PUMPABLE ROOF SUPPORTS: AN EVOLUTION IN LONGWALL ROOF SUPPORT TECHNOLOGY

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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 over 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 figure 1, is the most widely used standing support system in the United States for longwall tailgate applications. About 1/3 of the longwall tailgates in the United States are supported with the Can, with the highest percentage found in western 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 which 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 figure 1). 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 or CSA cement, which relies on ettringite formation to provide a high-yield, fast-setting grout. Over 110,000 of these supports have been installed in the past 5 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 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.

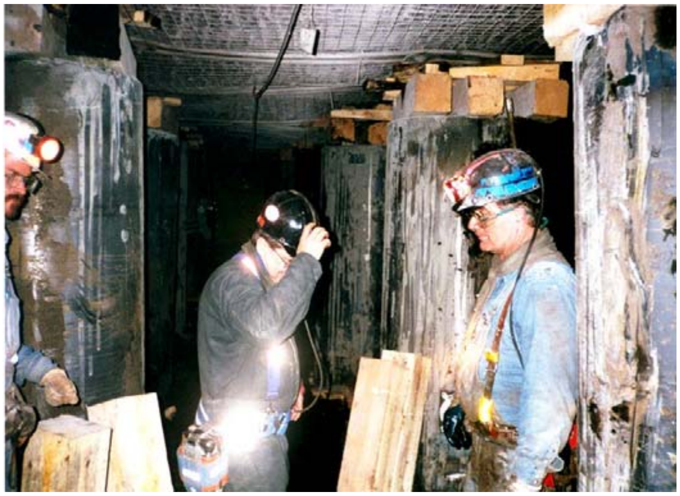

Figure 1. The Can is a commonly used tailgate support in the United States.

Considerable research has been done during the past few years to develop an alternative to CSA grouts. The Minova Tekpak support uses a High Alumina Cement 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 so 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.

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 figure 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,

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

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.

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

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 gateroads are developed in advance of the panel mining, in advancing longwall mining the gateroads are developed as the panel is mined as shown in figure 3 (see Appendix). 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 (currently 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. Since 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 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 U.S., having installed over 130,000 supports in 13 different mines (see figures 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.

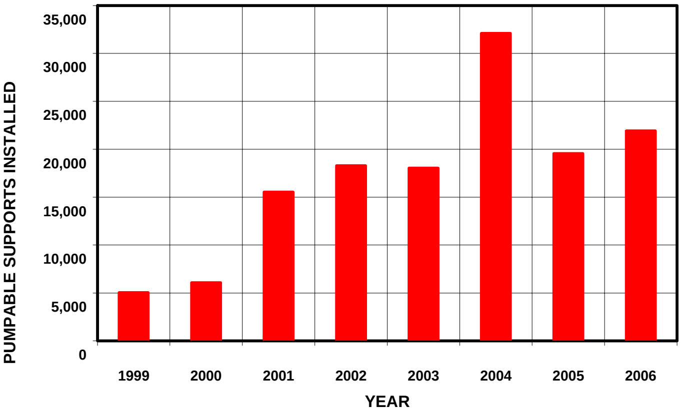


Figure 4. Installation of Heitech pumpable roof supports by year from 1999 to 2006.

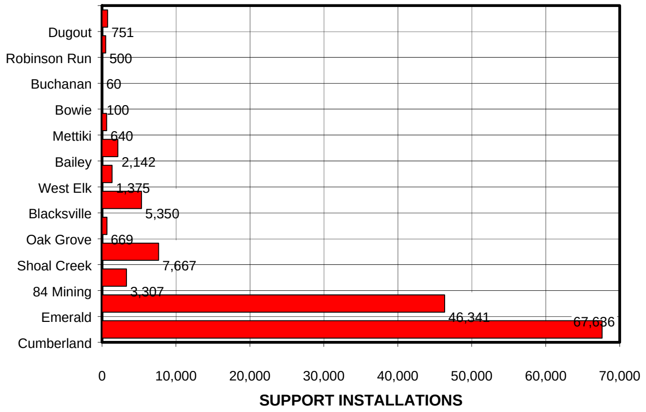


Figure 5. Heitech pumpable support installations by mine site during the period 1999 to 2006.

Application and Design Requirements of Pumpable Supports

The application of pumpable supports for longwall mining can be categorized into three areas: (1) bleeder applications, (2) tailgate support, and (3) pre-driven 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 since 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: (1) long-term support stability (5 years or more), (2) broad roof coverage, and (3) stiff support response. Stiff support response is needed since 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 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 600-800 feet of cover is a minimum support load of 150 tons, with no significant load shedding occurring before 1 inch of convergence. In other words, the support must be able to survive 1 inch of convergence without failing or sacrificing load carrying capacity.

Pre-Driven Recovery Room or Mine-Through Entries:

Pre-driven recovery rooms or mine-through entries provide a specialized set of load conditions. Pumpable supports are used in pre-driven 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 pre-driven 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. Since pumpable supports do provide a residual load capacity through several inches of convergence, they offer an advantage over concrete support systems which 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 figure 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.

Figure 6. Failure of concrete cribbing in longwall pre-driven recovery room.

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 1,000 lbs/yd^3. It cures to a final strength ranging from 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 (> 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 figure 7 (see Appendix), is an example of a pumpable support made from this material. The Tekseal material has been pumped 3,500 ft, using combinations of surface equipment and strategically drilled boreholes, for underground mine support installation. As previously mentioned, the Tekcrib was the first successful pumpable support used in a longwall tailgate. An example of the performance curve for a 42-in-diameter Tekcrib developed from full-scale testing in the NIOSH Mine Roof Simulator is shown in figure 8. The support begins to yield at about 120 tons of load and 0.5 inches of displacement, providing a maximum load capacity of about 180 tons at 5.5 inches of displacement. The support then sheds load through several inches of convergence, resulting in a final residual load capacity of about 100 tons after 12 inches 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.

Portland Flyash Cement:

Basically, this is a Portland cement blend with flyash 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 gateroad support, the single-component mix is likely to be pumped from an underground location due to the limited pumping distance of less than 3,000 ft. Bleeder entries could be pumped from a surface location if a borehole is within the vicinity.

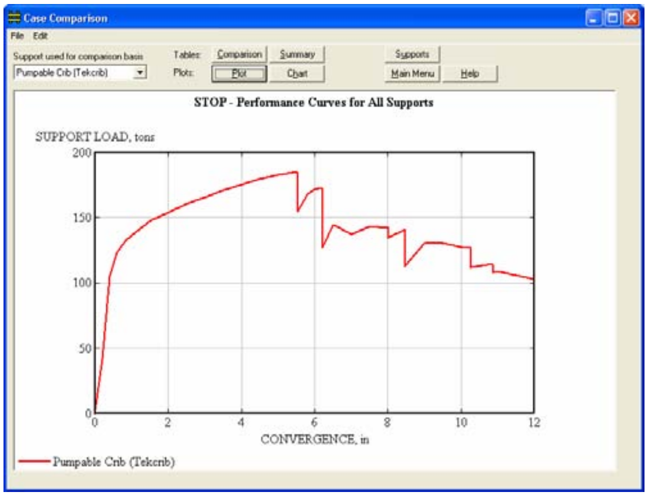

Support used for comparison basis: Pumpable Crib (Tekcrib)

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

An example of this type of cement application is the Mesh Pack Support developed by Strata Products USA as shown in figure 9 (see Appendix). The hardened grout that is used for support capacity is shown in figure 10 (see Appendix). 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 1-inch-wide steel bands spaced about one foot apart (see figure 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 figure 11.

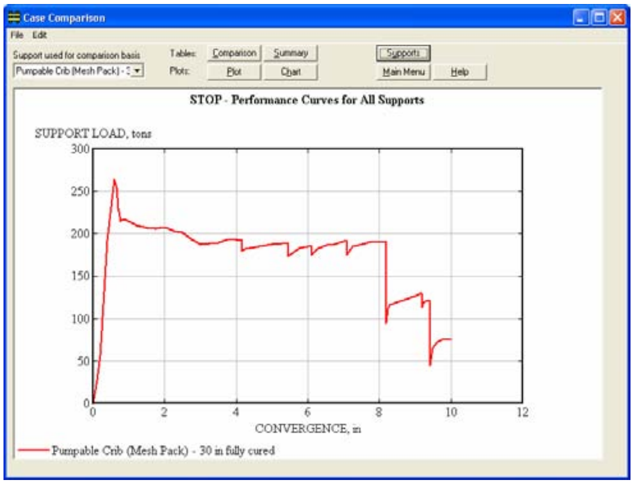

Support used for comparison basis: Pumpable Crib (Mesh Pack) - 3

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

Portland Pozzolan Cement:

This cement is made from Portland cement with various Pozzolan components, typically flyash 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 long pumping distances since the curing process is delayed until the material is inside the support containment bag. The final product is generally dark grey to black in color.

An example of this type of cement is the Tekpak P and Tekpak F formulations developed by Minova (see figure 12 in Appendix). Both use a symmetrical (equal volume), two-component approach as described above to allow for pumping distances greater than 10,000 ft since 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 non-combustible brown powder which 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 3 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 600 psi within the first 24 hours and 850 psi within the first 7 days. Figure 13 (see Appendix) shows the STOP performance chart for a 24-in-diameter Tekpak P support. As seen in the graph, the support is capable of producing a maximum support capacity of 150 tons in less than 1 inch of convergence. The residual load decreases with continued convergence due to loss of confinement, reaching 50 tons at 6 inches of convergence in this example. These results represent the average of two full-scale tests conducted in the NIOSH Mine Roof Simulator. A photo of the support at 8 inches of convergence being subjected to 47 tons of load is shown in figure 14 (see Appendix).

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

Ettringite-Based Cements:

Ettringite as a natural mineral is sparsely 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 shows 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 sulphate-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 several 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 four types, detailed below, based on the components used to produce the ettringite (Mangabhai, 1990).

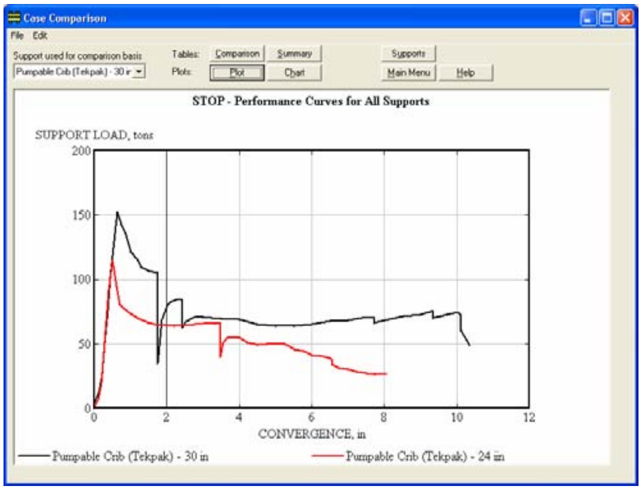
Types I and II: These early ettringite-based cements were used in the development of packwalls for gate road protection in advancing longwall systems and in retreat mining to re-use roadways in British coal fields in the 1970s (Nixon and Mills, 1981). Both of these cements utilized Ordinary Portland 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 since 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 725 psi. These slurries could also be pumped up to 1,500 feet.

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 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 over 24 hours of pumping life. Type III ettringite-based cement can be pumped over 15,000 ft horizontally through low-cost, small-diameter pipe or hose. The performance characteristics of 24- and 30-inch Minova Tekpak supports are illustrated in the STOP chart shown in figure 16. A 30-in-diameter Tekpak provides a maximum support capacity of about 150 tons at about 0.6 inches of convergence, with a residual load of about 70 tons at 6 inches 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 under oxidizing conditions, using a rotary calcining kiln, from limestone, bauxite, and gypsum (figure 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 USA for mining cements has been imported from England, 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, CA. The USA 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 1,000 psi.



Support used for comparison basis: Pumpable Crib (Tekpak) - 30 ir

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

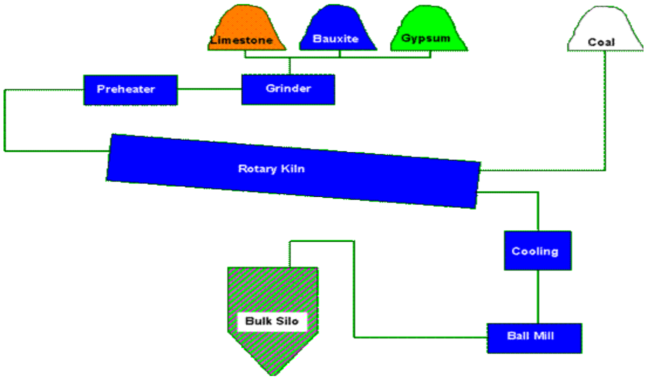


Figure 17. Illustration of the process of making calcium sulpho-aluminate (CSA) cement.

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 indicated in the Introduction, over 130,000 supports in 13 different mines have been installed. The two components used to make pumpable cribs are typically packaged in 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, PA. The aluminous cement constituent is packed separately from the sulphate, lime source, and aluminous cement accelerators. One is a white powder while the other is a dark powder. Each of the two parts is mixed with half the total water requirement and pumped through separate lines (figure 18), typically down a 6- to 8-in-diameter borehole to the support installation areas up to 30,000 ft away (figure 19). Here the two slurry lines are joined together through a tee section a few feet before entering the bag (figure 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 figure 21.

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.

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

The 24-in-diameter Heitech pumpable support provides over 125 tons of support capacity, while the 30-in-diameter support provides over 200 tons of support capacity. The performance curves developed from full-scale testing as recorded in the NIOSH STOP software are shown in figure 22.

Performance Characteristics of Pumpable Supports

In general, pumpable supports provide a very stiff loading characteristic, typically reaching peak loading between 0.5 and 1.0 inch 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 6 or more inches 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.

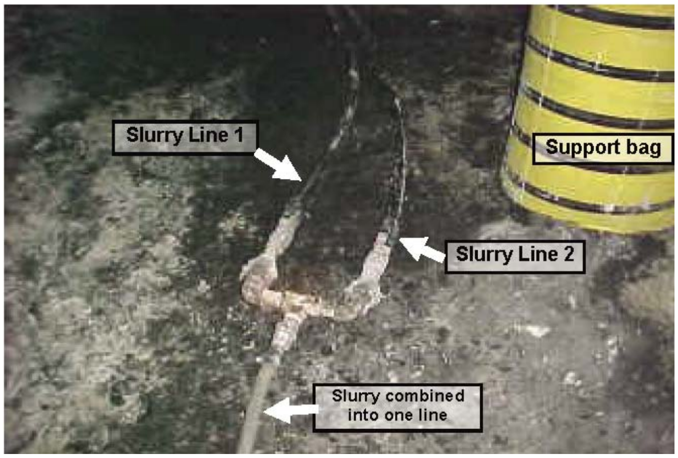


Figure 20. Components are pumped in separate lines and joined together just prior to entereing the bag.

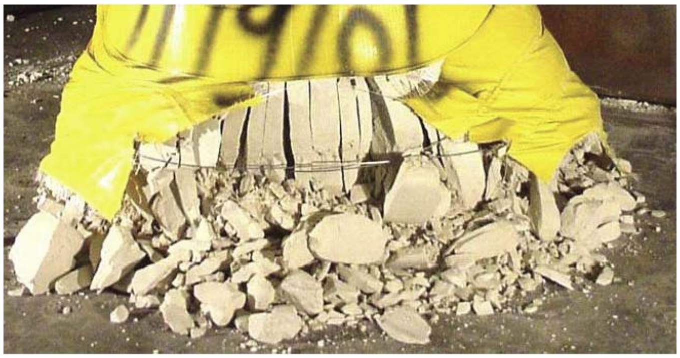
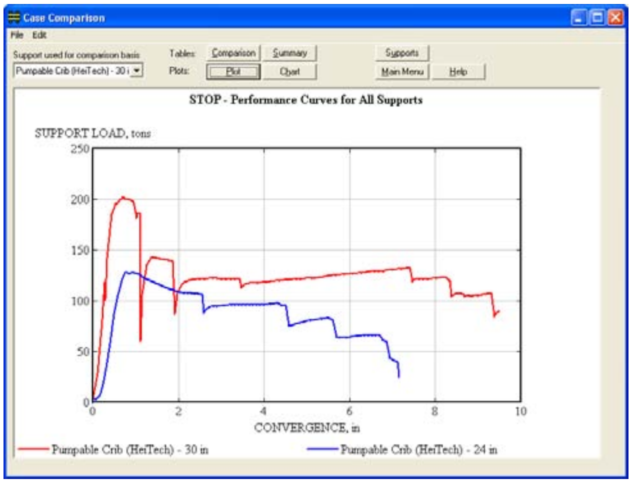


Figure 21. The final product produced from CSA grout is light in color and lightweight.



Support used for comparison basis: Pumpable Crib (HeiTech) - 30 i

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

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 in the previous section, the compressive strength of the material can vary. For Type IV cement (CSA-based ettringite), the laboratory-measured strength determined from 6-in-diameter samples is typically around 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 pre-existing fractures, probably due to expansion during the hydration of the cement components as the grout cures and hardens in the support bag. These pre-existing fractures can be seen on the surface of the support and appear to control the fracture behavior of the grout during load application (see figure 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.

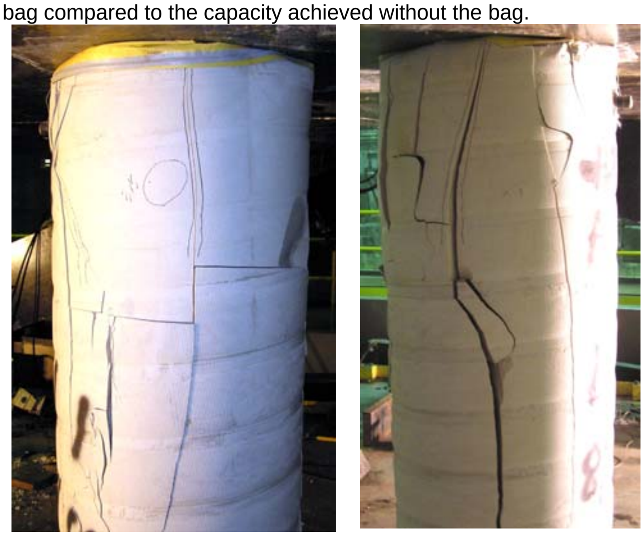


Figure 23. Fracture planes developed as grout strength is exceeded often occur along pre-existing fractures developed during curing.

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

Test Number	Maximum support capacity, tons		Loading stress at peak capacity, psi	
	With bag	Without bag	With bag	Without bag
1	246	26 and 47	696	74 and 133
2	181	92	512	260
3	135	32	382	91
Average	187	49	530	140

A considerable amount of development, particularly by ABC Industries in Warsaw, Indiana, has been made in producing the 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 figure 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 up to 500 lbs per inch width of fabric of tensile strength 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 figure 25. In order 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.

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.

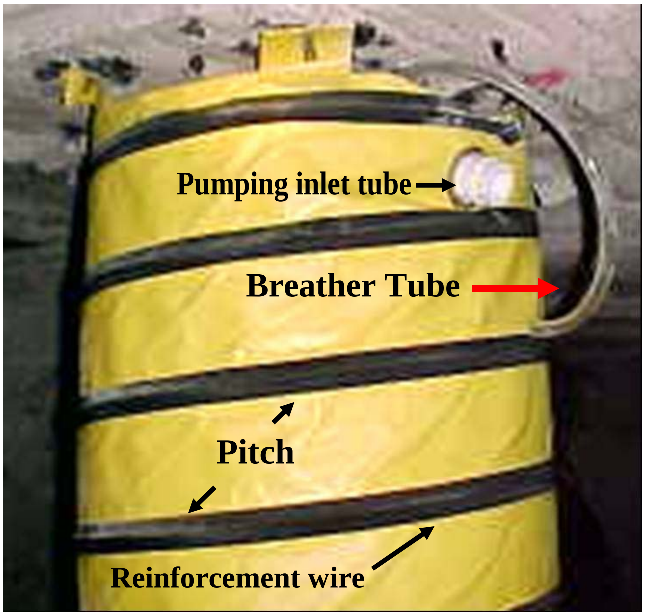


Figure 25. Bag construction showing inlet tube, breather tube, wire pitch, and reinforcment wire.

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 figure 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.

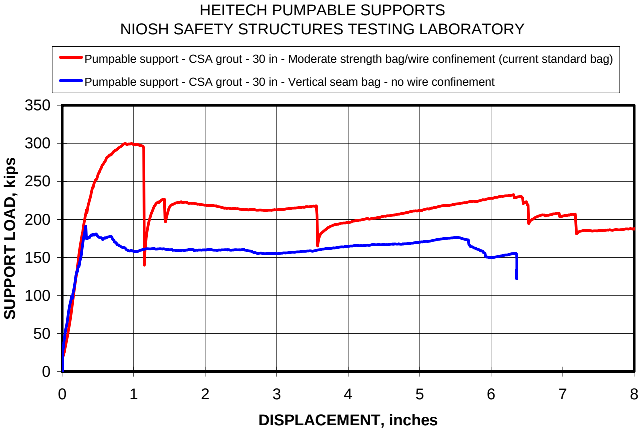


Figure 26. Peak load capacity of the support is increased by the wire wrap. Figure shows comparison between bag with wire and one without wire.

- **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 6-in and a 10-in wire pitch. The standard pitch (wire spacing) of the most commonly used bag manufactured by ABC Industries is 6 inches. The company also provides a 10-gage, 4-inch wire/seam pitch that also has been shown to increase support capacity beyond that provided by the standard 6-in-pitch bag.

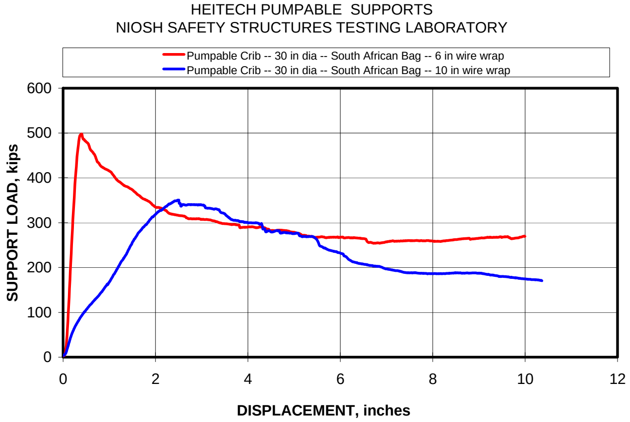


Figure 27. Closer wire spacing can also provide higher peak capacity due to the increased confinement. Chart compares 6-in and 10-in wire spacing.

- **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.

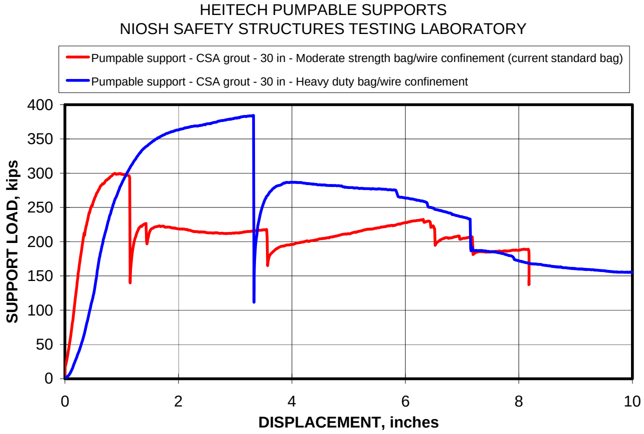


Figure 28. Peak load capacity of the support can be increased by additional confinement provided by the bag/wire system.

Support Stiffness:

The support stiffness (K) is theoretically defined by the following relationship of the support area (A), material modulus (E), and support height (L), resulting in the equation: K= (A x E)/L. 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 30- and 24-in-diameter supports. A 60% increase in loading stiffness was observed with a 63% increase in loading area when comparing the 24- to 30-in-diameter support, confirming the proportionality between the stiffness and loading area. To put the stiffness into perspective, the pumpable support stiffness of 293 to 486 tons/in compares to a stiffness of only 25 tons/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 since the confinement provided by the bag/wire is insufficient to prevent this from occurring. The initial load-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 figure 29, which compares the load-displacement relationship for a bag with a 6-in, 12-gage wire pitch and one with a 4-in, 10-gage wire pitch. The 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 8 inches 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.

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

Test number	Stiffness, tons/in	
	~30-in diameter (763-in^2 area)	~24-in diameter (467-in^2 area)
1	462	268
2	510	318
Average	486	293

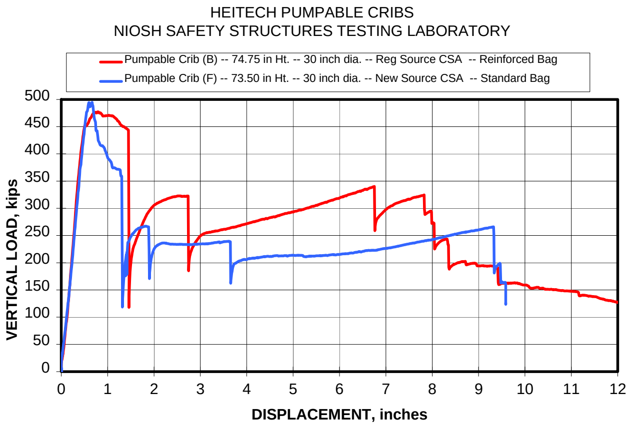


Figure 29. Comparison of 4-in (reinforced) and 6-in (standard) wire pitch bags. Reinforced bag delayed major load shedding and increased residual load capacity.

The installation of pumpable supports reflects a good safety record. Heitech reports 238 lost work days installing pumpable supports over a 5-year period from 2002 to 2006. During this time frame, approximately 110,000 supports were installed. This translates into approximately 21 lost work days 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 work days 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, since 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: (1) aerated cements, (2) Portland flyash cement, (3) Portland pozzolan cement, and (4) 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 flyash/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 flyash/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 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 which 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- 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.

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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Appendix

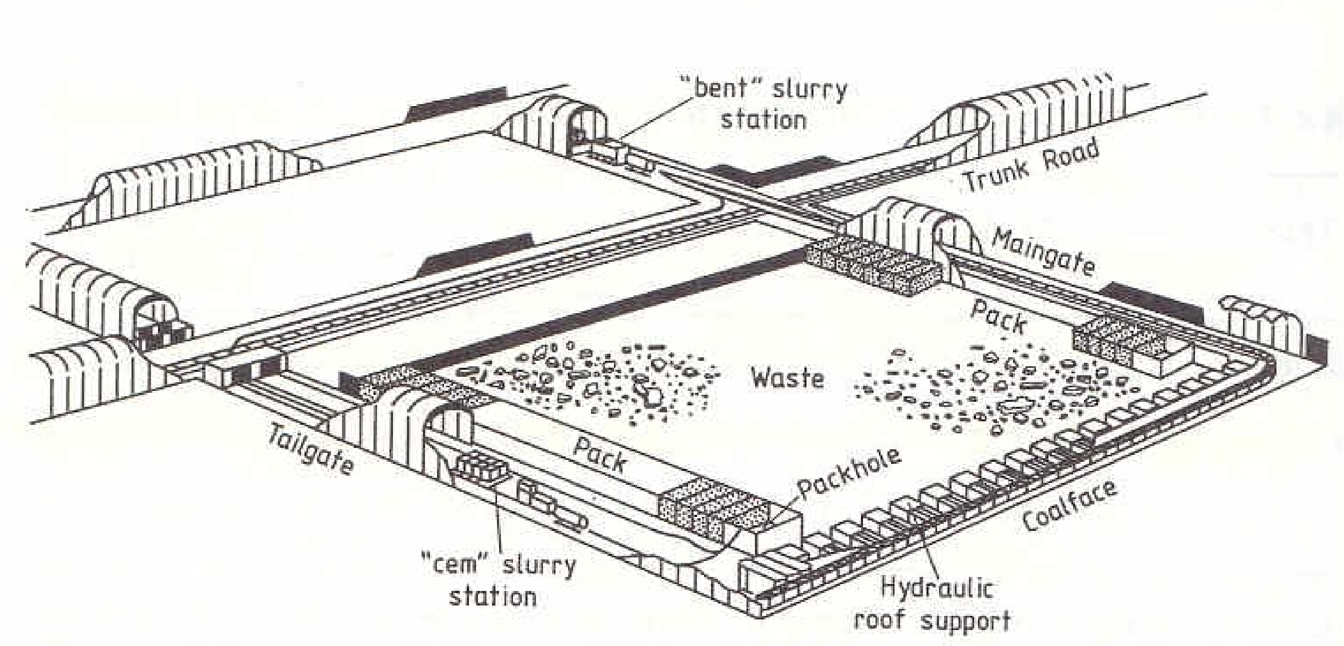


Figure 3. Packwalls in advancing longwall operations were the first systematic use of pumpable materials for support.

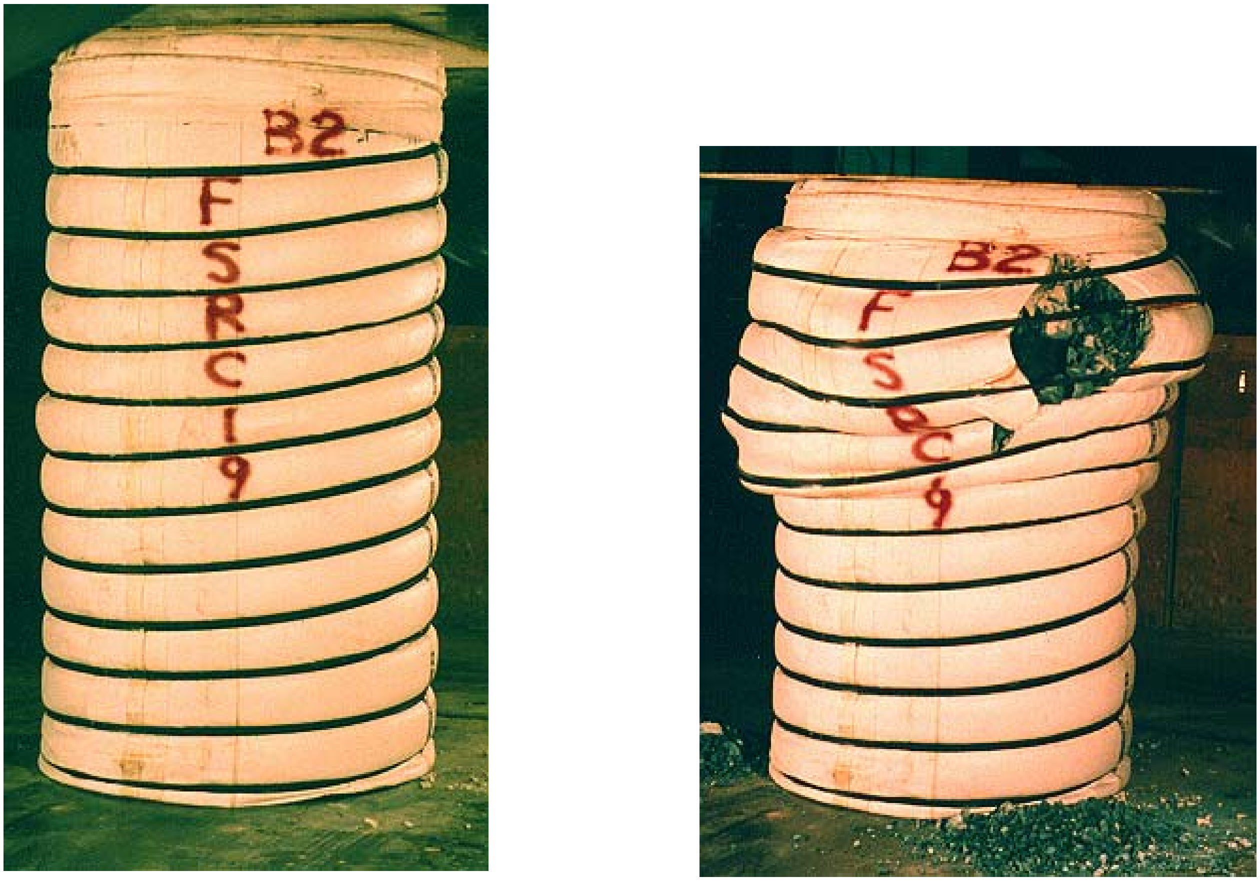
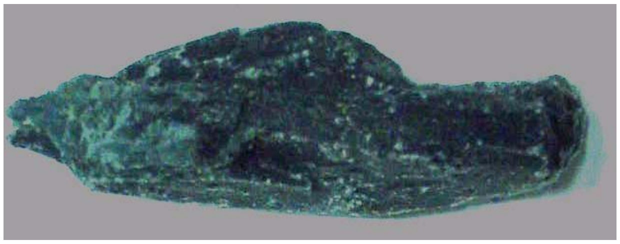


Figure 7. Tekcrib support. Version of this support was first pumpable support installation in longwall tailgate in the U.S. in 1993.

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

Figure 10. Portland flyash cement product used in Mesh Packs support.



Close-up of Tekpak P grout

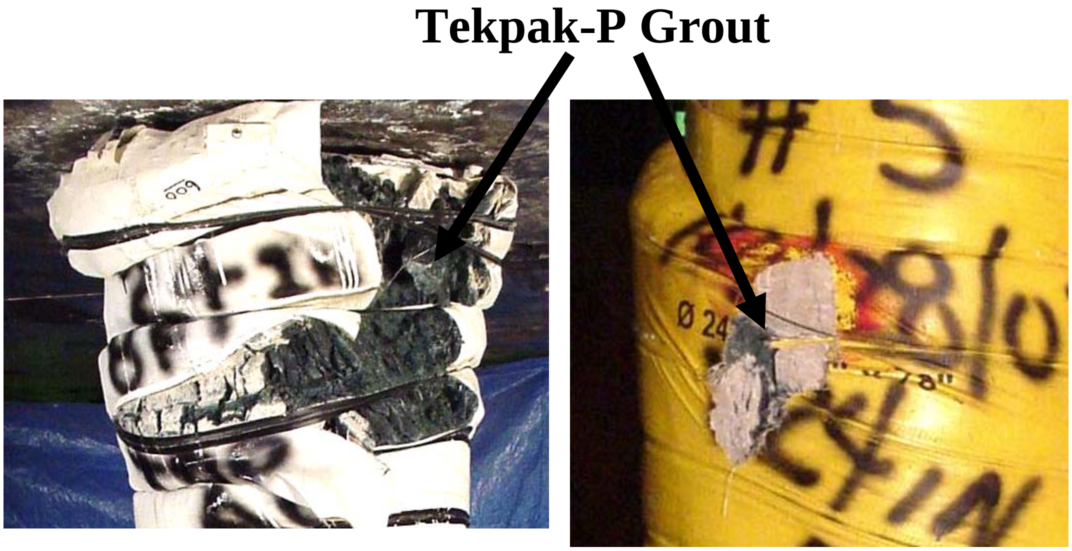
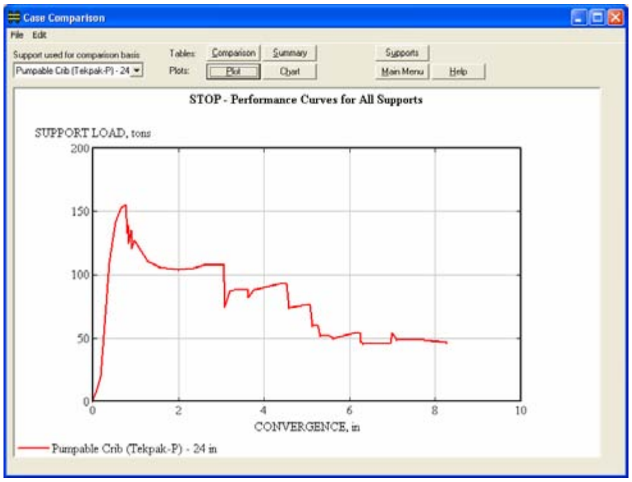


Figure 12. Tekpak P grout is an example of this Portland Pozzolan Cement category. It is dark, almost black, in color.



Support used for comparison basis: Pumpable Crib (Tekpak-P) - 24 in

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

Figure 14. Photo of Tekpak P pumpable support after 6 inches of convergence carrying a load of about 50 tons.