have been proven to be effective (19). This technology should increase the use of grout pillars as a means of support, because it is now possible to control the placement of the grout.

Grout bags are another way to control the spread of grout during the formation of grout columns. The bags are placed into the mine void through a 6- to 8-in-diameter borehole. The grout bag, once installed in the mine, contains the grout pumped from the surface so that an

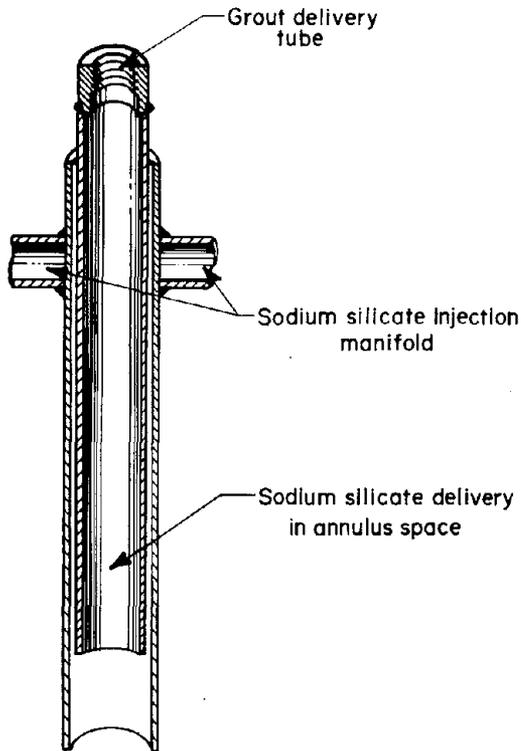


Figure 12.—Sodium silicate injector.

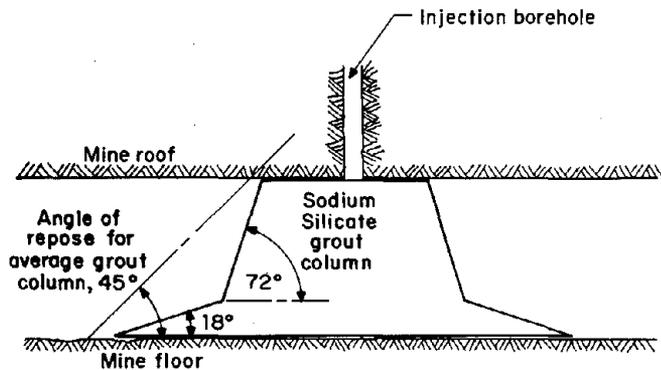


Figure 13.—Idealized grout column using sodium silicate technology.

artificial pillar of a specific size and shape can be remotely constructed. These bags have had limited application and have shown great promise (20). Further analysis and testing of the concept is required before the bags can be used on a regular basis.

PIERS

In-mine piers are simply in-mine supports to augment existing coal pillars. They are made from concrete, masonry, and in some cases timber cribbing. Although this method has been used for support in active mines throughout modern mining history, in-mine piers are rarely used in abandoned mines, since it is necessary to physically enter the mine void to install them. The primary application of support piers is to support a specific surface structure. Their use is generally limited to room-and-pillar mines, and the piers are usually constructed immediately after mining.

DEEP FOUNDATIONS

Deep foundations or pile foundations are limited to the protection of individual structures. These foundations are large-diameter drilled piers (usually 8- to 24-in diameter), which are drilled through the mine and bear on the firm strata beneath the mine. Such methods are used to found a structure on the competent rock beneath the mine opening (fig. 14). In general, deep foundations are not used at sites where the overburden thickness exceeds 100 ft. This method is limited almost exclusively to new construction.

The piers are steel casings driven from the surface into the rock beneath the mine and then filled with concrete. The surface structure is then constructed on beams supported by the piers.

BULKHEADS

Bulkheads are not a means of support, but they are used as barriers to control the flow of the backfill material in the mine. They are built between existing pillars so that the area to be backfilled is completely surrounded. In general, bulkheads are made from grout or gravel. They are constructed by drilling injection boreholes closely spaced across the known mine opening. The spacing of the boreholes must be close enough that the cone-shaped deposition spreads into a solid barrier rather than leaving void spaces near the mine roof.

Gravel bulkheads are preferred when used in conjunction with hydraulic flushing operations. The porous nature of the gravel allows the water in the slurry to pass but retains the solids (21).

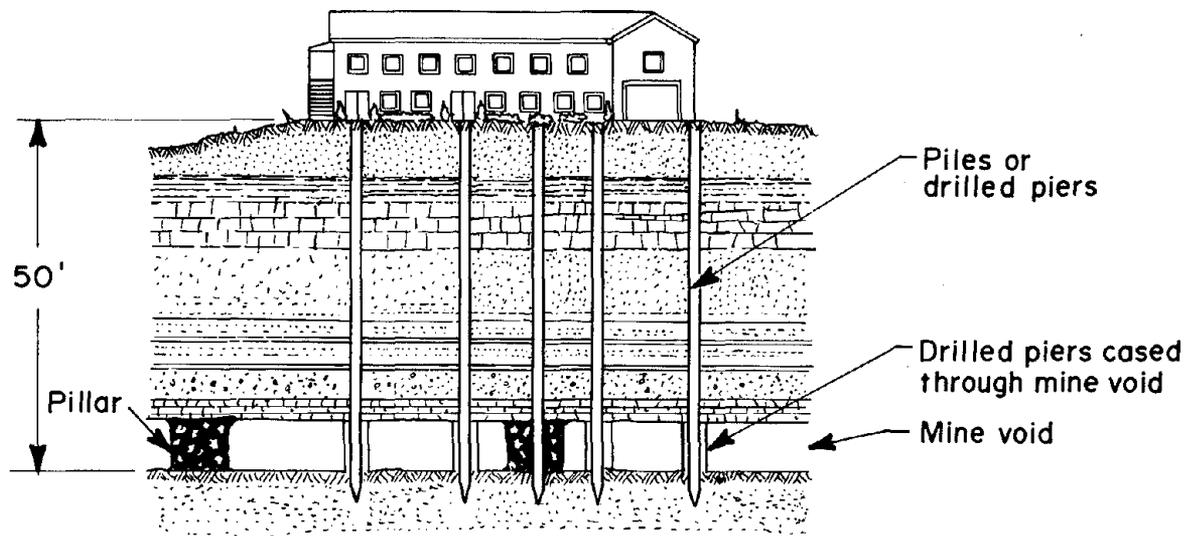


Figure 14.—Deep foundations for subsidence control.

TYPES OF BACKFILLING MATERIAL

The material used in a mine stabilization program is determined by local availability, transportation costs, and desired engineering properties. The most common materials used include waste rock; coal processing waste; fly ash; and prepared aggregates such as sand, gravel, or crushed rock. Almost any type of material can be used, as long as it is environmentally safe and its consistency is such that it can be easily injected into the mine and yet provide a positive support.

The engineering characteristics of a backfill material are very important to the long-term success of a subsidence abatement project. The material must be durable, in the sense that it will not degrade during handling or pumping; nonabrasive, because the wear on the system must be limited to the extent economically possible; strong, for long-term support; and stable, so that it will not become weak when exposed to the mine conditions. Many different types of material have been tried with varying success. However, the following remain the most common backfill materials.

PROCESSING WASTES

Processing wastes from local plants where rock is being crushed for aggregate can provide inexpensive fill material in the form of "off-spec" rock. This material often has sufficient engineering properties but does not meet highway sizing requirements. Limestone dust from such plants is

a highly desired mine fill additive because of its pozzolanic (cementing) properties.

MINE REFUSE

Waste product created by coal preparation plants consists of coal, clay, shale, and other rock. The bearing strength is low if the waste product contains a high percentage of clay particles. Therefore, this material is mostly used for stabilization of dry, shallow mines where the weight of the overburden is relatively low and roof falls are the major failure mode. "Red dog" or burned mine refuse has a greater bearing capacity than unburned refuse and can also be used as backfill. However, red dog is very abrasive and does not move freely once it is released from the end of the injection pipe.

FLY ASH

Fly ash and bottom ash are noncombustible residues that result when coal is burned. Fly ash is a fine-grained, lightweight aggregate composed of small globules of glass-like material. Fly ash is easy to transport pneumatically and in slurry form can be transported long distances in mine voids. Though fly ash often has natural pozzolanic properties, it is necessary to mix it with cement to develop significant bearing capacity (17). Bottom ash is coarse and heavier than fly ash. Bottom ash is better than fly ash for mine stabilization but is normally more expensive.

PREPARED AGGREGATES

Prepared aggregates are the preferred types of backfill material to use in a flushing or pneumatic stowing operation because the engineering properties of sand, gravel, and crushed stone are well documented by the roadway and heavy construction industries. The drawback to these materials is their cost. Depending on the location, prepared aggregates can cost up to four times as much as other backfill materials.

The environmental impact of backfilling abandoned mines with waste materials is not well understood. The most obvious danger is the contamination of ground water supplies that come in contact with backfill material. For example, coal refuse and fly ash may contain high levels of contaminants such as aluminum, arsenic, boron, cadmium,

chromium, copper, iron, lead, manganese, mercury, nickel, selenium, vanadium, and zinc. Research indicates that when this material comes in contact with water these elements go into solution, thus contaminating the water. There is the possibility that other backfill materials may also include one or more of these contaminants. The extent of the assimilation of these pollutants into the natural environment is a function of many variables that are unique to each site. To date, the documented research supports the belief that backfilling is not hazardous to the environment. However, the Environmental Protection Agency (EPA) regulates and classifies backfilling material using criteria stated in the Resource Recovery and Conservation Act and other health-related criteria. Research is currently under way at the EPA to identify the environmental impacts of backfilling.

EVALUATION OF PAST SUBSIDENCE ABATEMENT PROJECTS

Investigations have been performed to measure the results of a number of area-wide mine backfill projects. The majority of these projects, however, were conducted as a method to confirm the location of the fill material, and few or no tests were performed to evaluate the supporting capability of the backfill. One recent report by OSMRE does in fact evaluate the performance of four past subsidence abatement projects that used hydraulic backfilling in terms of lateral and vertical extent of the fill and the engineering parameters of the fill, i.e., grain size distribution, strength, and in situ bearing capacity (12). The sites evaluated were Green Ridge Demonstration Project, Scranton, PA; Farmington Subsidence Abatement Project, Farmington, WV; Watson Hill Subsidence Abatement Project, Fairmont, WV; and 70th Street Subsidence Project, Belleville, IL. All of the projects were demonstration projects sponsored by the Bureau in the 1970's. The methods and results of the first two were documented in Bureau reports.

The testing conducted at these sites was standard engineering practice for geotechnical investigations of subsidence-prone land, with the exception of the use of a specialized tool for the determination of the in situ bearing capacity of the backfilled material. Core samples were taken at various locations above the study sites, and split-spoon samples of the fill material were recovered. The general findings of the OSMRE report are as follows:

Backfilling of mine voids was very dependent on the configuration of the mine. Some portions of the mine void received very little fill material. This was presumed to be

due to roof falls, stoppings, or other debris that may have blocked the flow path of the backfill material into the void.

In mines that were considered to be successfully backfilled because of the significant amounts of material that were deposited, a void space of more than 1.0 ft was left between the roof of the mine and the top of the fill.

The flow pattern was not the radial distribution that Whaite and Allen (6) and Carlson (7-8) had described in reports on modeling hydraulic backfilling. Sieve analysis and observations of the bedded character of the backfill indicated that the slurry flowing from the injection point settled in the same manner as sediment in stream channels, forming bars and graded deposits. The fine material in the slurry was segregated from the coarse material and was transported farther from the injection point.

Large concentrations of water-saturated fine material showed very low compressive strengths and the material was determined to be plastic enough to yield when subjected to lateral or horizontal pressures.

In mines where coarse coal refuse was used as the backfilling material, degradation of the clays and shales was apparent. This suggests that backfill that contains large portions of these materials will randomly break down into finer fragments in a saturated environment and will be insufficient to support the overburden.

These findings cannot be applied universally to all remote hydraulic backfilling projects, but the problems found at these sites are consistent with the concerns of those working in the field. Discussions with individuals who have drilled into backfilled underground mines for reasons other than evaluation of the fill indicate that voids and very soft fill material are not uncommon.

SUMMARY AND DISCUSSION

Backfilling of mine voids is the most common method of stabilization used to abate subsidence and protect surface structures. The state of the art of mine backfilling is much the same as it was 10 to 15 years ago. In-mine methods are the most well developed and are the most effective means of constructing support. However, in abandoned mine areas, access to the mine void is rarely possible. Therefore, it is necessary to use remote or blind backfilling methods.

The most common method for the placement of backfill material has historically been hydraulic flushing, either by in-mine or remote methods. These have been area-wide projects in which several acres or more have been stabilized. Pneumatic stowing appears to be increasing in popularity as the technology advances. Other subsidence abatement techniques are available and may be more appropriate under different conditions. These techniques include the use of point support methods, which do not completely fill the mine void, but offer protection to small surface areas and surface structures.

At any location where a potential subsidence problem may exist, the primary task is a thorough investigation to determine the nature and extent of the subsidence problem. It is necessary to gather information on the condition of the overburden, the mine roof, the mine floor, and the mine pillars. Knowledge of the size and condition of the mine void is necessary to effectively design remedial measures to protect the surface. Historically, large area-wide hydraulic flushing methods have been considered the only way to fill the mine void with material to arrest the collapse of the mine opening. However, the development of improved methods for site investigations, the improvement in pneumatic and grouting technologies, the increase in the use of point support methods in emergency subsidence actions, and the increase in the cost of subsidence abatement actions has forced the industry to consider new or improved support methods.

Hydraulic flushing remains the only cost-effective method for backfilling a large area of unstable underground mine void. The reasons for using the area-wide approach are related to the type of subsidence, the size of the area affected, and more importantly, the knowledge of the site conditions. In areas where much is known about the geology, the mine configuration, and the condition of the mine, a specific remedial design can be made. In areas where little is known, area-wide methods are the only choice.

In areas where the cause of the subsidence can be pinpointed, a point source method can be applied. In some

cases, a number of point support structures may be necessary to strengthen a large area. Using point source methods is thought to be more cost effective than using area-wide methods if there is sufficient information to provide a sound remedial design.

The point source method most often used is the grouting technique. The grout mix used varies depending on the intent of the project. Where very good subsurface information is available, pinpoint drilling can be performed and low- or no-slump grout can be pumped into the void to provide the support needed in a specific area. As the uncertainty of the subsurface information increases, the size of the area into which the grout is pumped is increased. Grout additives such as foaming agents, plasticizers, or surfactants are used to meet a specific need, such as a slow setup time or increased strength. Using these additives significantly increases the cost of the project.

Pneumatic stowing may be an inexpensive alternative to grout in a dry mine. Pinpoint drilling as used for grouting could be utilized to locate the injection pipe near the collapsing section of the void. Ground support could then be built by directing the trajectory of the fill material.

Other methods are inappropriate for the majority of AML situations. Methods such as deep foundations or drilled piers are more suited to new construction than the mitigation of damage in a subsidence-prone area. Similarly, the blasting method may not be acceptable in urban areas. However, explosives are used regularly in urban areas for other purposes, and if the blasting method is proven to be a viable method for the abatement of subsidence, blasting could possibly be used in urban areas with proper care.

The development of methods for the abatement of AML subsidence has progressed only as fast as the need for new methods. Until recently the need was not a priority of many city planners. As the frequency of subsidence events has increased, so has the awareness of the lack of effective methods to abate subsidence. Parallel to this has been the development of techniques to evaluate the subsurface condition at an AML site. As the capabilities to determine the location and the condition of the mine site become more precise, remedial designs will require a variety of backfilling methods. It is clearly demonstrated from past work that it is possible to backfill a mine to an extent that will lessen or prevent subsidence-related damages. Much more research is needed, however, to provide simple, cost-effective solutions.

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