Evaluation of remotely installed mine seals for mine fire control

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ABSTRACT: Of the 19 major mine fire events (including thermal events) that have occurred in the last 6 years (2000–2005), it is estimated that remotely constructed mine seals could have been used at 65% of the events to control or suppress the fire. Underground observations of seals that have been remotely installed during mine fire events show that they often do not fully achieve mine roof-to-floor and rib-to-rib closure. Unfortunately, the inability to reliably close the mine void has limited or precluded the regular use of this technology. The National Institute for Occupational Safety and Health is conducting full-scale underground experiments at the Lake Lynn Experimental Mine to identify and remedy existing remote sealing technology shortcomings, to develop novel technologies, and to transfer the new or improved technologies to the mining industry. This paper will discuss the remote mine seal testing program and will provide the results of the in-mine experiments.

Disclaimer: The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

1 INTRODUCTION

It has been reported that from 1990–1999 there were 81 coal mine fires in the United States (DeRosa, 2004). Moreover, in the last 6 years, 19 major mine fires and thermal events have occurred in underground coal mines in the United States. On average, about three events have occurred each year with a maximum of five events over this time period. These statistics suggest that mine fires are occurring with alarming frequency. It is estimated that remotely constructed mine seals could have been used at 65% of the events to control or suppress the fire.

The need to evaluate, improve, and develop new technology to remotely construct mine seals was identified jointly by National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) in 2001. This need resulted in a NIOSH research project (NIOSH, 2001). In addition, MSHA agreed to serve as a technical partner in this effort. The first phase of the work involved the qualitative review of existing technology used to remotely construct mine seals. The review included materials used to construct mine seals, including cement and polyurethane foam, and an analysis of the available material mixing technologies (surface versus downhole mixing) (Trevits and Urosek, 2002). The second phase of the work involves the remote construction of mine seals. The research was conducted at NIOSH's Lake Lynn Experimental Mine (LLEM) located approximately 60 miles southeast of Pittsburgh, PA. The LLEM is a world-class, highly sophisticated underground facility where large-scale explosion trials and mine fire research is conducted (NIOSH, 1999) (figure 1).

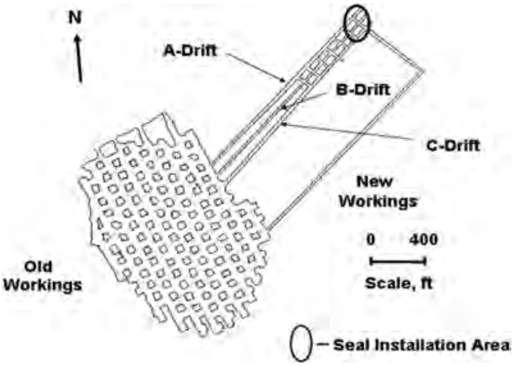

Figure 1. Layout of the Lake Lynn Experimental Mine.

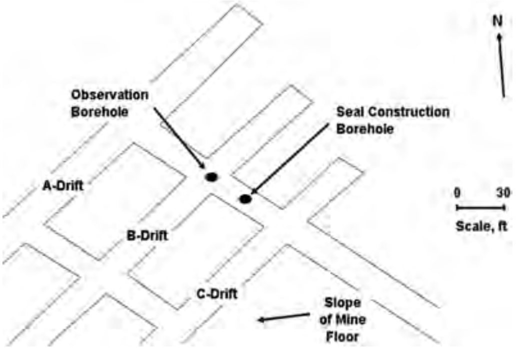

Figure 2. Underground layout of the seal construction site.

Figure 3. Directional elbow for bulk fill placement.

Howard Concrete Pumping Company (Howard) of Cuddy, Pennsylvania and GAI Consultants, Inc. (GAI) of Monroeville, Pennsylvania served as research partners with NIOSH in this effort. This paper describes the development of novel grout-based technology for remote mine seal construction, evaluation of the materials used, construction practices, and follow-up testing. An in-depth discussion of this work is described by Gray et al. (2004).

2 SEAL DESIGN CONSIDERATIONS

The objective of this work was to develop a specialty grout product and a method for placing the product through a borehole into a mine opening to form a mine seal. There were several additional factors that were included in the engineering design process. These factors are listed as follows:

- The methodology developed must be capable of being deployed quickly.
- The mine seal must be rapidly installed.
- The seal material used must be locally available.
- The grout material must be of a consistency to allow placement in a free space without excessive flow if the mine is open and unobstructed but must also be capable of filling a mine opening containing roof fall debris, cribbing, equipment or conveyor structures.
- The grout and the methods of application must facilitate mine roof-to-floor and rib-to-rib closure.
- The seal must be strong enough to withstand the force of a mine explosion (up to 20 psi).

Previously, a 6-in diameter cased borehole was completed in the first cross-cut between the B and C Drifts of the LLEM and it was determined that this borehole was suitable for the seal construction research (figure 2).

The thickness of the overburden in the area of the borehole is 197 ft. The cross-cut in the mine measured 19 ft wide, 40 ft long and 7 ft high, with a mine floor slope gradient of 1.13 percent. A second borehole, located about 30 ft away, was available for viewing the mine seal installation using a downhole video camera. Testing conditions for this technology was not designed as a “blind test” so in-mine to surface communication was facilitated through the use of a mine pager phone system.

3 IN-MINE MATERIAL PLACEMENT TECHNOLOGY

Prior to installing the mine seal at LLEM, a model mine opening was constructed at Howard’s facility for testing and direct observation of the performance of the downhole nozzle and pumping equipment. The model mine opening consisted of a small excavation in a hillside. The roof of the model mine was formed using crane mats so a drill rig could be located over the mine void to hold the pipe for the downhole equipment. Two series of tests were performed at the model mine along with an initial test at the LLEM before the final placement strategy and grout mixture was developed. Changes were made to the cement content, admixtures and additive ratios to improve stickiness, time-of-set and application uniformity. Some laboratory work was also conducted to improve the grout blends by modifying admixtures and additive ratios. After each test, modifications were made to the materials, equipment and equipment usage.

The final technique developed included a specialized directional elbow for directional placement of bulk fill material (figure 3) and a spray nozzle for material to address the remaining open areas in the mine void (figure 4).

The specialized nozzle required the use of two strings of pipe (one inside of the other) to convey two streams of material to the nozzle. The spray nozzle permitted the blending of the two-part grout accelerator mix while allowing sufficient air velocity to

Figure 4. Spray nozzle.

transport the grout to the mine roof-and-rib areas. The bulk grout was pumped to the borehole using a positive displacement pump and compressed air. The sprayed grout was moved to the borehole using a conventional grout pump and compressed air.

4 GROUT MATERIAL

Constructing an effective mine seal through a single borehole is a difficult engineering challenge. The grout mixture cannot be too fluid or it will merely flow away from the borehole. If the grout mixture is too stiff, it will tend to build quickly forming a mound at the bottom of the borehole and will not flow and fill the mine roof-rib areas. It was decided that the first material to be placed in the mine would be a bulk fill material designed to fill most of the open space. This was also the least costly component of the fill material and would help to lower the overall cost of the seal. The bulk fill material used a mixture consisting of fly ash, Portland cement, and 2A (3/4-in minus) crushed limestone aggregate. A conventional concrete admixture was used to accelerate the set of the grout. The material was blended to achieve a pumpable mixture that had adequate strength and rapid setting properties. The amount of fly ash added was sufficient to produce a mix that could be pumped to the borehole, travel down the borehole without segregation and provide a moderate degree of flowability. Once the grout was in-place, the aggregate would provide sufficient shear resistance for the grout to be somewhat immobile until the mix set. Typical initial set time for this mixture could be achieved in 15 to 20 minutes and would support foot traffic in 30 to 45 minutes.

The second material to be used to fill any remaining open space above the bulk fill along the roof-rib line was a two-part grout blend that was developed with the assistance of Master Builder's Concrete Products Laboratory in Cleveland, Ohio. The basic grout was to be a blend of ASTM Class-F fly ash and Portland cement. The initial testing of the grout indicated that a conventional shotcrete accelerator would not produce sufficient stiffening in the desired time frame. Additionally, it did not exhibit suitable rheological and hardening properties required for the grout application. Further testing determined that Master Builder's TCC system was more effective in providing the desired grout characteristics than conventional admixtures. The Master Builder TCC System is made up of two-parts. Part A improves the pumping characteristics and provides a reaction platform for Part B and is mixed with the grout before it is pumped into the borehole. Part B is a liquid, high-performance shotcrete and grout accelerator that reacts with Part A to create an immediate stiffening of the grout. Part B is added to the grout mixture using the spray nozzle (positioned at the mine level) using the stream of air that also transports the grout to the mine roof-and-rib surface. The reaction between the Part A and Part B admixtures essentially provides the initial stiffening through a flocculation process that is unrelated to the chemical hydration of the cement products in the grout. Therefore, a concrete accelerator was also added at the nozzle to accelerate the hydration process. The addition of the accelerator along with the cement content of the grout facilitated rapid strength development of the in-place grout spray. To improve the stiffening properties of the grout and produce the required stickiness for the grout spray to adhere to the mine roof-and-rib areas, the water content of the mix was adjusted while retaining the fluidity and pumpability of the mix through the addition of a high-range water-reducing additive.

As the work on the seal material development progressed, it became apparent that the uniform, consistent blending of the constituents in the sprayed grout was critical to the grout performance. The final portion of the grout mix design work focused on a sensitivity study that identified the grout's reaction to deviations in the blending process. It was concluded that it would be necessary to very finely meter the ingredients in the grout mix to achieve the desired performance from the sprayed grout. After a series of field and laboratory tests, adjustments were made to the equipment used to control material feed and a significant improvement of the material mix was achieved by the GAI engineers.

5 MINE SEAL CONSTRUCTION

Pumping of the first part of the remote seal (bulk material) began using a sand, fly ash and cement mixture. This material was pumped into the mine opening using the directional elbow. The bulk material was pumped in a series of lifts to fill the mine most of the opening. Pumping was terminated after approximately 55 yd^3 of

Figure 5. View of bulk fill placement for mine seal.

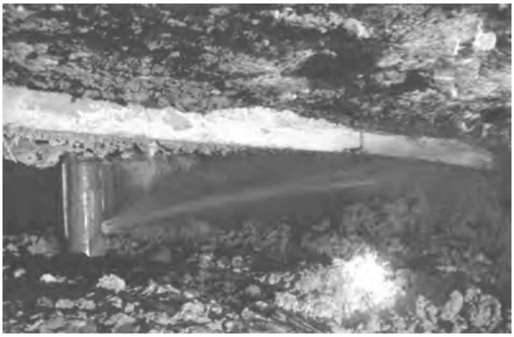

Figure 6. Use of spray nozzle during mine seal construction.

material had been placed into the cross-cut. It should be noted that that communication with underground personnel was allowed to orient the directional elbow and complete the construction of the base. Underground examination revealed that seal material was placed to within 1.5 ft of the mine roof below the borehole and within 2.5 to 3 ft of the mine roof near the rib areas (figure 5).

It was decided to remove 6-in of material near the top of the seal to allow sufficient room to test the capability of the spray nozzle. After conducting a 10 yd^3 surface test of the seal mixture (fly ash, cement and accelerators), a dual string of drill pipe and casing affixed with the spray nozzle was then placed into the 6-in diameter borehole in preparation for the second part of the seal construction. Once the nozzle penetrated the mine opening, seal material was sprayed in a back-and-forth motion along the mine rib areas to fill in the gaps. Interaction between observers underground and engineers on the surface ensured that the nozzle was aimed in the proper direction. Good mine roof-and-rib contact was made with the sprayed material. The problematic corner areas at the mine roof-rib intersection were filled before the grout began to build up and migrate towards the spray nozzle (figure 6).

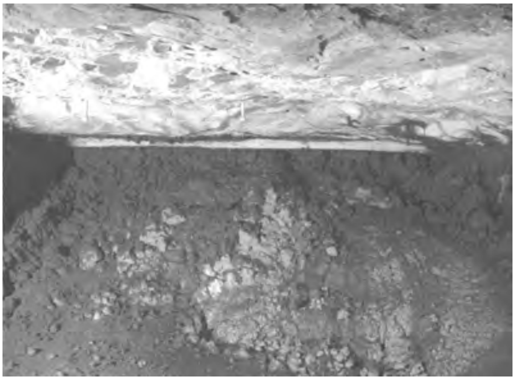

Figure 7. View of completed mine seal.

Filling of the remaining area near the borehole was accomplished by lowering the spray nozzle into the wet material below the nozzle and then rotating the operating spray nozzle through a 360 degree arc. Eventually, the material built-up around the nozzle and closed the mine opening (figure 7). In all, a total of 22.5 yd^3 of sprayed material was used to close the mine opening. An underground examination showed that the mine seal material (both bulk and sprayed material) had flowed about 12 ft from the borehole towards the B-Drift and only about 9 ft from the borehole towards the C-Drift. The shape of the seal approximated a truncated pyramid whose base measured 19 ft wide (the width of the cross cut) by 21 ft deep and whose top measured 19 ft wide (the width of the cross cut) by 3 to 5 ft deep.

6 MATERIAL AND MINE SEAL TESTS

Unconfined compressive tests were conducted on 3-in diameter cylinder samples (cylinder area – 7.07 in^2) that were collected during seal construction. Samples were collected underground as the material was being placed in the mine void. The results of the tests are shown in Table 1. The compressive strength of the bulk fill material is substantially higher than that of the sprayed fill material. The reason for the lower compressive strength of the sprayed material is that the sprayed mix does not contain sand and had air bubbles trapped in the mixture from the mine seal material placement process.

Although the major thrust of this research effort was aimed at development of material mixes and mine seal construction techniques, the benefits of constructing the seal at the LLEM included the option of testing the seal's ability to confine mine air and also to withstand the forces of a mine explosion. Air leakage tests were conducted by building a frame on one side of the mine seal and covering that frame with brattice cloth. Next

Table 1. Results of compressive strength tests on cylinder samples.

Bulk fill material		Spray fill material	
Age, days	Compressive strength, psi	Age, days	Compressive strength, psi
9	2403	5	230
28	3818	7	270
–	–	28	468
–	–	56	765

Table 2. Results of air-leakage tests on mine seal.

Differential pressure across the seal, inches of water gage	0.52	1.05	1.52
Air-leakage rate, ft^3/min	252	322	426

an opening was made in the brattice cloth the size of an anemometer to facilitate air velocity measurements. Once this work was completed, air flow in the mine was adjusted to produce a desired differential pressure and the air leakage through the seal was measured. Air leakage tests were conducted on the mine seal and the results are shown in Table 2 (Weiss, 2003).

Prior to conducting the air leakage tests, several holes (on the order of about 1 inch diameter) were observed in the seal near the mine roof area. Therefore, the air leakage values observed in the table were not totally unexpected.

To conduct the explosion test, a known quantity of methane gas was injected in the end of the C-Drift near the cross-cut where the seal was installed. This area was temporarily closed with a frame and brattice cloth to confine the gas. The gas was diluted with air to achieve an explosive concentration. The gas was then ignited producing an explosion. The mine seal withstood a static load pressure of 18 psi from the explosion with no visible signs of damage (Weiss, 2003).

7 RESEARCH FINDINGS AND RECOMMENDATIONS

The overall objective of the work was to determine if a mine seal could be constructed remotely from the ground surface. This objective was achieved as a seal was successfully built through a borehole and was confined to the cross-cut of the mine opening. The technology used to build the seal was tested and the correct material mix design was developed. The results of follow-up testing showed that a strong and robust seal was constructed as required in the design constraints. The issue of air-leakage can be addressed by slowing the rotation of the spray nozzle to allow for a more substantial build-up of seal material. As an additional remedy, it may be also be possible to insert the spray nozzle into the observation borehole and spray the entire face of the seal to close and fill any remaining holes.

Results of the work to date suggest that this remote seal construction system may have merit for isolating a mine fire. This technique however does require additional trials since considerable communication with the subsurface personnel was needed to achieve rib-to-rib and roof-to-floor closure. One of the fundamental keys to successful in-mine construction is the ability to directly observe the progress of construction. Because this was a research and demonstration project, communication between the surface operation and the underground seal location was permitted. This will not be the case when a mine fire occurs. Additional research is therefore planned to further refine the construction method. A mine seal should be constructed at the LLEM without voice communication with the surface. The only means of observing the progress of construction should be via the nearby borehole equipped with a downhole video camera with sufficient resolution capabilities and lighting. Experience gained during this work also suggests that a downhole laser or radar imaging device should be developed that offers real-time imaging and is capable of penetrating smoke, dust or the fog that forms in the mine opening as the seal material begins to set.

A 6-in borehole was used during the trials at LLEM and the downhole equipment was designed to meet this need. The issue of working with this equipment in smaller diameter boreholes should be addressed along with the fact that deeper overburden depths will undoubtedly be encountered. Perhaps an additional spray nozzle should be constructed to facilitate remote seal construction in small-diameter boreholes.

Finally, it is suggested that this technology should be further evaluated through construction of a mine seal at LLEM in a mine entry that is obstructed with debris (roof fall material) and mine structures (possibly cribbing, track, or conveyor structures). This approach will test the ability of the seal material to flow around obstructions and still form a seal while closely matching the conditions most likely found in an underground mine.

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