Pumpable roof supports: an evolution in longwall roof support technology

T.M. Barczak and S.C. Tadolini
Senior research engineer and chief rock safety engineer, respectively, Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, Pennsylvania

Abstract
Pumpable roof supports provide an alternative approach to secondary support in underground mining. Unlike all other supports that are either partially or fully prefabricated prior to being transported into the mine, the pumpable support is fabricated in place in the mine entry. This reduces the underground material handling efforts and thus the injuries historically associated with in-mine support construction. On-site fabrication also facilitates application of the support in areas that are inaccessible to transportation equipment such as scoops or rail cars, making it ideal for many bleeder applications. One of the main advantages of the pumpable support is that it fully bridges from the mine floor to the roof, thereby eliminating the requirement of "topping off" the support with wooden wedges or crib blocks that soften most other support responses. This report examines the development of modern pumpable roof support technology and provides a full description of the performance capabilities of each of the support products now on the market.

Introduction

The search for the optimum roof support system continues with more than 50 standing roof support products now on the market for longwall tailgate and bleeder applications. Overall, the Can support manufactured by Burrell Mining Products Inc.[1], shown in Fig. 1, is the most widely used standing support system in the United States for longwall tailgate applications. About a third of the longwall tailgates in the United States are supported using the Can, with the highest percentage found in western U.S. mines, where timber products are scarce and expensive. The Can provides a high-deformation support system and consistent loading through as much as 50% strain, thereby improving ground support in many applications where lower capacity, less stiff and less stable supports, such as wood cribbing, have been utilized. Equally important is the fact that the Can supports are installed with a machine that avoids much of the material handling associated with conventional crib construction.

Despite the success of the Can support, there are some disadvantages. First, the support must be topped off with something, usually timbers, to establish roof contact. This will typically "soften" the support response due to the contact compatibility of the timbers with the uneven roof, requiring wedges or small pieces of wood to provide a tight fit (see Fig. 1). "Soften" means that roof convergence can occur with minimal resistance. When less than full support contact with the Can is achieved, the wood response alone can cause a softer response. Finally, poor construction practices, in which multiple timber layers are placed on top of the Can, may provide hinge points that can also reduce the overall stability of the support system.

There are several different cementitious materials used in pumpable roof support technology. The first modern pumpable roof support installed in the United States was by FOSROC Inc. in the Southern Ohio Coal Company's Meigs No. 2 Mine in southeastern Ohio in 1993. The support employed foamed cement similar to that used in Tekseal seal construction. Today, the most common material in pumpable roof supports is a calcium sulfo-aluminate (CSA) cement, which relies on ettringite formation to provide a high-yield, fast-setting grout. More than 110,000 of these supports have been installed in the past five years in several different mines, primarily in the eastern United States. The CSA material has traditionally been imported from England, contributing to the very high cost of this support technology, but it is now obtained from Mexico by Heitech Corporation. The CSA-based grout has been the most effective and commonly used grout for pumpable supports, but it remains an expensive support system in terms of material costs.

Considerable research has been done during the past few years to develop an alternative to CSA grouts to reduce costs. The Minova Tekpak support uses a high-alumina cement

1 Reference to company name or product does not imply endorsement by the National Institute for Occupational Safety and Health.

Figure 1 — The Can is a commonly used tailgate support in the United States.

Figure 2 — Pumpable roof support in longwall tailgate showing how the support can achieve full contact with mine roof.

instead of the imported CSA cement to provide the ettringite formation. Other products rely on portland-based cements in an effort to reduce the cost of the system. One such support is the Tekpak-P product developed by Minova. Full-scale laboratory testing has shown that the Tekpak-P support is comparable to the supports using CSA grout, but far fewer supports using Tekpak-P material have been installed. The Mesh Pack support developed by Strata Products was successfully demonstrated at a Jim Walters Resource's mine, although the pumping was more difficult and considerably slower by comparison to the CSA systems used elsewhere because the materials had to be pumped from an underground location.

Pumpable roof support technologies were developed to compete with the Can support and overcome some of its deficiencies. Because these supports are filled in place in the mine entry, they eliminate transportation into the mine and material-handling bottlenecks associated with the bulky Can support. They also eliminate the need for a secondary material to establish roof contact (see Fig. 2). The pumpable supports easily conform to the mine roof and floor, providing a stiffer initial response than the Can supports with wood topping. In addition, the pumpable supports provide the potential for limited active roof loading.

By definition, a pumpable support involves the support material being pumped from a remote location to the supported area in the underground mine. The material is some form of cementitious grout, which is typically pumped into a flexible bag that is hung from the mine roof to form a supporting column. The cementitious material and size of support vary depending on the manufacturer and application, but they all share this basic concept.

History of pumpable supports in coal mining

Coal mining applications of pumpable support systems date back to the development of packwalls for advancing longwall operations in European mines. Unlike retreating longwall operations, where the gate roads are developed in advance of the panel mining, in advancing longwall mining the gate roads are developed as the panel is mined as shown in Fig. 3. A fabricated "packwall" is formed to establish a single-entry roadway that is developed in advance of the longwall face and protected from the forming gob. The first system was developed in Germany using anhydrite, which was blown by compressed air to the longwall site. The material would harden on contact with water. Anhydrite has a high compressive strength but does not yield, and these non-yielding packwalls would not work well in weaker strata conditions. This system also required large amounts of compressed air for dispersion of the anhydrite, in volumes not available at these locations underground. The British developed a two-component monolithic pack in which one component, composed of a filler slurry of bentonite and coal fines with water, was pumped by a large reciprocating piston pump to a shuttered packhole behind the face. Meanwhile, the second component, rapid setting cement slurry, was prepared and injected to harden the mass (Kellet and Mills, 1980). An improvement to this system was the addition of accelerators to a prehydrated bentonite-coal slurry waste to improve pumping life.

The first pumpable roof supports for U.S. longwall tailgate applications were installed by FOSROC Inc. (now Minova) at the Southern Ohio Coal Company's Meigs No. 2 Mine in southeastern Ohio in 1993 (Amick et al., 1993). At that time, the only available supports were conventional wood cribbing and concrete cribbing. FOSROC had been doing cavity-filling work in the mine and asked to install a test area using the pumpable (Tekcrib) support. Ten supports were installed in the longwall tailgate and their performance was thought to be an improvement over conventional wood cribbing. At the time, the No. 31 mine had severe problems in a four-entry longwall tailgate, where excessive roof falls in the middle two entries had left only the active tailgate to provide ventilation and secondary escape. Because the area was not readily accessible, the situation was ideal for taking advantage of the pumpable support. Seventy-five Tekcribs were installed in conjunction with mechanical jacks. The tailgate survived without any roof falls. This test demonstrated the flexibility of pumpable supports being installed in inaccessible areas, which remains a major incentive for many applications of pumpable roof support systems.

Despite the success of this initial trial, pumpable supports were not used again until Heitech began installing a new generation of supports at Foundation Coal Company's Emerald

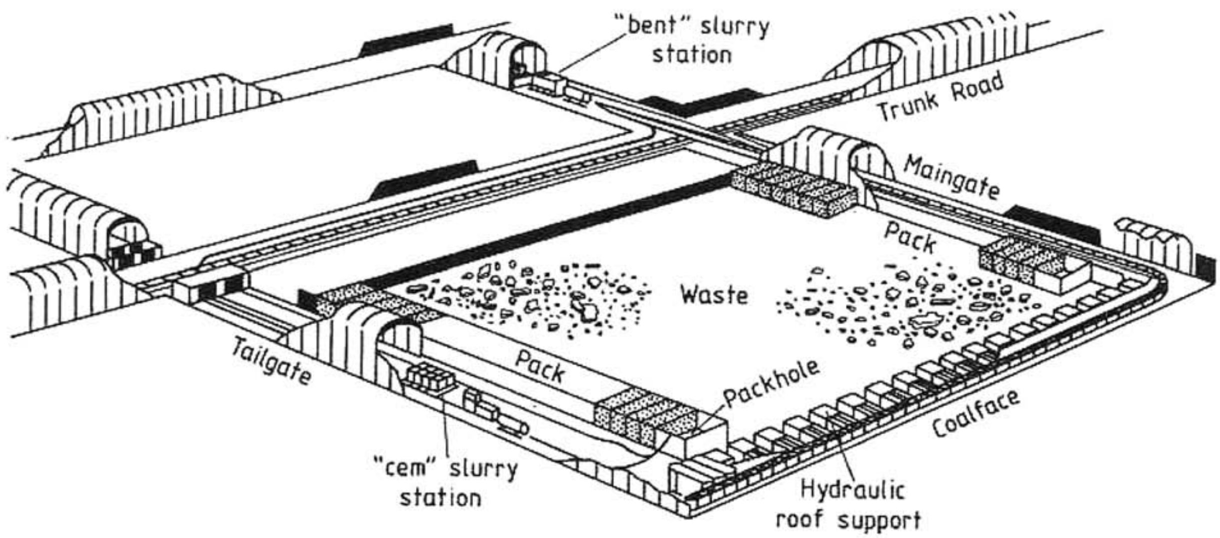

Figure 3 — Packwalls in advancing longwall operations were the first systematic use of pumpable materials for support.

mine in southwestern Pennsylvania in 1999 (Barczak et al., 2003). The supports have provided good ground control in areas where conventional wood cribbing performed poorly in the past. Emerald continues to use pumpable roof supports in both the tailgate and bleeder entries today, and Heitech remains a leader in the installation of pumpable roof support systems in the United States, having installed more than 130,000 supports in 13 different mines (see Figs. 4 and 5) since this initial application in 1999. Micon, in partnership with Minova, has also installed thousands of pumpable cribs in several different mines. The major drawback to increased utilization of this support technology has been the high material cost of the support due to the cement and the containment bag. It is still the most expensive support used for tailgate and bleeder applications. This limitation has spurred current research to develop less costly cementitious materials for this application.

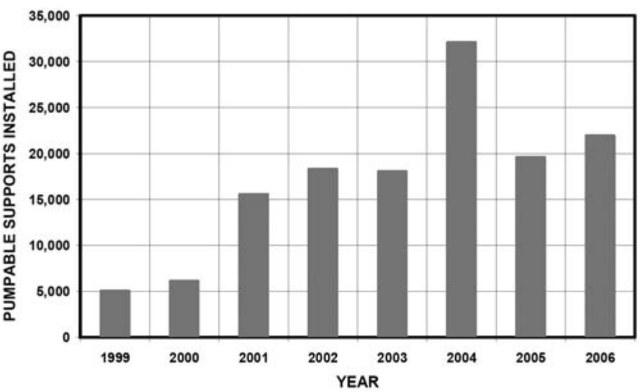

Figure 4 — Installation of Heitech pumpable roof supports by year from 1999 to 2006.

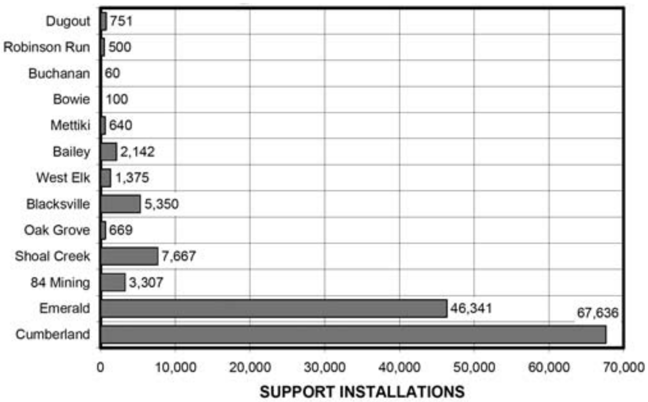

Figure 5 — Heitech pumpable support installations by mine site during the period 1999 to 2006.

Application and design requirements of pumpable supports

The application of pumpable supports for longwall mining can be categorized into three areas: bleeder applications, tailgate support and predriven recovery room or mine-through entries.

Bleeder applications. The first major use of pumpable support systems in U.S. longwall operations was in the support of bleeder entries. Bleeder entries are established around the perimeter of a set of longwall panels and are used to control methane liberation. The support of bleeder entries is ideal for pumpable supports that can be remotely installed, because access to these areas is generally restricted due to power constraints, presence of belt and track structures, or previously installed standing support. The support design requirements for bleeder applications are generally long-term support stability (5 years or more), broad roof coverage and stiff support response. Stiff support response is needed because main roof loading activity is likely to be limited, and the primary requirement is to control the time-dependent deformation of the immediate roof.

Tailgate applications. The success of bleeder applications using pumpable supports led to extended trials in longwall tailgate applications. Here, the support duration is much shorter, but the load conditions are much greater due to the development of the side and front pressures associated with the panel extractions. Recent studies have shown that much of the tailgate loading is

Figure 6 — Failure of concrete cribbing in longwall predriven recovery room.

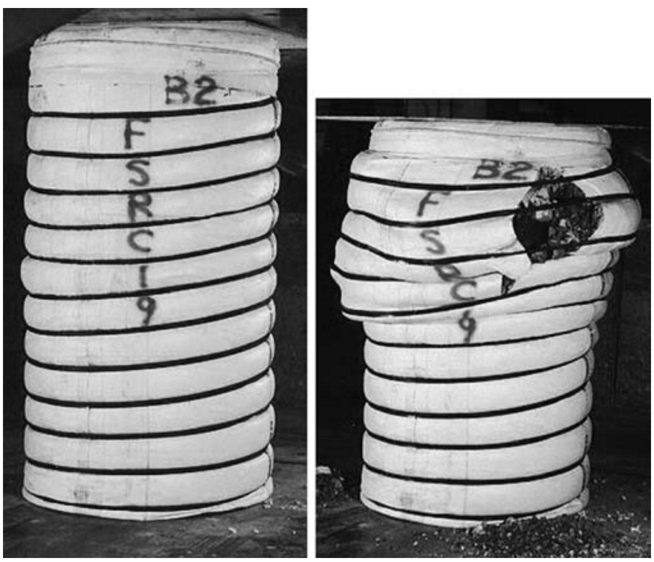

Figure 7 — Tekcrib support. Version of this support was first pumpable support installation in longwall tailgate in the U.S. in 1993.

derived from the main roof activity and elastic responses of the strata and pillars to the stress increases (Barczak et al., 2005). This response can be considered "uncontrollable convergence," meaning that the support system cannot prevent the convergence from occurring. The support system must be able to sustain roof loading through this range of convergence to be able to provide support of damaged rock structures at the longwall face or localized roof failures that occur outby. The degree of convergence will depend on the mine site and conditions. For example, the specification currently required by Foundation Coal for the western Pennsylvania mines operating below 180 to 240 m (600 to 800 ft) of cover is a minimum support load of 136 t (150 st), with no significant load shedding occurring before 25.4 mm (1 in.) of convergence. In other words, the support must be able to survive 25.4 mm (1 in.) of convergence without failing or sacrificing load carrying capacity.

Predriven recovery room or mine-through entries. Predriven recovery rooms or mine-through entries provide a specialized set of load conditions. Pumpable supports are used in predriven recovery rooms largely because the longwall shearer can easily cut them out for easy removal as the longwall advances into the room. They are also easy to install, providing flexibility to the timing of the support installation. As the longwall panel approaches the predriven recovery room, yielding of the panel fender causes uncontrollable convergence, resulting in yielding of the shield supports and the standing supports prior to the advancement of the shields into the recovery room (Barczak et al., 2006). However, unlike with the tailgate design criteria described above, the uncontrollable convergence in the recovery room is likely to exceed the yield load rating of the pumpable support; hence, the residual loading capacity and length of time the support can sustain this load during convergence establishes the support design criteria. Because pumpable supports do provide a residual load capacity through several inches of convergence, they offer an advantage over concrete support systems that use timber to soften the support response to survive the uncontrollable convergence but provide very little useful residual load once the concrete members fail (see Fig. 6).

Pumpable support technologies

The differences in the cementitious grout define the various types of pumpable support technologies as well as their performance capabilities. Most construction cements are based on ordinary portland cement (OPC), which is primarily formulated from limestone, certain clay minerals and gypsum in a high-temperature process that drives off carbon dioxide and chemically combines the primary ingredients into new compounds. As a hydraulic cement, these compounds hydrate when combined with water and then slowly harden to gain strength. They retain their strength and stability but remain insoluble in water as this process is completed. Those pumpable support systems that are not based on portland cements use a radically different chemistry and a completely different hydration process.

Aerated cements. Aerated cements are formed by incorporating foaming agents into the cement to create air bubbles that are stable and able to resist the physical and chemical forces imposed during mixing, placing and hardening of the foamed cement. The foamed cement is similar to that used in constructing ventilation seals. The air voids are easily visible to the naked eye. For the mining application of pumpable supports, the cement product blended with the foaming agent is typically provided as a powder in bags. The powder, when mixed with the proper amount of air and water in a specially designed placer unit, begins to gel within minutes of discharge and forms a non-toxic, non-combustible product with a density of less than 593 kg/m^3 (1,000 lbs per cu yd). It cures to a final strength ranging from 0.69 to 3.45 MPa (100 to 500 psi), which is much lower than ordinary portland cement, which can achieve a compressive strength of several thousand pounds per square inch. The aerated cements for mining applications are designed to allow reasonably long pumping distances >300 m (>1,000 ft) without destroying the integrity of the void formation, which is more common with portland-based foamed cements because of their more fragile cell structure.

Developed by Minova USA, the Tekcrib, as shown in Fig. 7, is an example of a pumpable support made from this material. The Tekseal material has been pumped 1,070 m (3,500 ft), using combinations of surface equipment and strategically drilled boreholes, for underground mine support installation. As mentioned above, the Tekcrib was the first successful pumpable support used in a longwall tailgate. An example of the performance curve for a 1.07-m (42-in.-) diameter Tekcrib developed from full-scale testing in the NIOSH Mine Roof Simulator is shown in Fig. 8. The support begins to yield at about 109 t (120 st) of load and 12.7 mm (0.5 in.) of displacement, providing a maximum load capacity of about 163 t (180 st) at 140 mm (5.5 in.) of displacement. The support then sheds load through several inches of convergence, resulting in a final residual load capacity of about 90 t (100 st) after 300 mm (12 in.) of displacement. While this curve is considered to be representative of the product, the residual load response can vary depending on the nature of the grout fracturing and bag confinement.

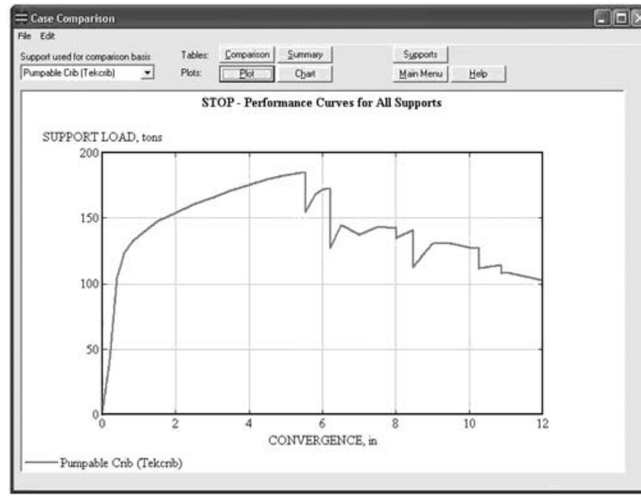

Figure 8 — Full-scale performance curve for Tekcrib pumpable support taken from NIOSH STOP software.

Portland fly ash cement. Basically, this is a portland cement blend with fly ash added to reduce the portland cement and water content and help preserve early strength. The strength can be varied depending on the amount of portland cement used in the mix. For longwall gate road support, the single-component mix is likely to be pumped from an underground location due to the limited pumping distance of less than 910 m (3,000 ft). Bleeder entries could be pumped from a surface location if a borehole is within the vicinity.

An example of this type of cement application is the Mesh Pack Support developed by Strata Products USA, as shown in Fig. 9. The hardened grout that is used for support capacity is shown in Fig. 10. The containment bag does not need to be waterproof, but must provide a high degree of confinement because of the brittle nature of the OPC concrete. This requirement is satisfied by 25.4 mm (1-in.-) wide steel bands spaced about one foot apart (see Fig. 9) and wire mesh to enhance the confinement provided by the bag fabric. The performance curve for a Mesh Pack pumpable support as acquired from STOP is shown in Fig. 11.

Figure 9 — Mesh Pack pumpable support showing laboratory test specimen on left and in mine trials on right (courtesy of Strata Products USA).

Portland pozzolan cement. This cement is made from portland cement with various pozzolan components, typically fly ash and ground-granulated blast-furnace slag and a retarding agent to provide adequate pumping time. These components allow the cement to be mixed with large quantities of water, generally more water than solids. This slurry is then combined with an alkaline activator to overcome the retarding action near the location where the support bag is filled. The two-component approach, where each component is pumped separately to the support site, is designed for simplicity of use and allows for

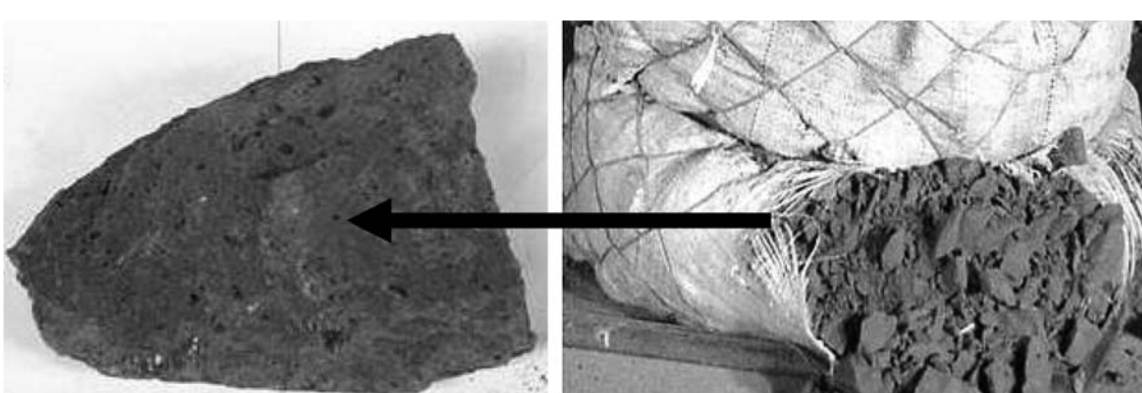

Figure 10 — Portland fly ash cement product used in Mesh Packs support.

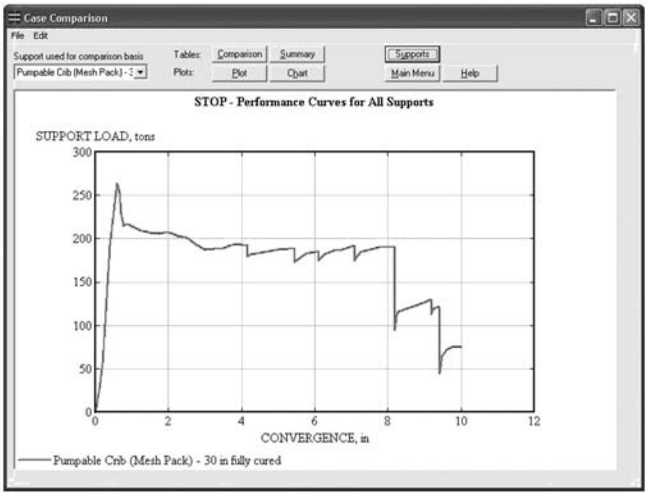

Figure 11 — Full-scale performance curve for Mesh Pack pumpable support taken from NIOSH STOP software.

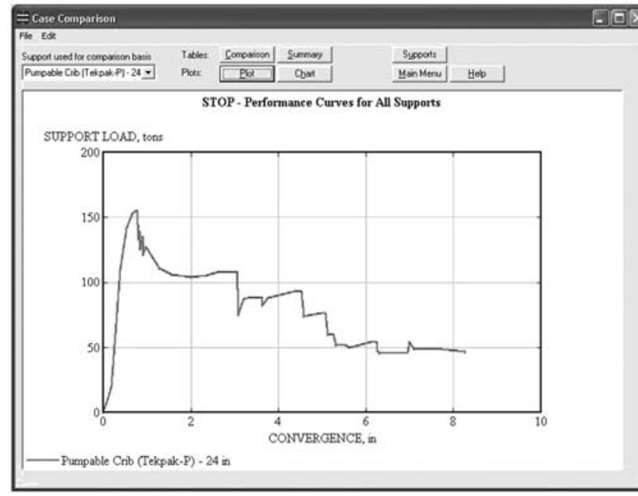

Figure 13 — Full-scale performance curve for Tekpak P pumpable support taken from NIOSH STOP software.

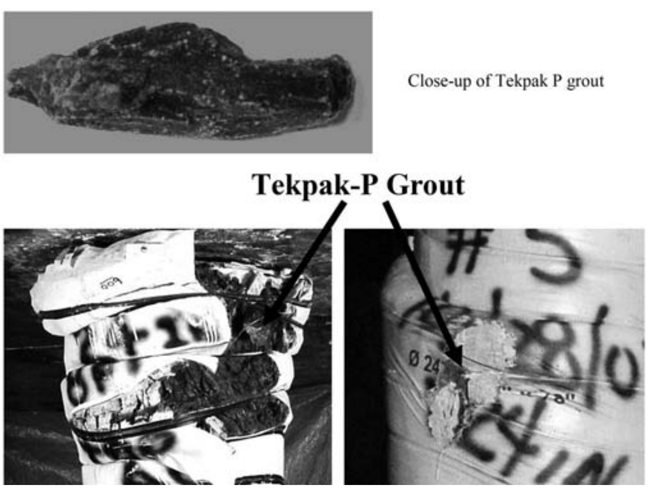

Figure 12 — Tekpak P grout is an example of this portland pozzolan cement category. It is dark, almost black, in color.

long pumping distances because the curing process is delayed until the material is inside the support containment bag. The final product is generally dark gray to black in color.

An example of this type of cement is the Tekpak P and Tekpak F formulations developed by Minova (see Fig. 12). Both use a symmetrical (equal volume), two-component approach as described above to allow for pumping distances greater than 3,000 m (10,000 ft), because the two slurries are not joined until they are near the support location. The two components are labeled Tekpak P or F and Tekbent P or F. The P and F designations primarily represent strength variations, with the F series designed to have a higher strength than the P series. The Tekcem portion represents the portland cement side and is a noncombustible brown powder that forms easy-to-pump slurry with water. It has a minimum 12-hour pumping life. The Tekbent portion consists of the alkaline activator. It is in liquid form and has an indefinite pumping life. The components can be mixed in any standard batch or continuous mixer, requiring about three minutes of mixing time. Once the two slurries are combined, they set very rapidly (in a few seconds) and cure quickly, developing compressive strength of 4.14 MPa (600 psi) within the first 24 hours and 5.86 MPa (850 psi) within the first 7 days. Figure 13 shows the STOP performance chart for a 610-mm- (24-in.-) diameter Tekpak P support. As seen in the graph, the support is capable of producing a maximum support capacity of 136 t (150 st) in less than 25.4 mm (1 in.) of convergence. The residual load decreases with continued convergence due to loss of confinement, reaching 45 t (50 st) at 150 mm (6 in.) of convergence in this example. These results represent the average of two full-scale tests conducted in the NIOSH Mine Roof Simulator. Figure 14 is a photo of the support at 200 mm (8 in.) of convergence being subjected to 43 t (47 st) of load.

Ettringite-based cements. Ettringite as a natural mineral is found in only a few areas of the world. It was first discovered near Ettringen, Germany, from which it got its name. The other locations where the mineral is mined include South Africa and Ireland. Figure 15 is a photo of the ettringite mineral. It is bright yellow in color and is formed as a precipitate from hydrothermal solutions by the underground burning of an alumina-rich oil-bearing stratum that is overlain by limestone. Calcium aluminates are formed during the burning. Following the burning, the ground eventually cools to the point where the sulfate-saturated ground waters can pass into the shrinkage fissures, forming ettringite crystals that grow on the surface of aeolean sand grains. This natural process has been taking place for thousands of years. A defining feature of ettringite is that four out every five atoms in this mineral is either part of a water molecule or a hydroxide. Thus, ettringite is almost all water and, as such, is the key ingredient in the high-yield, rapid setting grouts used for the pumpable roof support systems. However, the mineral itself is not used directly; rather ettringite is formed as part of the chemical process in the hydration and formation of the cement products. Ettringite-based grouts can be subdivided into the four types detailed below based on the components used to produce the ettringite (Mangabhai, 1990):

Types I and II: These early ettringite-based cements were used in the development of packwalls for gate road protection in advancing longwall systems and in retreat mining to reuse roadways in British coal fields in the 1970s (Nixon and Mills,

Figure 14 — Photo of Tekpak P pumpable support after 150 mm (6 in.) of convergence carrying a load of about 45 t (50 st).

1981). Both of these cements utilized ordinary portland cement (OPC) in combination with high alumina cement (HAC) and calcium sulfate and lime to produce the ettringite. These cements had very rapid strength development as desired and were high yield; meaning high water content could be used. The high water content was a huge advantage over previous non-ettringite cements, but the Type I product still had a short pump life.

The development breakthrough for the Type II cement came from the idea of transferring the accelerator, sodium carbonate, from the cement slurry to the bentonite slurry (Mills, 1988). This improved the pumping life to about 20 minutes because the cement did not harden nor activate until the two components were mixed together, followed by the slurry mixing. Another improvement was that the high level of ettringite formation in this process allowed the aggregate materials (coal fines) to be replaced by water. The slurries were pumped in separate pipes and mixed at the desired location curing to a compressive strength of about 5.00 MPa (725 psi). These slurries could also be pumped up to 460 m (1,500 ft).

Type III: The Type III mine cement developed in 1982 removed the portland cement and relied solely on the high alumina cement (HAC) to formulate the ettringite (Beale and Viles, 1982). The sodium carbonate was also replaced by a small amount of lithium carbonate in the "bent" slurry to act as an accelerator. The high content of HAC and calcium sulfate led to the formation of greater quantities of ettringite with the final product composed of 90% water by volume compared to about 85% for the Type II cement product.

Minova currently uses a version of Type III, ettringite-based cement in the Tekpak pumpable support for longwall tailgates and bleeders (Mills and Long, 1989). Again, the key factor is

Figure 15 — Ettringite mineral. Ettringite is a key component that provides high yield (more water than solids) and facilitates fast setting and high strength.

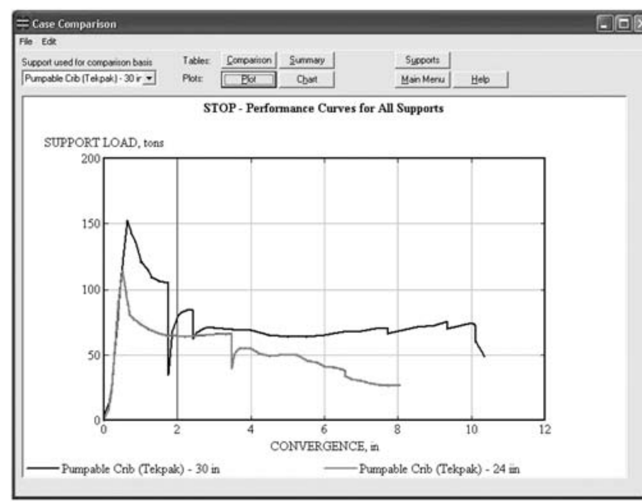

Figure 16 — Full-scale performance curve for Tekpak pumpable support taken from NIOSH STOP software.

that HAC is used to formulate the ettringite. The cured grout material is light gray to white in color. The pumpable support material is a two-component system consisting of the Tekcem component and the Tekbent component, which are mixed with water and pumped as slurries separately, then mixed together at the support installation location. Both are blended powder materials packaged in bags for transport. The Tekcem portion is a non-combustible dark brown powder, which forms milky alkaline slurry with water. The Tekbent component is a non-combustible off-white powder that, when mixed with water, results in a mildly alkaline slurry with a creamy milk appearance. Each material has more than 24 hours of pumping life. Type III ettringite-based cement can be pumped more than 4,500 m (15,000 ft) horizontally through low-cost, small-diameter pipe or hose. The performance characteristics of the 610- and 760-mm (24- and 30-in.) Minova Tekpak supports are illustrated in the STOP chart shown in Fig. 16.

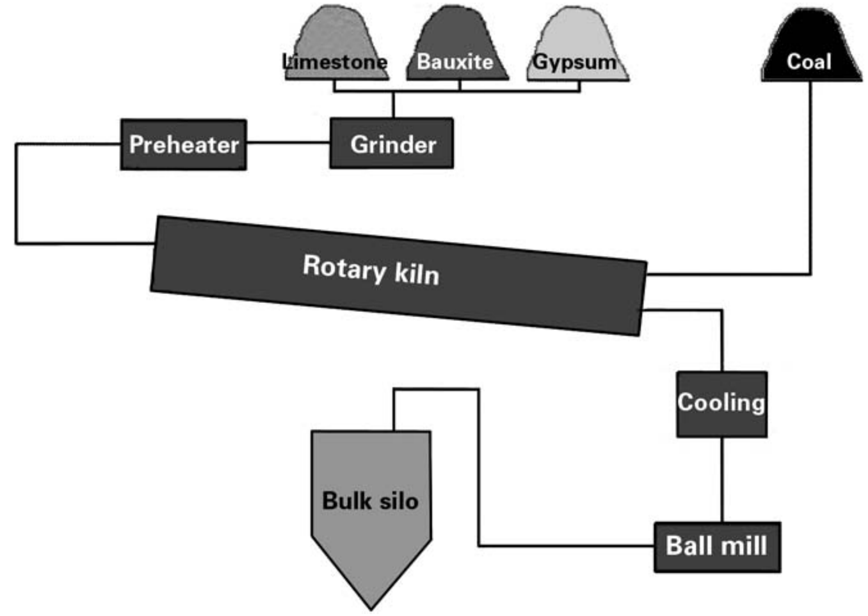

Figure 17 — Illustration of the process of making calcium sulpho-aluminate (CSA) cement.

Figure 18 — The two-components (powders) used to produce the CSA grouts are packaged separately in bags and delivered to the pumping site where they are mixed with water.

A 760-mm- (30-in.-) diameter Tekpak provides a maximum support capacity of about 136 t (150 st) at about 15.2 mm (0.6 in.) of convergence, with a residual load of about 64 t (70 st) at 150 mm (6 in.) of convergence in this representative full-scale test in the NIOSH Mine Roof Simulator.

Type IV: Type IV ettringite-based cements utilize calcium sulfo-aluminate (CSA), also known as Klein's compound, as the primary ingredient in the ettringite production instead of the HAC used in the Type III cement. This product has a close relationship to Type K expansive cements. Calcium sulpho-aluminates are manufactured from limestone, bauxite and gypsum under oxidizing conditions using a rotary calcining kiln (Fig. 17). It takes less energy to produce CSA than HAC cements; however, CSA cements are produced in only a few locations throughout the world. Much of the CSA material used in the United States for mining cements has been imported from England and manufactured by Blue Circle Cement (now owned by La Farge) at the Barnstone facility in Nottingham. Recently, CSA cement has been delivered from Mexico through CTS Cement Manufacturing Corporation in Cypress, California. The United States experimented with CSA cements several years ago, but China pioneered the large-scale manufacture of CSA cements and continues to produce the product, although it is not routinely imported for mine use in the United States. The CSA (Type IV) cement provides the highest water content, exceeding 85% by volume, for water to solids ratio of 1.75 to 1, which is typically used in the mining applications. Like all the ettringite-based cements, it sets and cures rapidly. The CSA-based grouts have high compressive strengths, with the mining mixes typically above 6.9 MPa (1,000 psi).

The pumpable support system developed by Heitech Corporation (subsidiary of Heintzmann Corporation) is made from CSA or Type IV cement. These Heitech supports have been the most commonly used longwall pumpable supports since their inception into the U.S. industry in 1999. As was indicated in the Introduction, more than 130,000 supports in 13 different mines have been installed. The two components used to make pumpable cribs are typically packaged in 25-kg (55-lb) bags, although a batch system, whereby the material is transported in bulk on rail cars to storage silos or for bulk bagging, is now under development at the Foundation Coal site in Waynesburg, Pennsylvania. The aluminous cement constituent is packed separately from the sulfate, lime source and aluminous cement accelerators. One is a white powder and the other is a dark powder. Each of the two parts is mixed with half the total water requirement and pumped through separate lines (Fig. 18), typically down a 150- to 200-mm- (6- to 8-in.-) diameter borehole to the support installation areas up to 9 km (30,000 ft) away (Fig. 19). Here the two slurry lines are joined together through a tee section a few feet before entering the bag (Fig. 20). The splash mixing of the two slurries as they enter and fill the bag is sufficient to provide a consistent concrete structure once the bag is filled. The hydration reactions of the minerals are considerably exothermic, which creates heat as the cement hydrates. Heat can be felt on the support bags within minutes after being filled and they remain warm for several hours as the hydration continues. The final product is lightweight, brittle and has a light color, as shown in Fig. 21.

The 600-mm- (24-in.-) diameter Heitech pumpable support provides over 113 t (125 st) of support capacity, while

Figure 19 — Cement slurries are pumped down the borehole in separate lines (pump mixing station in background).

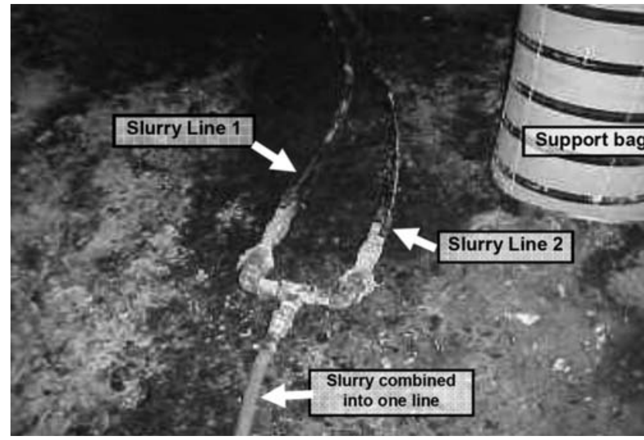

Figure 20 — Components are pumped in separate lines and joined together just prior to entering the bag.

Figure 21 — The final product produced from CSA grout is light in color and lightweight.

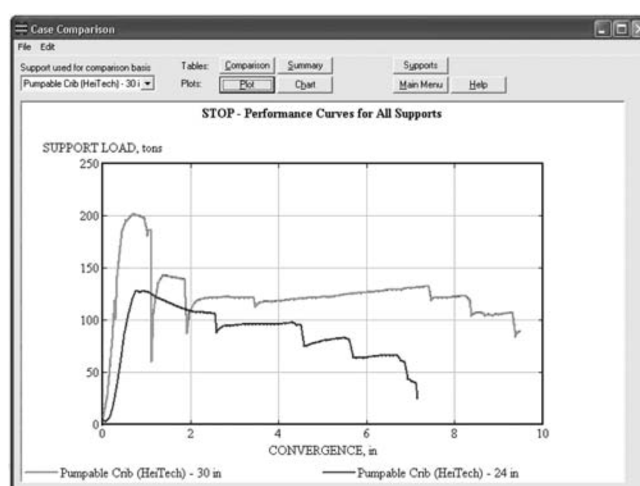

Figure 22 — Full-scale performance curves for Heitech pumpable supports taken from NIOSH STOP software.

the 760-mm- (30-in.-) diameter support provides more than 180 t (200 st) of support capacity. The performance curves developed from full-scale testing as recorded in the NIOSH STOP software are shown in Fig. 22.

Performance characteristics of pumpable supports

In general, pumpable supports provide a very stiff loading characteristic, typically reaching peak loading between 12.7 and 25.4 mm (0.5 and 1.0 in.) of convergence. The peak load is followed by a load-shedding behavior, often with sudden dramatic drops in load as the grout fractures from the induced stress of the convergence, followed by a useful residual load being maintained through 150 mm (6 in.) or more of convergence, depending on the confinement and integrity of the bag as the convergence continues. Factors that affect these generalized performance characteristics are examined below.

Maximum support load. The maximum support capacity is obviously controlled largely by the compressive strength of the cementitious grout, with greater grout strength providing higher maximum support capacity. However, the full material strength is never realized in full-scale support constructions, implying that there are other factors involved that affect the maximum support capacity. Depending on the cement type, as discussed above, the compressive strength of the material can vary. For Type IV cement (CSA-based ettringite), the laboratory-measured strength determined from 150-mm- (6-in.-) diameter samples is typically around 6.9 MPa (1,000 psi). However, full-scale testing of the support indicates that the full compressive strength of the grout is not achieved.

Two factors account for the observed degraded full-scale strength. First, uneven ends (top and bottom) of the support can contribute to non-uniform loading of the specimen in the stiff mine roof simulator, where the large steel platens of the load frame are positioned to remain parallel to each other prior to and during load application. The second, and believed to be more significant factor, is the presence of hairline preexisting fractures, probably due to expansion during the hydration

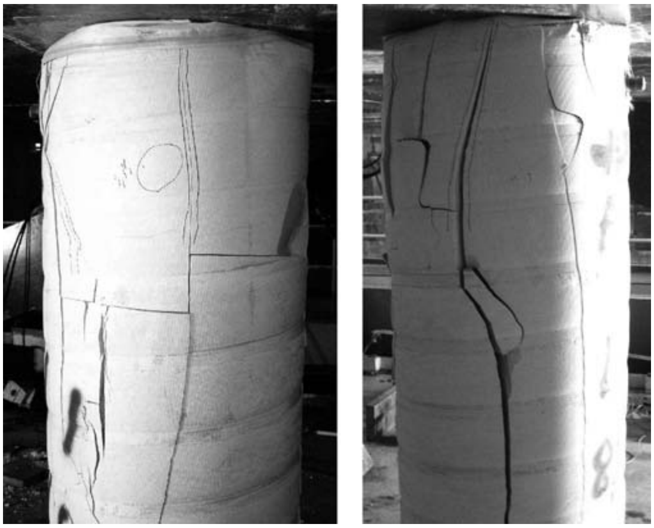

Figure 23 — Fracture planes developed as grout strength is exceeded often occur along preexisting fractures developed during curing

Figure 24 — Bag construction showing polyester yarn and waterproof fabric on a section of bag that ripped open during performance testing in NIOSH Mine Roof Simulator.

of the cement components as the grout cures and hardens in the support bag. These preexisting fractures can be seen on the surface of the support and appear to control the fracture behavior of the grout during load application (see Fig. 23), resulting in failure at far less stress than the material strength would suggest.

Confining pressure provided by the containment bag can significantly offset these weaknesses. Table 1 shows results from three full-scale tests comparing the maximum support capacity with the containment bag as normal and with the containment bag removed after the support was pumped and the grout fully cured. On average, the support capacity was increased by 282% by the confinement of the bag compared to the capacity achieved without the bag.

A considerable amount of development, particularly by ABC Industries in Warsaw, Indiana, has been made in producing the

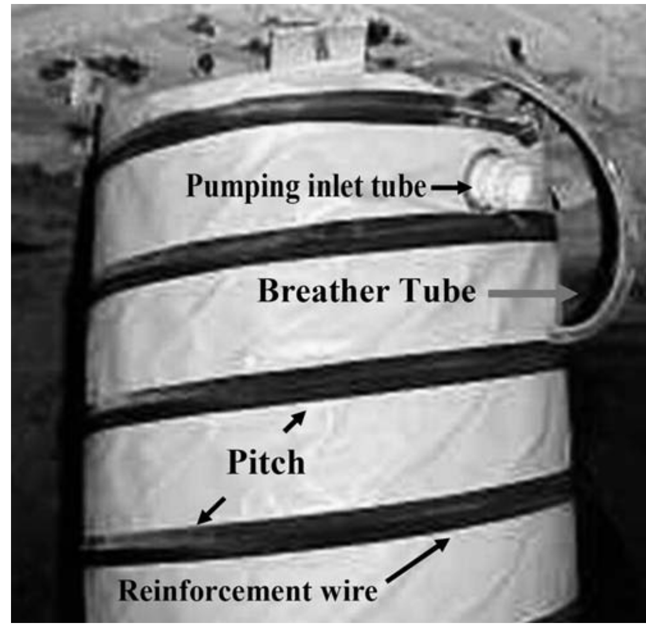

Figure 25 — Bag construction showing inlet tube, breather tube, wire pitch and reinforcement wire.

bag containment system for the pumpable roof supports. The current production containment bag is constructed by a spiral wrap of high-tenacity fabric with woven polyester yarn in a grid to provide tensile strain resistance in two orthogonal directions (see Fig. 24). The seams are strengthened by overlapping and welding the fabric together to provide a strength equivalent to that of the bag fabric. The polyester fibers provide a tensile strength of up to 8,900 kg per meter width of fabric (500 lbs per inch width of fabric) and can elongate about 25% before breaking. The bag also incorporates a 10- to 12-gage metal wire that is spiraled from the top to the bottom of the bag, secured either in the seam or externally to preserve the seam strength, with the heavier gage wire as shown in Fig. 25. For the bag system to improve the maximum support capacity, it must provide active confinement in conjunction with the filling of the bag. For adequate confinement to be achieved, once the bag is full and contacts the mine roof, the grout must be pressurized to cause the bag to expand slightly.

The confinement, as described above, can be enhanced, thereby causing higher support capacity in the following ways:

- *Heavier gage wire:* The benefit of the wire can be seen in a Fig. 26, which shows the performance for a bag with a vertical seam without the wire reinforcement that is used in the spiral wrap bag construction. Both the peak load and the residual load are increased in the support with the wire-wrap construction. A test using a prototype high-strength wire and containment bag is also shown in this chart. It is seen that this system provided the largest peak load of the three supports. Heavy-gage wire can provide higher initial confining forces in the sense that larger-diameter wire will develop more tensile stress with less deformation than smaller diameter wire. However, the impact on the peak load is thought to be rather small for the range of wire diameters practical to install.

Table 1 — Comparison of maximum support capacity with and without the containment bag.

Test	Maximum support capacity, t (st)		Loading stress at peak capacity, MPa (psi)	
	With bag	Without bag	With bag	Without bag
1	223 (246)	24 and 43 (26 and 47)	4.80 (696)	0.51 and 0.92 (74 and 133)
2	164 (181)	83 (92)	3.53 (512)	1.79 (260)
3	122 (135)	29 (32)	2.63 (382)	0.63 (91)
Average	170 (187)	44 (49)	3.66 (530)	0.97 (140)

- *Tighter wire spiral:* Reducing the spacing between the wire wrap can increase the total system confinement and thereby increase the support capacity. Figure 27 shows the improvement in both stiffness and support capacity from an early developmental test using a South African manufactured bag comparing a 150 mm (6-in.) and a 250 mm (10-in.) wire pitch. The standard pitch (wire spacing) of the most commonly used bag manufactured by ABC Industries is 150 mm (6 in.). The company also provides a 10-gage, 100-mm (4-in.), wire/seam pitch that also has been shown to increase support capacity beyond that provided by the standard 150-mm- (6-in.-) pitch bag.
- *Stronger/enhanced bag fabric:* The primary function of the bag is to contain the material between the wire wraps. However, the bag does provide secondary confinement and can contribute to the peak support capacity. Figure 28 compares developmental testing of two prototype bags showing that the stronger bag with thicker wire provided higher support capacity than the weaker bag.

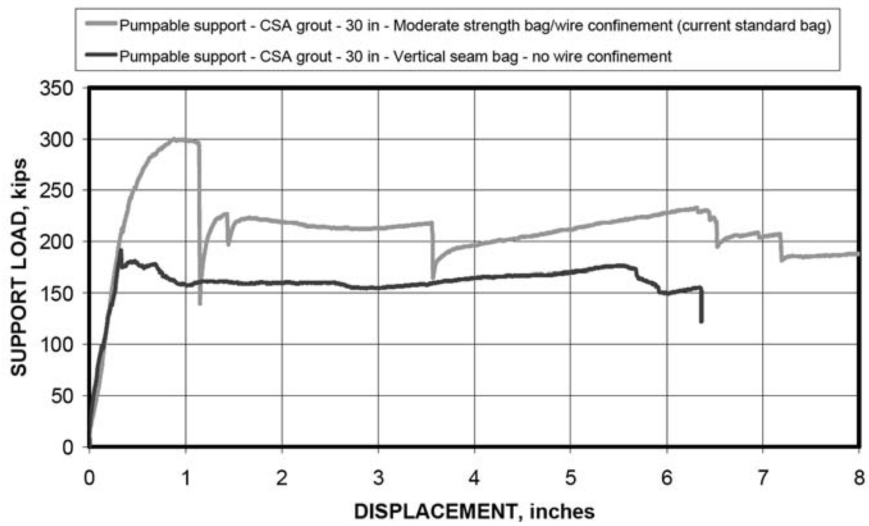

Figure 26 — Peak-load capacity of the support is increased by the wire wrap. Figure shows comparison between bag with wire and one without wire.

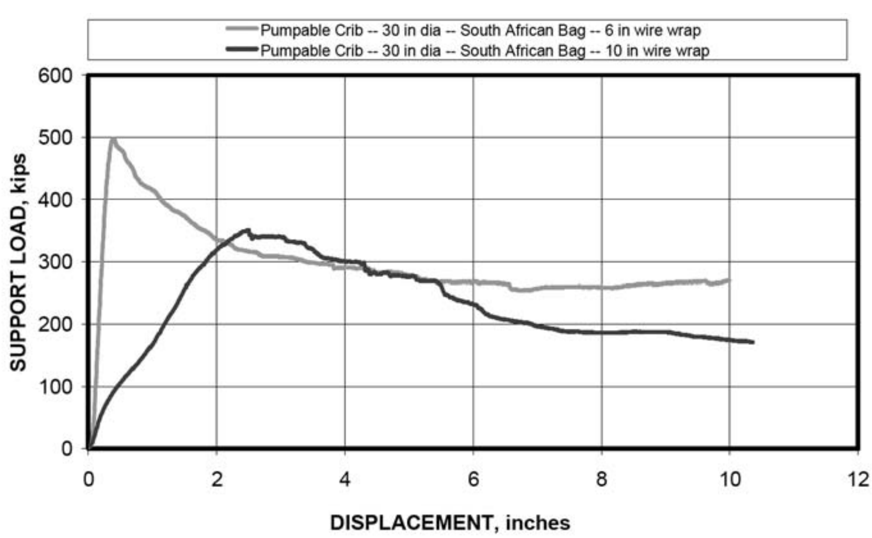

Figure 27 — Closer wire spacing can also provide higher peak capacity due to the increased confinement. Chart compares 150- and 250-mm (6- and 10-in.) wire spacing.

Support stiffness. The support stiffness (K) is theoretically defined by

$$K = (A \times E)/L \qquad (1)$$

where
A is the support area,
E is the material modulus and
L is the support height.

Assuming that the material modulus does not change, the diameter of the support will largely control its stiffness. Table 2 compares the loading stiffness of 761- and 610-mm- (30- and 24-in.-) diameter supports. A 60% increase in loading stiffness was observed with a 63% increase in loading area when the two support diameters were compared, confirming the proportionality between the stiffness and loading area. To put the stiffness into perspective, the pumpable support stiffness of 10.5 to 17.4 t/mm (293 to 486 st per in.) compares to a stiffness of only 0.89 t/mm (25 st per in.) for a 4-point wood crib structure.

Residual load. The residual load capacity is highly dependent on the confinement provided by the containment bag. Pumpable supports typically shed load after reaching their peak support capacity because the confinement provided by the bag/wire is insufficient to prevent this from occurring. The initial load-

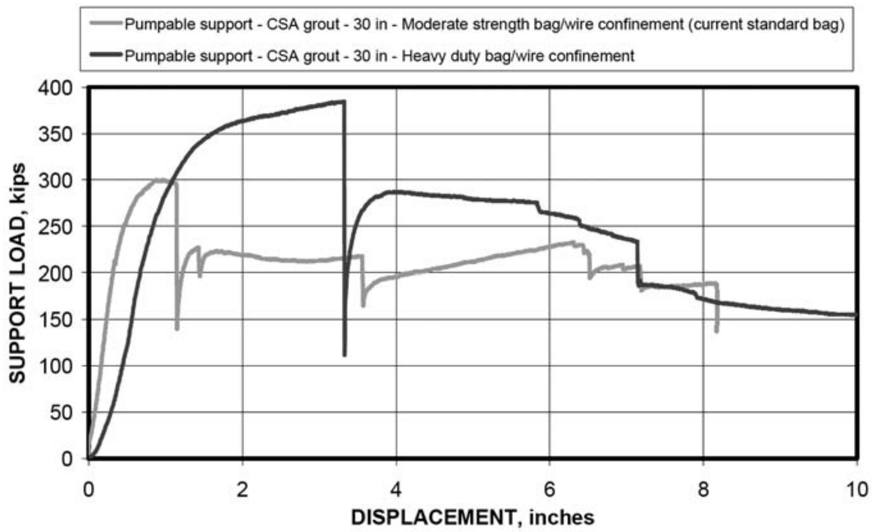

Figure 28 — Peak load capacity of the support can be increased by additional confinement provided by the bag/wire system.

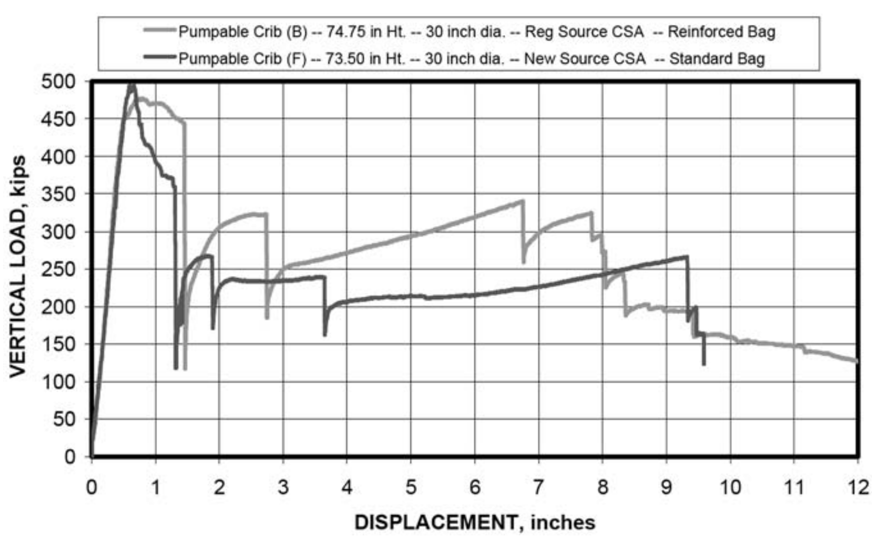

Figure 29 — Comparison of 100-mm (4-in.), reinforced, and 150-mm (6-in.), standard, wire pitch bags. Reinforced bag delayed major load shedding and increased residual load capacity.

shedding event is often very dramatic due to the brittle nature of these cementitious grouts. This is difficult to control, but higher active confinement during pumping appears to limit the onset of the initial load-shedding event. An example is shown in Fig. 29, which compares the load-displacement relationship for a bag with a 150-mm (6-in.), 12-gage wire pitch and one with a 100-mm (4-in.), 10-gage wire pitch. The 100 mm (4-in.) wire pitch also appears to increase the residual loading as the convergence continues beyond the initial load-shedding event up to the point where the wire system is failing, which in this case occurs at about 200 mm (8 in.) of convergence. Even passive confinement, meaning that the confinement does not occur until the grout fractures and bulks, can significantly improve the residual loading capacity by extending the amount of convergence and load that the support can sustain. This was proven by experimental trials where the support bag after filling was wrapped with additional material including "house wrap" (material used to wrap residential houses to minimize air leakage) and chain link mesh. Although these materials are not used in production bag designs, these trials show the advantage of such passive confinement.

Installation and safety-related performance comparisons

The installation of pumpable supports reflects a good safety record. Heitech reports 238 lost workdays installing pumpable supports over a five-year period from 2002 to 2006. During this time, approximately 110,000 supports were installed. This translates into approximately 21 lost workdays per 10,000 supports installed. The injuries are primarily due to sprains resulting from slips or falls while handling the grout material, with occasional chemical burns. Most injuries have been minor with lost time less than 15 days. Overall, the average is 2.5 lost days per incident. This compares to 41 lost workdays per incident in U.S. coal mines in 1990 based on MSHA accident statistics, when wood cribbing was primarily installed. It is anticipated that the injuries can be further reduced by the application of a batch system, which would eliminate some of the material handling of the cement at the pump site.

Conclusions

Pumpable roof supports provide a new alternative to conventional standing support application in underground coal mines. The support consists of a bag made from fabric that can be transported in a collapsed form and then hung from the mine roof to create a form for filling with cementitious grout. The desirable feature of this support technology is that it can be installed in place in the mine as opposed to being pre-fabricated and brought into the mine as a unit. Furthermore, because the main component of support, the cementitious grout, can be pumped from the surface in most cases, the support can be installed in areas that are inaccessible to equipment. This makes the support ideal for longwall bleeder and tailgate applications.

There are several pumpable support products now on the market. Although they all pump material into a fabric bag and thus can look very similar to each other, there are significant differences in the grout materials used. These materials are categorized into four main groups: aerated cements, portland fly ash cement, portland pozzolan cement and ettringite-based cement. Of these, the ettringite-based cements, calcium sulfo-aluminate (or CSA) cements in particular, have been the most successful and by far the most widely used material. These cements have several superior qualities that, so far, have not been matched by the other grouts. The CSA-based grout has the highest water content (+85% by volume with water-to-solids ratio of 1.75 or 2.00 to 1). Essentially, the support is mostly water, making the slurry the most fluid and easiest to pump. It also has the most practical set-up time. Once the two-component grout is mixed together at the underground support installation location, the grout sets in 10 to 15 minutes. This provides some flexibility in the final pumping phase, but still allows the support to be completely formed in just a few lifts. The ettringite-based grouts have provided consistent in-mine capacity for the support, but ettringite formation — more specifically, the control of its formation — requires a finely balanced mix with the proper constituents. Failure to control these parameters can degrade the support performance. Therefore, it is a rather sophisticated grout that is much more complex than the common Portland-cement products. The major disadvantage of the CSA product is that no domestic source of the component is available and importation is expensive.

There has been extensive research conducted in the past few years to develop portland-based alternatives to the ettringite-based products, ideally alternatives that can be produced domestically. Conventional portland cements have been around for a long time, and this technology is well-proven. The mining application is also expected to be reliable, but the pumping of conventional fly ash/sand mixtures is considerably more problematic in that the material can plug the lines if allowed to set and it cannot easily be pumped very long distances. The pumping also requires higher pressures and stronger pipe. Therefore, conventional fly ash/sand mixtures may be a viable alternative, but their limitations are likely to make them less attractive than the ettringite-based grouts. Nevertheless, some applications such as bleeder installations do not require long pumping distances, and there is likely to be a role for a material than can be reliably pumped 900 m (3,000 ft), particularly if it is a lower cost material. It is likely that additional research will continue in this area.

One hybrid portland-based product that has had some success is the Tekpak P/F product developed by Minova. Like the ettringite-based cements, this system is a two-component mix utilizing an accelerator to overcome the retarding agents necessary to provide long pumping life with fast setting times once the components are mixed together. The strength of this grout can be designed to exceed that of the ettringite-based grouts, but the current mine applications provide similar strengths. Here, too, the accelerator and hydration chemistry is critical to providing consistent strength and desired in-mine performance. Aerated or foamed cements have some desirable qualities in terms of sustaining peak loading through a larger convergence prior to severe load shedding. However, their strengths are considerably weaker, requiring more material to provide equivalent strength to the ettringite-based or portland-based supports. As a result, it is not likely that aerated or foamed cements will replace these grouts on any large-scale installation.

Table 2 — Comparison of support loading stiffness for two support sizes.

Test number	Stiffness, t/mm (st per in.) Diameter, ~760 mm (~30 in.) [1]	Diameter, ~610 mm (~24 in.) [2]
1	16.5 (462)	9.6 (268)
2	18.2 (510)	11.4 (318)
Average	17.4 (486)	10.5 (293)

[1] Area = 0.492 m^2 (763 $in.^2$)

[2] Area = 0.301 m^2 (467 $in.^2$)

Disclaimer

The findings and conclusions in this report have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

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