USE OF GROUND PENETRATING RADAR AND SCHMIDT HAMMER TESTS TO DETERMINE THE STRUCTURAL INTEGRITY OF A MINE SEAL

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Abstract

Over the years, more than 20,000 mine seals have been erected in underground coal mines in the United States. Seals are used extensively in underground mines to isolate worked-out areas, active mine fire zones, and to control water inundations. Seals are most often built directly in the mine and can be fabricated from blocks made of wood or cementitious material. Recently, several explosions occurred within sealed areas of underground U.S. coal mines. These explosions, believed to be initiated by lightning strikes on the surface, destroyed numerous seals and caused considerable damage external to the sealed area. The National Institute for Occupational Safety and Health is conducting research to develop design guidelines, to investigate noninvasive techniques to characterize seal strength properties, and to evaluate seal test methods. As part of this work, a 30-ft wide, 16.1-ft tall and 4-ft thick seal was built in an underground experimental mine using cement and foamed water. Two types of noninvasive techniques are currently being investigated, namely the Schmidt Hammer for measuring compressive strength and ground penetrating radar (GPR) for detecting the presence of anomalies (e.g., voids, discontinuities) within the seal. Once these noninvasive tests were completed, the seal was subjected to destructive explosion testing. This study presents the results of the Schmidt Hammer tests, GPR scans, and the characteristics of seal failure during explosion testing.

Introduction

Mine seals are used extensively to isolate mined-out areas and to control water inundations in underground coal mines. Mine seals are also used to isolate fire zones or areas susceptible to spontaneous combustion. Over the years, more than 20,000 seals have been erected in underground coal mines in the United States. Mine seals, along with generalized rock dusting and ventilation, represent the fundamental means of preventing underground coal mine explosions. Since 1993, seven documented explosions of methane gas and/or coal dust have occurred within sealed areas of underground U.S. coal mines. These explosions, believed to be initiated by lighting strikes on the surface, destroyed numerous seals and caused considerable damage external to the sealed area. Fortunately, these explosions did not cause fatalities or injuries (Sapko and Weiss, 2001).

To effectively isolate areas within a mine, a seal should be designed to control air exchange between the sealed and open mine areas to prevent toxic and/or flammable gases from entering the active workings and to prevent mine air from entering the sealed workings. A seal must also be capable of preventing an explosion from propagating into or out of the sealed area (Weiss, et al, 1993). Since the early 1990's, the former US Bureau of Mines (USBM), the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) have been jointly investigating the capability of various existing and new seal designs to meet or exceed the requirements of Title 30, Part 75.335 of the Code of Federal Regulations (CFR). According to the CFR, if methods or materials other than concrete blocks are used to create a mine seal, the seal must be able to withstand a static horizontal pressure of 20 psi. Before any new seal design type can be deemed suitable by MSHA for use in underground coal mines, the seal design is generally required to undergo full-scale performance testing at NIOSH's Lake Lynn Laboratory (LLL) (Sapko and Weiss, 2001; Triebsch and Sapko, 1990).

Lake Lynn Laboratory

The Lake Lynn Laboratory is a unique research facility designed to provide a full-scale mining environment for the testing and evaluations of mine health and safety technology. LLL is located about 50 miles southeast of Pittsburgh, Pennsylvania near the town of Fairchance and occupies more than 400 acres at the site of a former limestone mine. The underground entries at LLL were built 49-ft wide by 33-ft high and were developed when surface mining ceased in the late 1960's. Later, under the auspices of the USBM, 7,545 ft of new underground development was constructed using 19.7-ft wide by 6.6-ft high entries. These entries, in conjunction with the novel use of two explosion-proof bulkhead doors, can be configured to simulate modern-day mining, including room-and-pillar and longwall mining conditions (Triebsch and Sapko, 1990).

Test Chambers (Sapko and Weiss, 2001)

In 1998, as a alternative to the evaluation of mine seals in multiple entries against methane and/or coal dust explosions, two underground chambers were constructed in the LLL. The chambers were designed for pneumatic, hydrostatic, or explosion pressure loading tests of mine seals and to assist in the development of size-scaling guidelines for seals in mine entries in excess of 7.9 ft high and/or 20 ft wide.

The chambers vary in size and are referred to as the large and small chambers. The dimensions of the large chamber are 30 ft wide by 16.1 ft high with a maximum cross sectional area of 483 ft^2. The smaller chamber is 20 ft wide by 8.0 ft high and can accommodate a seal design with a cross sectional area up to 160 ft^2. Both chambers are connected via remote-controlled air valves to two diesel-driven air compressors which provide 1,000 cfm of air. The air compressors are used to conduct the pre- and post-explosion leakage measurements. During air leakage testing, a seal is pressurized to about 4.7 in of water gage and, as the air leaks out, the pressure decline is recorded. The rate of pressure decline is then converted to an average volumetric flow rate using adiabatic and isothermal models. Air pressure can be slowly increased to apply a load on the seal up to as high as 20 psi depending on the leakage rates through the seal.

Internal explosions of methane gas and oxygen are used to characterize the ultimate failure strength of a mine seal. To achieve methane gas-air ignitions, each chamber is equipped with a methane gas and oxygen injection system. Oxygen and 99.9% pure methane gas are supplied by compressed gas cylinders to the chambers. A pre-determined amount of methane gas is fed into the void space behind the seal and is thoroughly mixed with oxygen using a fan located within the sealed area of the chamber. Uniformity of pre-test gas concentrations in the void space are determined by drawing gas through tubing and into an on-line infrared methane gas analyzer and a paramagnetic oxygen analyzer. Void space gas samples are also collected in evacuated glass tubes for subsequent analysis by gas chromatography. When the appropriate gas concentration has been achieved, the gas mixture is ignited at the center of the combustible volume by a 0.5 s electrical discharge from a 30 kV luminous tube transformer across a 0.125 in spark plug gap.

The two chambers are equipped with internal 0-200 psia strain gage pressure transducers for measuring the internal explosion pressure history. Three spring loaded linear variable displacement transducers (LVDT) are mounted around a 90-degree bend outside the chamber exit and connected to the test seal via lightweight nylon (fishing) line. This mounting system protects the LVDTs from flying seal fragments. During testing, one LVDT is connected at the exact center (mid-height and mid-width) of the seal. A second LVDT is connected at a 1/4-height and mid-width point. A third LVDT is connected at the 3/4-height and mid-width point. As the seal is pressure loaded, the seal displaces outward and the LVDTs measure this displacement by generating an output signal. The LVDT output is recorded at 2,000 samples/s per channel with a WINDAQ- PC-based data acquisition system.

Mine Seal Construction

As part of the ongoing research program to determine geometric size scaling relationships, a large mine seal was constructed in the large chamber at the LLL. The thickness of the seal was set by NIOSH researchers and was based on the overall cost of the seal and the need for performance data on a seal of this geometry. Since this seal was designed as a poured-in-place structure, building a form was the first step in the construction process. The vertical components of the front and back portions of the form were built from 6.5 in by 5 in posts that extended from the mine floor to roof. A post was placed at both ribs and additional posts were spaced between the rib posts on 35 in centers. The void space behind the posts in the chamber was 8 ft on the left side and 6 ft on the right side. Next, 8 in wide by 1 in thick boards were placed in a horizontal position and were nailed to each post. The boards were placed at the bottom of the form and an 8 in horizontal space was left between each row of boards. This procedure was followed on the front and back walls of the form (figure 1). Fiberglass insulation was then packed into any void space on the mine roof, ribs, and floor areas to minimize slurry leakage around the form. A 48.5 in space was left by design between the front and back walls of the form for the mine seal.

Figure 2. Mine seal form under construction showing posts and cross members.

Mine brattice cloth was placed on the inside area of the form and was overlapped on the mine roof and rib areas and was secured with straps to form a tight seal. Eye bolts were then attached to each post through the brattice cloth and were tied together with 1/8-in galvanized steel cable that was extended between the front and back of the form. The eye bolts were spaced approximately 32 in apart on each post and were used throughout the vertical extent of the form. The eye bolts and cable served to tie the front and back walls of the form together and assisted in keeping the walls parallel and straight.

The mine seal was constructed in a series of three lifts over a three-day period. The seal mixture used was made of 18 gallons of foam concentrate, approximately 436 gallons of water and 989 bags of Quikrete cement.[1] The water and foam concentrate was mixed together and was added to the cement at a rate of 8.5 gpm. The resulting slurry was then pumped into the form. The first lift was poured to a height of 72.5 in above the mine floor and was left to set overnight. The next day, before the second lift was poured, it was observed that a hard surface had formed at the top of the lift. The second lift was poured to a height of 77.5 in (or 150 in above the mine floor) using the same mixing procedure and was also allowed to set overnight. As had been observed the previous day, it was noticed that a hard surface had formed at the top of the second lift. The third lift was constructed using the same procedure as the first two lifts to fill the remaining 43.2 in space to the mine roof. The overall dimensions of the resulting mine seal were 30 ft wide by 16.1 ft tall by 4 ft thick (figure 2).

Figure 3. View of mine seal at a late stage in construction.

Mine Seal Testing

Since the entire amount of material used during the construction of the seal was not mixed in bulk at the same time and because the seal was constructed as a series of lifts, it was felt that variations in mixing of the slurry components could lead to changes in the compressive strength of the mine seal, development of anomalies within the seal, and possibly a weakness in the structure. Furthermore, because the seal was constructed as a series of lifts, it was theorized that the bubbles in the foam could have been squeezed or compressed from the lower portions of each lift thus causing variations in the compressive strength of the mine seal. One way of determining if such change had occurred in the mine seal was to collect core samples from the seal and perform compressive strength tests on the recovered core samples. Unfortunately, the collection of core samples was not possible because the resulting drill holes (even if plugged) could compromise the structural integrity of the mine seal during follow-up explosion testing.

In order to determine the internal conditions of the seal, non-destructive testing was performed to measure the compressive strength and the structural integrity of the seal. Two methods were chosen to evaluate the mine seal. The first involved the use of a Schmidt Hammer, a common tool for evaluating the strength of concrete. The second method involved the use of ground penetrating radar (GPR) to determine if anomalies, such as voids or discontinuities, existed within the seal that could indicate changes in the mine seal properties or to expose the existence of flaws that may have developed during the construction process.

The seal was cured for 33 days before testing was performed. In order to gain direct access to the face of the seal, three vertical sections were cut into the wooden form and brattice cloth. The three vertical sections were approximately 8 inches wide and exposed the seal material from the mine floor to roof. The vertical sections were located at 4 ft from the left rib (Section 1), about 12 ft from the right rib near the

[1]Specific mention of a product name or company does not imply endorsement by NIOSH.

middle of the seal (Section 2), and 4 ft from the right rib (Section 3). Each vertical section was subdivided into both one-inch and one-foot segments for use as reference points during the tests.

An inspection of the seal was conducted to determine if any flaws on the exposed face of the seal were discernable. Such flaws could have been created during seal construction or as a result of the curing process. The inspection included a physical evaluation of the exposed seal face and sounding of the seal face with a hammer to determine if near-surface voids were present. Overall, it was observed that the areas where the horizontal boards were not used, the seal material flowed out beyond the form creating bulges that extended outward up to 1 in at some locations. Table 1 shows the results of the examination of the exposed seal face over the three vertical sections.

Table 1. Results of examination of exposed area of seal face.

Section 1		**Section 2**		**Section 3**	
Interval	Observation	Interval	Observation	Interval	Observation
3.0 to 4.3 ft	Hollow when sounded with hammer	4.8 to 6.1 ft	High angle fractures almost vertical	3.0 ft to 4.0 ft	Small holes less than ½ in dia.
4.0 to 4.5 ft	High angle fractures almost vertical	10.0 to 11.0 ft	Small holes less than ½ in dia.	11.0 to 12.0 ft	Small holes less than ½ in dia.
5.0 ft to 5.6 ft	Hollow when sounded with hammer				

Schmidt Hammer Tests

The standard method of evaluating the quality of concrete in buildings or structures is to test specimens cast simultaneously for compressive, flexural and tensile strengths. The main disadvantages are that results are not obtained immediately; that concrete in specimens may differ from that in the actual structure as a result of different curing and compaction conditions; and that strength properties of a concrete specimen depend on its size and shape. Although there can be no direct measurement of the strength properties of structural concrete for the simple reason that strength determination involves destructive stresses, several non-destructive methods of assessment have been developed. These depend on the fact that certain physical properties of concrete can be related to strength and can be measured by non-destructive methods. One such non-destructive method is the use of a rebound hammer. The rebound hammer is a surface hardness tester for which an empirical correlation has been established between strength and rebound number. The Schmidt Hammer is an instrument that uses the rebound principle for concrete testing and is suitable for both laboratory and field work. The Schmidt Hammer provides an inexpensive, simple and quick method of obtaining an indication of concrete strength, but accuracy of ±15 to 20% is possible only for specimens cast cured and tested under conditions for which calibration curves have been established. The results are affected by factors such as smoothness of surface, size and shape of specimen, moisture conditions, and type of cement used. (Feldman, 1997; Malhotra 1976)

Schmidt Hammer tests were performed on the seal using a pendulum-type unit as shown in figure 3. Tests were made in triplicate at each location over the vertical extent of each section of the seal. The resulting values were then averaged for each location and this average value was used to calculate the compressive strength for any given height. The results of the Schmidt Hammer tests expressed as compressive strength are shown in Figures 4 to 6. It is assumed that the values of compressive strength only represent the conditions of the mine seal to a depth of about 1 ft. As can be observed in each figure, there appears to be an overall gradual decrease in compressive strength progressing higher through the vertical extent of the mine seal. Although the exact reason for the change in compressive strength is unknown, it is speculated that the following factor could be responsible. Bubbles in the foamed water in the lower portions of the seal may have been compressed or squeezed-out during construction. This process would then create a seal with more dense material near the lower portions and progressively less dense material moving upward towards the top of the seal.

Figure 4. Miner performing Schmidt Hammer test on Section 3 of the mine seal.

Examining each lift, there is a marked increase in compressive strength near the top of lift 1 across all sections. This increase is also observed near the top of lift 2 in Section 1 (although not as dramatic) and similarly in Section 3. During the construction process for each lift, all components of the seal material were mixed and blended in a pipeline, rather than in a bulk mixing tank. As the seal was being poured towards the top of the lift, it is speculated that the liquid components of the mix may not have been added at the exactly the same concentration (perhaps lower) as was used earlier in the pour. If this occurred, then the resulting material, when cured, would have a higher compressive strength at the upper area of a lift.

Ground Penetrating Radar (GPR)

Ground penetrating radar is a non-invasive geophysical method that uses electromagnetic wave propagation and scattering to image, locate and quantitatively identify changes in electrical and magnetic properties in the subsurface (Olhoeft, 2001). The first ground penetrating radar survey was performed as early as 1929, however the variety of current uses did not occur until 1974. (Olhoeft, 1999). GPR has applications in archeological, construction, environmental, and geological work, and a whole host of other engineering studies. GPR is often used to determine the location and depth of buried objects along with determining the lateral continuity of strata and other geological or man-made features.

The equipment used to perform the ground penetrating radar surveys of the seal was a GSSI SIR® System 2 (SIR-2) Model No. DC-2 built by Geophysical Survey Systems, Inc.[1] (Molinda et al, 1996). The SIR-2 is certified as intrinsically safe for use in underground mining applications and is a lightweight, portable, general-purpose radar system (figure 7). The system generates an electromagnetic pulse which is transmitted into the ground via an antenna that is moved along the surface at a uniform speed and direction. The transmitted energy of the pulse is radiated in an elliptical conical pattern roughly 90° front-to-back and

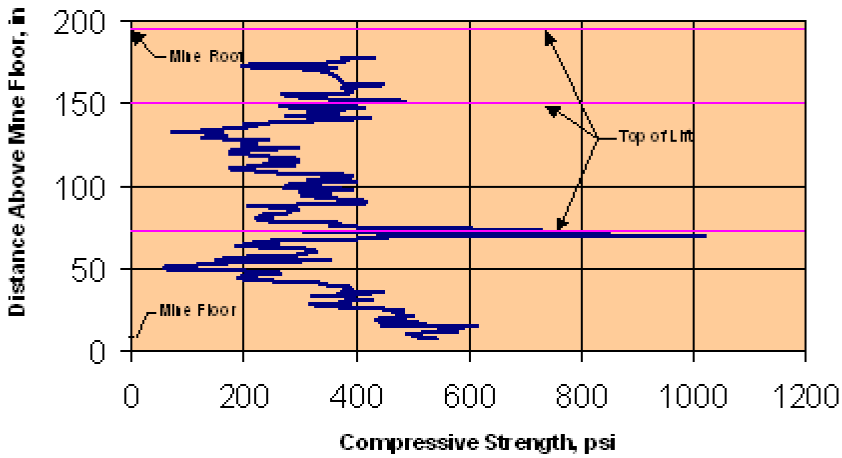

Figure 5. Plot of calculated compressive strength from Schmidt Hammer test data versus distance above the mine floor for Section 1.

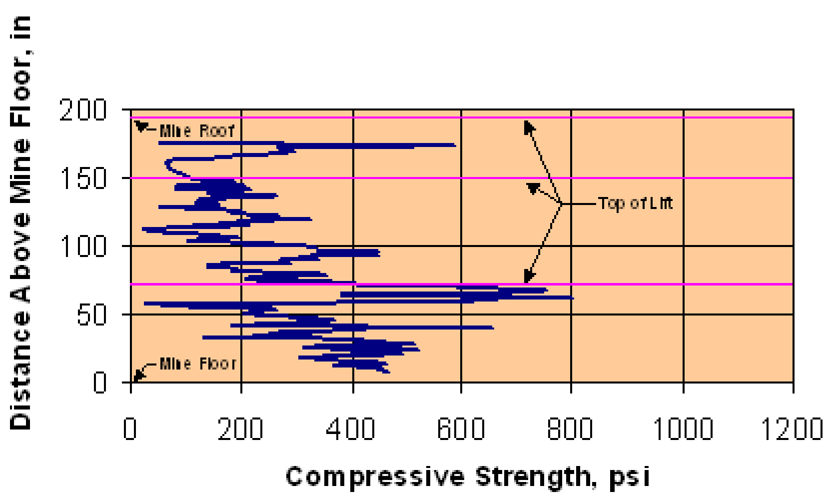

Figure 6. Plot of calculated compressive strength from Schmidt Hammer test data versus distance above the mine floor for Section 2.

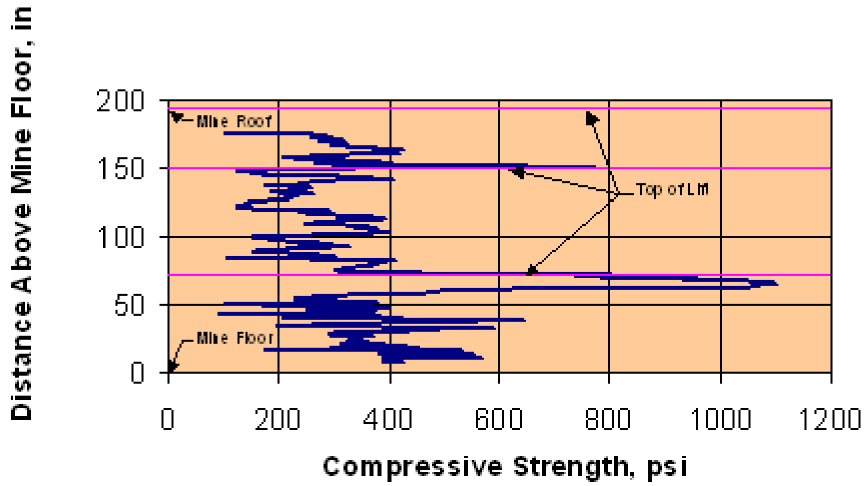

Figure 7. Plot of calculated compressive strength from Schmidt Hammer test data versus distance above the mine floor for Section 3.

60° side-to-side. The transmitted pulse encounters various earth materials, each with different dielectrical properties. Whenever there is a change in the subsurface material and dielectric constant, a portion of the pulse energy is reflected back to the surface and is detected by the receiving antenna. This reflected pulse provides information regarding two-way travel time and attenuation characteristics (signal strength) associated with the subsurface material. The received return pulse is then processed by the control unit in the radar system, and the data are displayed on a monitor and/or stored on an internal hard disk. The output display can be (1) a single wiggle trace (analogous to an oscilloscope trace), (2) a waterfall plot of the wiggle traces, or (3) a multicolored line scan in which the reflected signal amplitudes are represented by various colors according to a user-selected color look-up table. The data can also be printed via an external printer.

Figure 8. Engineer monitoring SIR-2 unit during GPR scan of mine seal.

The two-way travel time is determined by measuring the time interval between the start of the transmit pulse and start of the received reflected signal. The amplitude of the reflected signal is influenced by the size and geometry of the target, the signal attenuation characteristics of the geological materials, and the total distance that the pulse has to travel.

How well GPR works depends on two electrical properties of the geological materials under investigation: dielectric constant (relative dielectric permittivity) and electrical conductivity. The dielectric constant affects the velocity of propagation of the radar pulse. The dielectric constant ranges from 1 for air (fastest propagation) to 81 for water (slowest propagation). The greater the difference in dielectric constant between two materials, the stronger the reflected pulse energy becomes. Electrical conductivity controls the depth of pulse penetration. The lower the conductivity of the material, the deeper the pulse can penetrate. The conductivity is controlled by the water, mineral, and clay content in the subsurface. The depth of penetration of the pulse also depends on the frequency of the antenna. Higher frequency antennas (e.g., 900 MHz) provide high resolution, but shallow depths of penetration; conversely, lower frequency antennas (e.g., 200 MHz) have low resolution, but can detect significantly deeper targets.

GPR Surveys of the Mine Seal

Given the large size of the mine seal and the fact that access to the seal face was accessible along the sections cut into the forms for the Schmidt Hammer tests, it was decided only to scan the seal along the section areas. Using this approach, it would then be possible to directly compare the results of the GPR work to the Schmidt Hammer test data. Because of the excessive height of the seal, surveys of each section were conducted in two parts; one that extended from the mine floor area to a height of 8 ft and the second that extended from a height of 8 ft to the mine roof (height of 16.1 ft). Since the thickness of the mine seal was known, it was decided to use a 400, 500 and 900 MHz antenna to image the seal. After a short series of tests, it was determined that the 900 MHz antenna was of too high a frequency to penetrate the entire thickness of the mine seal and was not used further. Also, only scans of the lower section of the mine seal were conducted with the 400 MHz antenna because of technical problems with this antenna. The setup parameters used for each scan using the 400 and 500 MHz antennas are shown in table 2.

Table 2. SIR 2 set-up used for GPR scans of the mine seal.

Parameter	**Setting for 400 MHz Antenna**	**Setting for 500 MHz Antenna**
Data collection mode	Continuous	Continuous
Range, ns	25	25
Samples per scan	512	512
Resolution, bits	16	16
Number of gain points	5	6
Vertical high pass filter, MHz	60	50
Vertical low pass filter, MHz	1000	800
Scans per second	32	32
Horizontal Smoothing, scans	4	4
Transmit Rate, KHz	64	64
Dielectric Constant	4.5	4.5

A total of 25 scans were made of the mine seal. Each scan was made by placing the antenna against the seal face and then moving downward at a constant velocity (figure 8). Reference points were placed into the record corresponding to the 1 ft marks on the mine seal. In this manner, it was easy to associate any observed anomalies with the specific location on the mine seal. The scan data were analyzed using GSSI's Radar Data Analyzer for Windows NT (RADAN) software.[1] This package allows the user to operate in the Windows environment with application-specific modules. An example of an interpreted radar record showing an anomaly is displayed in figure 9. Figure 10 shows the positions of all observed anomalies from the GPR scans of the mine seal. As shown in figure 10, a total of 12 anomalies were observed in scans where the 500 MHz antenna was used and 4 anomalies were observed in scans where the 400 MHz antenna was used.

Figure 9. Researchers performing GPR scan of mine seal.

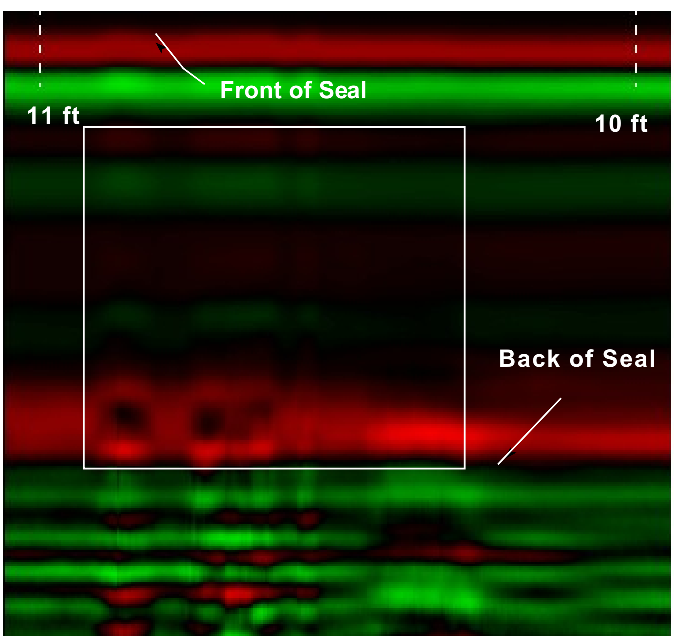

Figure 10. Interpreted radar plot from GPR scan of Section 2 from a height of 10 to 11 ft above the mine floor. Note the anomaly is shown in the box.

From table 3, it can be observed that 11 of the 16 anomalies were located about 12 in from the top of a lift. The top of a lift represents a boundary in the seal. This was apparent from observations made during mine seal construction that showed a hard surface had formed overnight on the top of the first and second lifts. Furthermore, the 11 anomalies are also located at or near the areas of increased compressive strength as calculated from the Schmidt Hammer test results.

Of the remaining five anomalies, four were located at the position of an eyebolt and galvanized wire connection that was used to secure the front and back of the seal form (refer to the discussion on mine seal construction earlier in this paper). Also, examinations of the compressive strength data showed that the position of each of the five remaining anomalies were located near areas where the compressive strength values of the seal material were changing from either a local high or low value.

Air Leakage and Explosion Testing

Once the Schmidt Hammer test and GPR scans of the mine seal were completed, an explosion test was conducted. An air-leakage test was not conducted on this seal because of problems with the air compressors.

The mine seal was tested using an explosive concentration of air and methane gas using the procedure outlined earlier in this paper. Once the gas was ignited, the seal started to rupture and vent explosive gases along a vertical centerline crack as

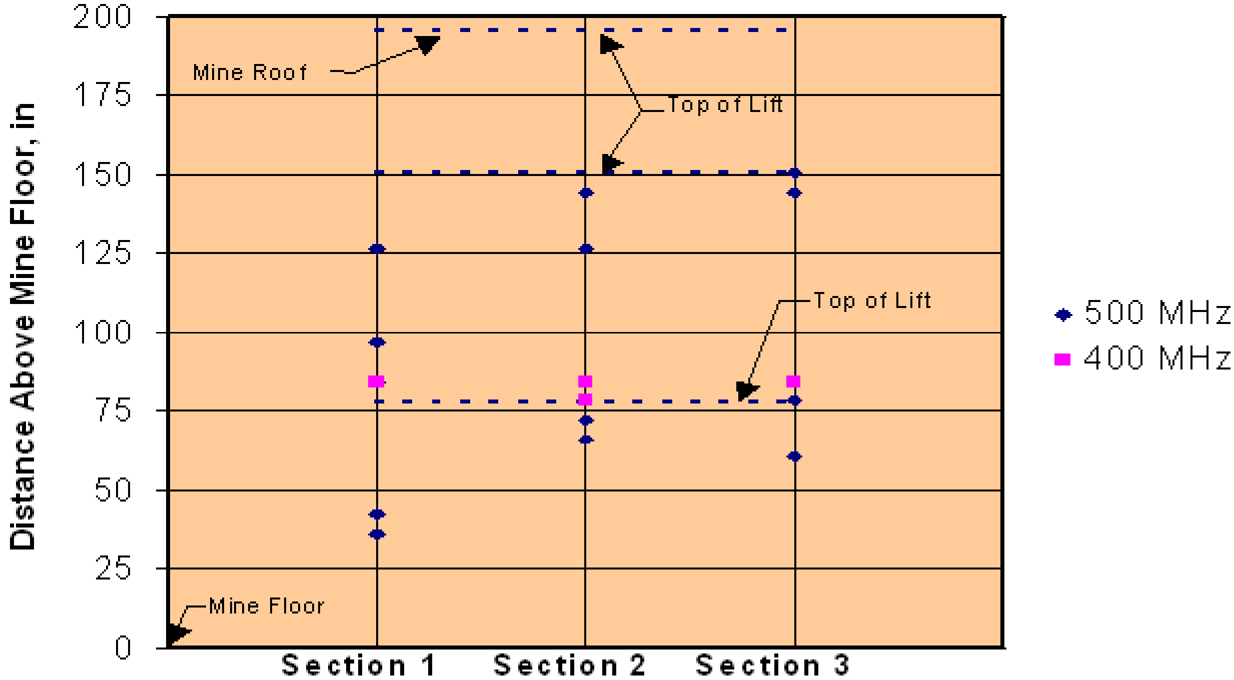

Figure 11. Plot of observed anomalies from GPR scans versus distance above the mine floor.

Table 3. Location of anomalies detected by GPR.

Section No.	Height of Lift, in	Location of anomaly from mine floor, in	Distance from top of nearest lift[2], in
1	72.5	36	-36.5
1	72.5	42	-30.5
1	72.5	84	11.5
1	72.5	96	23.5
1	150	126	-24
2	72.5	66	-6.5
2	72.5	72	-0.5
2	72.5	78	5.5
2	72.5	84	11.5
2	150	126	-24
2	150	144	-6.0
3	72.5	60	-12.5
3	72.5	78	5.5
3	72.5	84	11.5
3	150	144	-6.0
3	150	150	0.0

[2]Negative values indicate the distance the anomaly is below a lift line and positive values indicate the distance the anomaly is above a lift line.

the confined methane-air explosion pressure reached 8 psi. A total of 120 ft^3 of methane gas was used in the test. Figures 11 to 14 is a sequence of photos showing the progression of the explosion test. NIOSH research on similarly constructed seals in the small chamber suggested that this seal would fail below the 20 psi threshold. As expected, failure occurred in the center area of the seal since this area was not confined by the mine roof ribs and floor. The sequencing of seal failure did not appear to correlate to the variations in compressive strength observed in the data or to any of the anomalies observed in the GPR scans.

Figure 11. Mine seal just prior to explosion test.

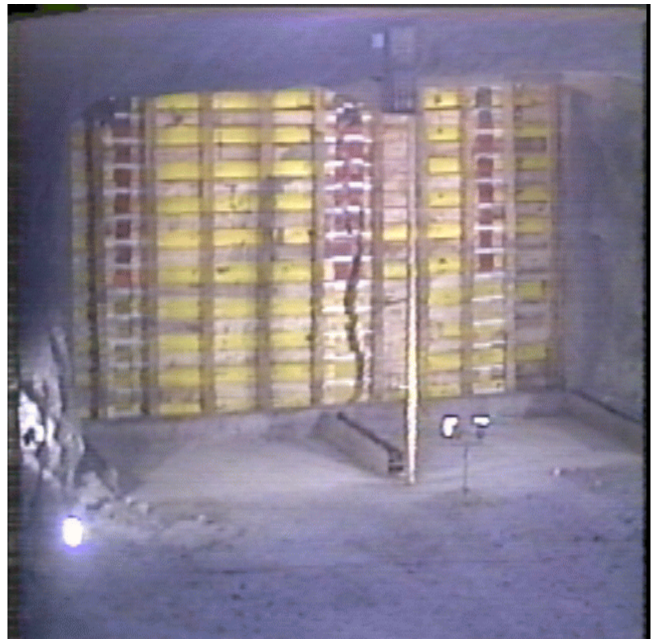

Figure 12. Mine seal showing fracture formation near center of mine seal.

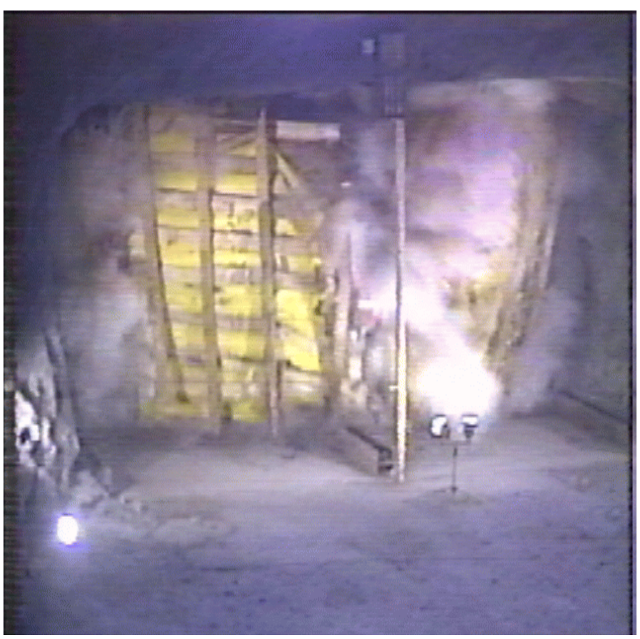

Figure 13. Failure of middle-right side of seal.

Figure 14. Complete failure of seal.

Summary and Remarks

Two different noninvasive techniques were used to measure compressive strength and the presence of anomalies within a poured-in-place mine seal. Schmidt Hammer tests were used to calculate the compressive strength for any given height along three vertical sections of the seal. Further examination of each lift showed a significant increase in compressive strength towards the top of the lift in all sections for lift 1 and in Sections 1 and 3 for lift 2. The results of the tests show a gradual decrease in compressive strength as one progresses higher through the vertical extent of the seal. Although the exact reason for the change in compressive strength is unknown, it is speculated that bubbles in the foamed water in the lower portions of the seal were compressed or squeezed-out during construction creating more dense material near the lower portions and progressively less dense material moving upward towards the top of the seal. Also, any change in compressive strength may be related to changes in the concentration of the liquid components of the mixture used during seal construction.

GPR can be used to detect anomalies within a seal and variations in seal material providing there are differences in the respective dielectric constants. A total of 16 anomalies were observed from the GPR scans of the seal. Of the anomalies observed, 11 were located near the top of a lift and were either related to the hard surface that had formed at the top of the lift or areas where the seal components could have been mixed at different ratios. The five remaining anomalies could be related to the construction practice of the mine seal (use of eyebolts and galvanized wire). Further examination of the compressive strength data shows that the position of these anomalies appear to correspond to areas where the compressive strength values of the seal material were changing from either a local high or a low value.

The sequencing of mine seal failure during explosion testing did not appear to correlate to the compressive strength trends observed from the Schmidt Hammer test data or to any of the anomalies observed in the GPR scans.

Because this was a first attempt to at using noninvasive testing technology to determine the structural integrity of a mine seal, much work remains before firm conclusions can be made about the universal applicability of any of the methods used in this study.

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