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TECHNOLOGY FOR REMOTE MINE SEAL CONSTRUCTION

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ABSTRACT

Mine fires can be especially perilous because toxic products can quickly spread well beyond the fire zone thereby exposing all underground miners to dangerous and deadly conditions. Since November 1998, there have been six major underground coal mine fires or explosions in the United States (Willow Creek (twice), Sanborn Creek, Loveridge No. 22, West Elk and the Jim Walter Resources No. 5 Mine). In each case, the entire mine or specific areas of the mine had to be sealed due to the build-up of dangerous gases and the fear of uncontrolled spread of the fire. Effective placement of mine seals can deprive a mine fire of oxygen and is often followed by water flooding or injection of inert gas into the affected area. When access to the fire zone is impossible because of safety reasons, airtight mine seals can be constructed, in the area of the fire, remotely from the surface through vertical boreholes. Remotely constructed mine seals are commonly made from cementitious material. Since these mine seals are typically erected blindly, it is difficult to determine if mine roof-to-floor and rib-to-rib closure has been obtained. This paper provides a review of the available materials and technology used to remotely construct mine seals through vertical boreholes.

INTRODUCTION

Mine fires constitute one of the greatest threats to the health and safety of those working in the underground mine environment. Since November 1998, there have been six major underground coal mine fires or explosions in the United States. Table 1 shows a summary of these events. As can be observed in the table, mine fires occur with an alarming frequency and each event has the potential for disastrous consequences. A mine fire can be especially perilous because the toxic products of the fire can spread well beyond the fire zone in a very short period of time.

The technology employed to control and extinguish a mine fire is usually focused on removal of one leg of the fire triangle (oxygen, heat, and fuel). The most direct approach involves the application of water, foam, chemicals, rock dust or sand. This method is very effective, because the extinguishing material is placed directly on the fire. Unfortunately, this approach also places firefighters in close proximity to the fire and can expose them to deadly hazards. Furthermore, this approach is limited to the very early stages of mine fire development.

An indirect approach is used when the fire cannot be fought directly because of safety reasons (build-up of gases, bad mine roof conditions, etc.), the supply of available firefighting materials is limited, the fire zone is too large for available underground firefighters, or underground access is blocked or limited. The indirect approach involves the construction of mine seals to limit the inflow of oxygen and enclose the fire zone. Mine seals can be constructed from within the mine or remotely through vertical boreholes. The process can be followed by flooding the affected area or the entire mine with water, inert gases, silt or other material to control and extinguish the fire.

Besides addressing the immediate need to isolate mine fires, mine seals (in-mine construction) are also used extensively to isolate mined-out areas, to control the air exchange between the sealed and open mine areas, to prevent toxic and/or flammable gases from entering the active workings, and to close-off those mine areas susceptible to spontaneous combustion. A seal must also be capable of preventing an explosion from propagating into or out of the sealed area (Weiss et al., 1993). It is estimated that more than 20,000 seals have been erected in underground coal mines in the United States for these purposes (Sapko and Weiss, 2001).

Table 1. Summary of the Most Recent Coal Mine Fires or Explosions.

Date of Fire	Mine Name	Nearest City, State	Fatalities
36123	Willow Creek Mine	Price, UT	0
36185	Sanborn Creek	Somerset, CO	0
36332	Loveridge No. 22 Mine	Fairview, WV	0
36552	West Elk Mine[1]	Somerset, CO	0
36737	Willow Creek Mine	Price, UT	2
37156	Jim Walter Resources No. 5 Mine	Brookwood, AL	13

[1]Considered a thermal event by MSHA

When underground access is impossible or too dangerous, remote mine seal construction can be attempted through vertical boreholes. In theory, this method has great merit because boreholes can be drilled to specific areas of the mine and seals can be positioned close to a fire zone. In this manner, oxygen inflow can be controlled and the spread of a fire can be limited without exposing miners to the hazards. The technology currently employed (injection of cementitious material) however, can be largely ineffective when the seals leak and do not provide effective barriers to air flow or cannot be used to impound water and other inerting materials. Unfortunately, no other viable alternatives exist other than to seal the entire mine at the ground surface.

IN-MINE SEAL CONSTRUCTION

Since the early 1990's, the former US Bureau of Mines, the National Institute for Occupational Safety and Health (NIOSH), and the Mine Safety and Health Administration (MSHA) have been cooperatively investigating various existing and new in-mine seal designs. The focus of this work is to evaluate whether or not these seal designs meet or exceed the requirements of Title 30, Part 75.335 of a Code of Federal Regulations (Code of Federal Regulations, 2001).

According to the Code of Federal Regulations, (CFR), a seal constructed in the mine after November 15, 1992, shall be–

- Constructed of solid concrete blocks at least 15.2 x 20.3 x 40.6 cm (6 x 8 x 16 in), laid in a transverse pattern with mortar between all joints;
- Hitched into solid ribs to a depth of at least 10.2 cm (4 in) and hitched at least 10.2 cm (4 in) into the floor;
- At least 40.6 cm (16 in) thick. When the thickness of the seal is less than 61.0 cm (24 in) and the width is greater than 4.9 m (16 ft) or the height is greater than 3.0 (10 ft), a pilaster shall be interlocked near the center of the seal. The pilaster shall be at least 40.6 cm (16 in) by 81.3 cm (32 in); and
- Coated on all accessible surfaces with flame-retardant material that will minimize leakage and that has a flame-spread index of 25 or less, as tested under ASTM E162-87, "Standard Test Method for Surface Flammability of Materials Using A Radiant Heat Energy Source."

Alternative methods or materials may be used to create a seal if they can withstand a static horizontal pressure of $1.38x10^2$ kPa (20 psi) provided the method of installation and the material used are approved in the ventilation plan. If the alternative methods or materials include the use of timbers, the timbers shall be coated on all accessible surfaces with flame-retardant material having a flame-spread index of 25 or less, as tested under ASTM E162-87, "Standard Test Method for Surface Flammability of Materials Using A Radiant Heat Energy Source" (CFR, 2001).

Before any new in-mine seal design type can be deemed suitable by MSHA for use in underground coal mines, the seal is generally required to undergo full-scale performance testing at NIOSH's Lake Lynn Laboratory (LLL) located near Fairchance, Pennsylvania (Triebsch and Sapko, 1990; Sapko and Weiss, 2001).

REMOTELY CONSTRUCTED MINE SEALS

Remotely constructed mine seals have been used in both abandoned and active mines. In the abandoned mine application, the technology is used to stabilize the mine opening (in the case of actively collapsing mine workings or subsiding overburden, the technology is often called grouting), to serve as a barrier for water, air, and gas migration, and to block the advancement of a mine fire. The types of material used in the construction of seals in an abandoned mine case includes a wide range of materials with cementitious properties (including combustion by-products from power plants).

In an active mine, the materials used have been generally restricted to the cementitious-based materials because of problems associated with the impact of extreme heat or fire. Resin-based materials have not been recommended for application in proximity to an active mine fire because of the possibility that the material may be combustible and as such rendered useless. The combustion of the non-cementitious seal material could also produce toxic products of combustion. Some manufacturers however, claim that certain additives are available that can retard the combustion of resin-based materials (Zekas, 2001).

Underground conditions in the area of a borehole can dictate whether or not an entry can be effectively closed when using remote mine seal technology. If the entry is free of debris, then remote sealing is indeed possible. However, if the mine opening is obstructed with roof fall material, timber, cribbing, pipes or pipelines, equipment or conveyor structures, etc., then construction of effective air-tight seals, using the current technology, becomes somewhat problematic. Conditions become even more difficult if the mine opening is partially flooded because the effects of additional water may significantly change the properties of the seal material if it is not specifically designed for application in a wet mine environment.

Because this technology of seal construction occurs blindly, it is impossible to know if the material being pumped underground is flowing around obstructions and filling the void spaces. Typically, pumping of seal material continues until refusal, until a specified pressure has been achieved, or a specific volume of material has been injected into the borehole. Unfortunately, one does not know if an air-tight seal has been constructed until the pumping process is completed. At this point, it is impossible to reenter the borehole and backfill any remaining voids. If the seal is not effective, then another borehole must be drilled and the extent of the sealing operation can be evaluated using a television camera. If the prior pumping process is deemed inadequate, then the process must be repeated in a new borehole or the one used for the television scan. In some cases, several boreholes can be used along an entry. Bulkheads are constructed through the outside boreholes and grout or seal material is injected under pressure through the interior boreholes (Gray, 1992).

MSHA and NIOSH-Pittsburgh Laboratory have recently initiated a cooperative research project to evaluate single borehole remote mine seal construction technology. Work under this project includes a review of the available material, in-mine construction and testing of seals at NIOSH's LLL, and a field demonstration.

REMOTE MINE SEALING TECHNOLOGY

Several companies that construct mine seals were contacted to determine the kind of material and technology that is either being used or could be used to remotely construct mine seals. Table 2 shows the reported properties and characteristics of remote mine seal material. Although this list of companies may not be all inclusive, it provides a good sampling of the types and kinds of material available. Table 3 shows remote mine seal surface site and borehole considerations. It should be reported that the information shown in table Nos. 2 and 3 were provided by the individual companies. The reported material properties or capabilities were not verified by the government as part of this study. The following provides a discussion of each table.

Table 2 - Material Properties and Characteristics

Material Type - Cement and non-cement based materials were selected as the broad category headings primarily because they represent two differing types of in-mine applications. Resin-based (non-cement) materials may be very useful as a sealant or bonding material in some mining applications, but cement-based materials appear to be the most appropriate choice for mine seal construction near a fire zone. It was reported earlier however,

Table 2. Properties and Characteristics of Remote Mine Seal Material.

Company[a]	MATERIAL PROPERTIES AND CHARACTERISTICS				
	Material Type		Compressive Strength of Material, kPa (psi)	Will Material Flow in a Mine Opening	Application in Flooded Mine Conditions[d]
	Cement Based[b]	Non-Cement Based[c]			
Fosroc (Amick, 2002)	Y	N	$1.38x10^2$ - $2.76x10^4$ (20- 4000)	Y	Y
Heintzmann-Heitech (Breedlove, 2002)	Y	N	$1.38x10^3$ -$8.28x10^3$ (200 - 1200)	Y	N
Halliburton (Bour, 2002)	Y	N	$2.07x10^4$ (3000)	Y	Y
Micon Services, Inc. (Zekas, 2002)	Y	Y	12.1-$1.38X10^5$ (1.75 - 20,000)	Y	Y/N[e]
Howard Concrete Pumping Co. (Crayne, 2001)	Y	Y	$3.45x10^3$ (500)	Y	Y
R.G. Johnson (Adasiak, 2002)	Y	Y	$1.38x10^3$-$1.38x10^4$ (200-2000)	Y	Y

[a] Mention of a specific company name does not imply endorsement by NIOSH or MSHA.
[b] Also includes fly-ash and other power plant by-products.
[c] Includes chemical resin-based materials.
[d] Includes partially flooded workings.
[e] Depends on the material used for the mine seal.

Table 3. Remote Mine Seal Site and Borehole Considerations.

Company[1]	SITE AND BOREHOLE REQUIREMENTS				
	Bulk Mixing Requirements		Minimum Diameter Borehole Needed, cm (in)	Material Mixing Requirements	
	In Transit	On Site		Surface[2]	Downhole
Fosroc (Amick, 2002)	Y[3]	Y	12.7 (5.0)	Y	Y
Heintzmann-Heitech (Breedlove, 2002)	N	Y	10.2 (4.0)	N	Y
Halliburton (Bour, 2002)	N	Y	5.1 (2.0)	Y	Y
Micon Services, Inc. (Zekas, 2002)	N	Y	15.2 (6.0)	Y	Y
Howard Concrete Pumping Co. (Crayne, 2001)	Y[3]	Y[3]	15.2 (6.0)	Y	N
R.G. Johnson (Adasiak, 2002)	Y[3]	Y[3]	10.2 (4.0)	Y	Y[4]

[1] Mention of a specific company name does not imply endorsement by NIOSH or MSHA.
[2] Includes mixing tanks and in-line applications.
[3] Depends on the material used.
[4] Depends on downhole conditions.

that additives are available to retard the combustion of the resin-based materials (Zekas, 2001).

Compressive Strength - This category was included to give insight to the range of strength of the materials that are available. An examination of the reported values shows that the strength of the material available varies from 12.1 kPa to $1.38X10^5$ kPa (2.0 psi to 20,000 psi).

Generally speaking, the higher compressive strength materials are most desirable. This assumes that the material can be used to remotely construct a mine seal of an appropriate geometry for the mine opening and that the seal extends from the mine roof-to-floor and from rib-to-rib.

Will Material Flow in a Mine Opening - Since the floor area of a mine opening could contain debris from a roof fall or otherwise be obstructed as discussed earlier, it is important to know if the material being used will flow into and fill openings without separating into solid and liquid portions. If the material is designed to set up quickly in the mine opening, it may not flow laterally very far and may simply build up and form a mound below the borehole.

Application in Flooded Mine Conditions - This category was included because it is common to find partially or fully flooded mine workings underground. It is therefore important to know if a particular mine seal material will break down, not cure, or become otherwise unusable in a wet mine environment. Table No. 2 shows that some materials cannot be used in a flooded mine environment. Typically, seal material must be specifically designed for application in partially to fully flooded mine workings. If dry mine materials are used in a wet mine environment and if mine water is added through mixing in the mine opening before the material can set-up, the resulting seal material may not have the desired properties.

Table 3 - Site and Borehole Requirements

Bulk Mixing Requirements - This category was included because it is important to know, in advance, the required geometry of the surface location around an injection borehole. If the material can be mixed while in transit to the site, then a smaller surface excavation may be required. If the materials are brought in and mixed on-site, then a bulk mixing plant may be required and a larger surface site must be prepared. In some cases, the surface site conditions are dictated by costs and the volume of material to be injected into a borehole or series of boreholes. One way to avoid a large surface excavation at each borehole is to mix the material at a central plant positioned near one of the injection boreholes. The material can then be transported via temporary pipelines to the other injection hole sites.

Minimum Borehole Diameter Needed - This category represents a key factor for correctly sizing the drill rig required, the diameter of borehole to be drilled, and casing needs. This factor may also dictate if the drill rig must stay on location because of material or pipe handling considerations or if a smaller workover rig can be used during mine seal construction operations.

Material Mixing Requirements - At first glance, this may seem to be a repeat of the Bulk Mixing Requirements category, rather, this category focuses on how the material is mixed and whether mine seal material mixing occurs on the surface (in-line or in a mixing tank) or at the bottom of the borehole. This has implications on the required size of the borehole to be drilled and cased. This factor is especially important if the lower part of the borehole is to be used as a mixing chamber for the various components of the seal mix.

As can be observed in table Nos. 2 and 3, a wide range of products are available to the mine operator. In the case of a mine fire, the availability of suitable materials to meet the underground conditions, the capability for a swift response, level of experience, and the financial aspects will dictate which company or product will be utilized.

Each mine operator should evaluate their specific conditions, the characteristics of the proposed material, the local availability of materials and equipment, and the ability to deliver the materials within the prescribed schedule. It is strongly recommended that a test pour be made into a framework, form or surface excavation that simulates a mine opening before any material is pumped into the mine opening. In this manner, the mine operator can make an on-site evaluation of the material mix, the delivery technology, and if necessary make adjustments. This procedure may not necessarily be required in each application, if the mine operator is familiar with both the material to be used and the experience of the company constructing the mine seal.

SUMMARY

Mine fires constitute one of the greatest threats to the health and safety of those working in the underground mine environment. A mine fire can be especially perilous because the toxic products of the fire can easily spread well beyond the fire zone, via the ventilation system, in a very short period of time. When direct underground access to a fire zone cannot be obtained, mine seals are constructed to limit the inflow of oxygen and enclose the fire zone. Mine seals can be constructed either from within the mine or remotely through boreholes. The requirements for in-mine construction are included in Title 30, Part 75.335 of the Code of Federal Regulations.

A wide range of materials is available for use in remote mine seal construction. Not all of the products discussed in this study can be deemed appropriate for application near an active mine fire zone. The mine operator should evaluate their specific conditions at the time of need, the mine area to be addressed, the characteristics of the proposed material, the local availability of materials and equipment, a company's level of experience, the ability to deliver the materials within the prescribed schedule, and the underground environment. If the conditions warrant, a survey of the mine opening with a permissible downhole television camera will provide useful data for designing the material mix for the mine seal. It is also strongly recommended that a test pour be made into a framework, form or surface excavation that simulates a mine opening before any material is pumped into the mine opening. In this manner, the mine operator can make a direct, on-site evaluation of the material mix and the delivery technology.

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