Time Dependent Roof Deterioration at a Central Ohio Coal Mine

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ABSTRACT

Roof deterioration in weak moisture-sensitive rock leads to roof falls in coal mines. An observation site was set up in intake air at an underground coal mine in central Ohio to evaluate the time-dependent deterioration of moisture-sensitive roof rock. By periodically collecting and weighing the rock falling from the roof, the National Institute for Occupational Safety and Health (NIOSH) was able to quantify the deterioration of the moisture-sensitive shale roof. The measurements showed that more roof rock is falling in the dry winter months. Movements in an intersection were monitored in order to determine if deformation correlated with seasonal changes in temperature and humidity. The rate of intersection roof-to-floor convergence was found to be cyclical and related to seasonal changes, with more convergence during the months of April through September. At the study site intersection, the roof beam did not show deflection indicating movement most likely due to mine floor deformation. The bolt load also increased in the warmer months before shedding load, possibly due to rock failure. Temperature and relative humidity sensors, placed in holes in the roof show that mine air does not mix with the air in the holes. Consistent saturation levels of relative humidity were measured in the holes and it appears that high levels of moisture may have migrated into the bolt holes from roof shales. A roof sealant applied to a portion of the test roof appears to be preserving the roof and reducing the amount of rock fall into the entry, while the screened area virtually eliminated rock falling from the roof.

INTRODUCTION

During the past 5 years, 2,300 U.S. coal miners have been injured by rock falls. There have also been 82 ground fall fatalities since 1995, and of these, 15 have been attributed to skin failure (Mark et al., 2009). Skin failures involve rocks that fall between roof bolts. The reasons for roof skin failures include weak bedding planes, slickensided surfaces, and moisture-deterioration of mudstones (Molinda et al., 2008; Molinda and Klemetti, 2008). Although there are numerous causes of roof skin failures, moisture sensitivity is the primary focus of this research.

Several moisture sensitivity index tests have been proposed in the past and laboratory comparisons of the tests have been performed (Klemetti and Molinda, 2009), yet there has been limited field evaluation of these indices and their relationship to the mining conditions. A more thorough evaluation of the moisture sensitivity index test results in relation to the condition of the mine's roof are still needed.

There is no established standard for controlling or characterizing moisture sensitive roof. Numerous mines and researchers have developed and utilized engineering controls to improve the condition of mines with weak, moisture-sensitive roofs. The primary function of these engineering controls is to provide maximum coverage of the roof to minimize roof skin failures (Compton et al., 2007). Gadde et al., (2006) recommends using roof screen to control roof skin failures when the roof is weak. Similar to roof screen, spray-on sealants have been developed for and utilized in mining applications. A successful application of a spray-on sealant was described by Mark et al., (2004). Numerous other sealants have been developed for mine roof coverage, including one developed by Kot Unrug at the University of Kentucky (Unrug, 1997). This sealant is a mining emulsion sealant designed to create a non-permeable membrane that will prevent moisture changes and therefore, protect the rock against weathering.

In mines with weak, moisture-sensitive roof rock, bolts must be fully grouted (Unrug et al., 2004). Roof bolts with exposed annulus allow moisture penetration parallel with bedding plans leading to much faster degradation of the roof rock. Degradation may also be accelerated by unsealed test holes in the mine roof. It has been speculated that roof damage is increased due to mine air entering open bolt and test holes (Unrug, 1997; Chugh and Missavage, 1980).

There is abundant evidence that the time an entry remains open and the humidity variations of the mine air affect the condition of the roof (Unrug and Padgatt, 2003). This is especially true in weak moisture-sensitive roof rocks and regions of the world where temperature and humidity change drastically throughout the year (Mark et al., 2004). The effect of these conditions on the mine roof can range from small roof rocks falling to larger roof falls. Moisture-sensitive rock can have an immediate impact, but more often is seen as a time-dependent deterioration. The stability of the mine openings can impact the safety and performance of the entire mine.

Due to these factors that can influence roof stability, NIOSH researchers designed a field study to evaluate these issues. The two primary goals were to evaluate (1) the long-term stability and (2) the seasonal affects on mine entries with highly moisture-sensitive roof rock. Secondary goals included:

- evaluating some engineering controls for weak moisture-sensitive roof rock;
- developing a case history to correlate laboratory moisture-sensitivity indices to mine roof conditions;
- studying the mixing and infiltration of entry air into drill holes in the roof.

The paper describes the study site, presents the instrumentation, evaluates the rock for moisture sensitivity through laboratory testing, presents the results from the field study, and presents the key issues determined from the study.

STUDY SITE DESCRIPTION

The subject mine of this study is located in eastern Ohio in the #7 seam. The mine is a three-year-old room-and-pillar operation, with a life of ~20 years. The mains are driven from a box cut on the surface. The depth of cover ranges from 100 to 300 ft. The coal seam thickness ranges from about 4.5 to 5.5 ft. The immediate roof consists of a shale layer of variable thickness overlain by a relatively thick, strong sandstone layer. A generic depiction of the immediate roof is shown in Figure 1. Throughout the mine, there are locations where the sandstone rolls down to the top of the coal causing the shale layer to vary in thickness between 0 and 12 feet. The shale layer is weak and moisture sensitive, whereas the sandstone is strong and not moisture-sensitive.

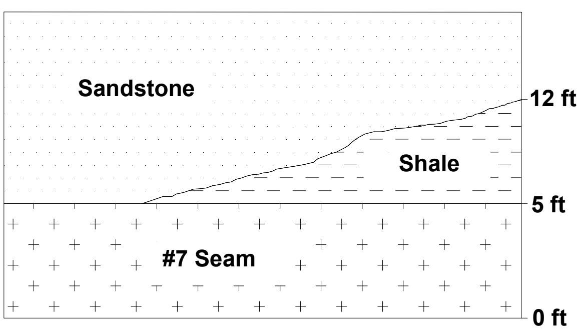

Figure 1. Generalized roof at the study.

The mine layout can be seen in Figure 2. The area to the north on the map is the old workings, which are now sealed. The entries are typically 19 ft wide. The main pillars in the mine are generally 60 x 60 ft on centers. The primary roof support consists of 5/8-in, fully-grouted, 5-ft-long bolts installed 4 per row with a 4-ft spacing. In addition, four 10-ft-long cable bolts were installed in the intersections. When the mine began operation, screen was installed in four entries; 1 intake, 1 return, travelway, and the belt. Screen was not installed in the cross-cuts.

The study site is located on the East Mains as seen in Figure 2. The layout of the study site, including instrumentation locations and roof rock collection areas, can be seen in Figure 3. In order to

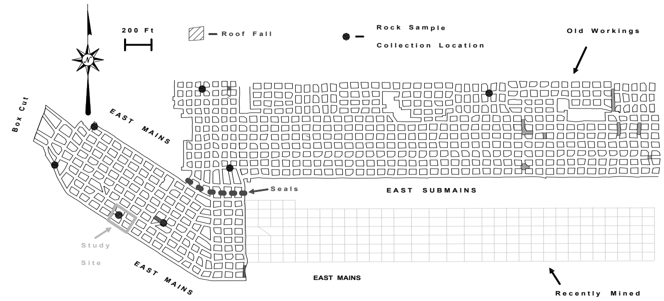

Figure 2. Study mine layout.

insure that the seasonal changes in temperature and humidity would propagate to the study site, a location approximately 700 ft inby the mine portal was chosen. Previous research has demonstrated that air is tempered after the air travels through the mine (Molinda and Klemetti, 2008). The study site was mined less than 3 months prior to the beginning of the study. Additionally, this study site was used to evaluate engineering controls for skin control in highly moisture sensitive roof rock. Two specific controls were evaluated in this study, roof screen and a sealant. Because screen was installed on cycle in 4 of 8 entries, the opportunity to evaluate this control was available. The sealant[1] used in this study was an emulsion fluid developed by Kot Unrug at the University of Kentucky to create a non-permeable membrane around the exposed rock. The sealant was applied to the roof with a spraying device similar to a garden sprayer at concentrations of 50% and 100%. It appears blue immediately upon application and shortly dries to form a surface barrier.

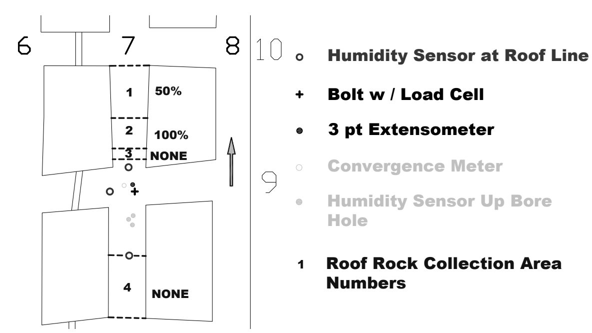

Figure 3. Study site layout with instrumentation and area locations.

This study used three methods to monitor the condition of the roof at this mine site: fallen roof rock, instrumentation, and visual observation.

EVALUATION TECHNIQUES

Roof Rock Collection

Fallen roof rock can be an indicator of the time dependent deterioration due to moisture. The roof rock collection component consisted of four distinct areas where the floor was covered with tarps to capture the rock falling from the roof throughout the study

1 Mention of company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

as shown in Figure 4. The tarps covering the floor were used to separate the fallen roof rock from that already on the floor. The roof rock on the tarps was collected in buckets and weighed with a portable scale. The resulting weights were recorded for each area during the visits to the study site.

Figure 4. Photo of roof rock collection areas 8-16-07, location 1.

Roof rock collection area 1 was sprayed with a 50% concentration of roof sealant, and area 2 was sprayed with a 100% concentration, as seen in Figure 3. The 50% concentration consisted of 50% sealant and 50% water. The remaining two areas were not sprayed with the sealant. All of the roof rock fall collection areas were originally quite similar in appearance.

Instrumentation

The instrumentation deployed at the study site consisted of a roof-to-floor convergence monitor, roof sag extensometer, bolt load cell, and humidity and temperature sensors as illustrated in Figure 3. The convergence monitoring was intended to show the seasonal effects on the roof and floor. The swelling and shrinking of the immediate rock surrounding the openings may be captured in the convergence measurements. The mechanical extensometer and the convergence rod may allow for determination of the roof and floor convergence individually. The bolt load may be another indicator of the swelling and shrinking occurring in the roof as well as the separation occurring in the roof. The relative humidity and temperature sensors were installed to document the seasonal changes in humidity and temperature in the entries as well as determine if there was communication of humidity from the entries into the roof. These sensors were used to investigate changes in grouted bolt holes, un-grouted bolt holes, and tests holes resulting from varying weather conditions.

There were two instruments used to measure convergence of the mine opening, the roof-to-floor convergence monitor and the roof sag extensometer. The roof-to-floor convergence monitor was a convergence rod installed in the center of the intersection between the roof rock collection areas. The convergence rod was simply installed between the roof and floor with no anchors. The roof sag extensometer used in this study was a three-point mechanical extensometer. The instrument has three string potentiometers to measure displacement. The potentiometers are connected to anchors installed at 2 feet, 8 feet, and 15 feet above the roof line. The anchor furthest up the hole defines the horizon of measurement, with the box holding the potentiometers connected to the roof. The two intermediate anchors can show where the separation is occurring. Depending on the spacing of the anchors, the separation can be located to within half the spacing of the anchors. The bolt load cell, a Geokon Model 3000, was a strain gage type cell. The cell was installed between the bolt head and bolt plate, with an initial load of approximately 17,000 lbf. The bolt was a 5-ft mechanical-anchored bolt installed centered between the primary bolt rows which were already installed.

The humidity and temperature sensors were positioned in two distinct locations, one within the entry and one up drill/bolt holes. There were initially three sensors installed in the entry hung from bolt plates along the roof of the study site. Additionally, 9 sensors were installed in the three holes drilled in the roof. The first hole had the sensors and setting rod up the hole, remained open, and is referred to as the open hole. The second hole was covered with a bolt plate attached to the roof with anchors. The third hole was sealed with clay to simulate a grouted hole. The sensors in the drill/bolt holes were located at 2-ft, 8-ft, and 12-ft horizons above the roof line.

Visual Observation

The visual observation component consisted of photographic documentation of the aging of the study site and the adjacent entry. The benefit of both the screen and sealant as well as the time dependent roof deterioration, can be seen through the photographs taken over the study period. The locations of the photos taken during each visit can be seen in Figure 5.

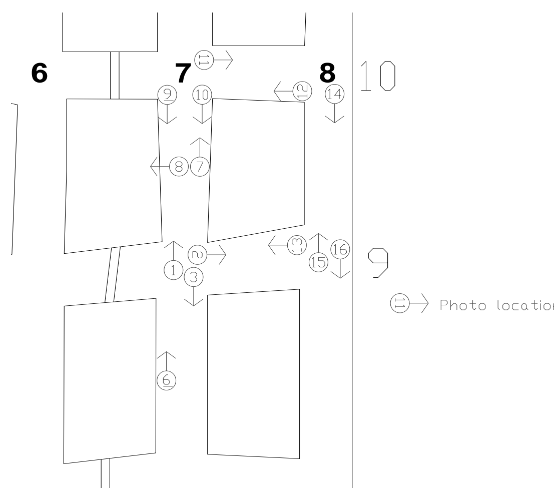

Figure 5. Study site layout with photograph locations.

MOISTURE SENSITIVITY TESTING

The University of Kentucky Weatherability test (Weatherability test) is a three part test, requiring special testing apparatus and specimens either from cores or roof slabs weighing between 500 and 2000 grams (Unrug, 1997). The first part is oven drying to a constant weight and weighing of the samples. The second part is the wetting (1 hour) and air drying (6 hours) of the samples. The final part is oven drying and weighing of the samples. The multiple wetting and drying cycles of the test simulate the seasonal wetting and drying that attacks coal mine roof. Details of the Weatherability test procedure are available in previous publications (Unrug, 1997). The resulting Weatherability Index is a ratio of the degraded material weight, based on the largest remaining intact fragment's weight, to the initial specimen's weight expressed as a percentage.

Weatherability Test Results

The Weatherability test was performed on 89 specimens obtained at several locations throughout the study mine, as shown in Figure 2. Figure 6 is a distribution of the results of the Weatherability Index of the 89 specimens of gray shale (Ferm No. 124) from the mine's immediate roof. The overall Weatherability Index average of the shales tested was 49%. While a majority (65%) of the values fall into the moisture sensitive range (>40%), there are a number of specimens that are not reactive to moisture. The variation in results may be attributed to the inherent variability of rocks. Rock characteristics vary widely throughout a mine as well as in a smaller sample. The variation may also be attributed to variations in bedding and spacing in the individual specimens. Another potential cause for the variation is the presence or absence of swelling minerals in the individual specimen samples.

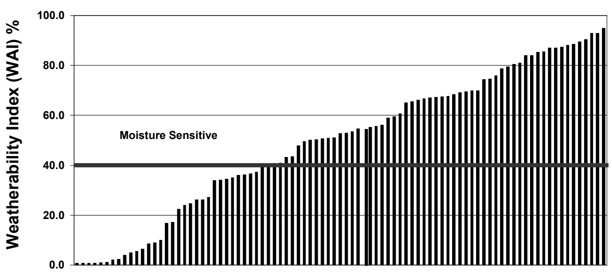

Figure 6. Moisture sensitivity variability of the immediate roof rock (gray shale, Ferm No. 124).

Spray Sealant Testing

Prior to the field study, samples from the study site area were evaluated using the Weatherability test, with and without being coated in the lab with the spray-on sealant used in this study. These tests were performed as a baseline for the results from the field study. Table 1 compares the moisture sensitivity indices from coated and uncoated samples collected at the study site. The location where the samples were collected can be seen in Figure 2. The coated samples showed a drastic decrease in the moisture sensitivity. The average Weatherability Index for the uncoated samples was 29.8% and for the coated samples was 0.7%. This indicates that the coated samples are no longer highly moisture sensitive. Therefore, it was anticipated that the study site would show a similar protection against moisture exposure where the sealant was applied.

STUDY SITE RESULTS

Roof Rock Collection

The fallen roof rock collection provided the most intriguing results from this study as presented in figure 7. The normalized average weight of roof rock collected per day was approximately

Table 1. Study Site Weatherability Index Test Results, Coated vs. Uncoated.

Sample Condition		Weatherability Index %
Uncoated	Average	29.8
	Maximum	69.8
	Minimum	2.2
Coated	Average	0.6
	Maximum	0.7
	Minimum	0.6

0.0069 lb/ft^2 in both coated areas, compared to about 0.0230 lbs/ft^2 for the uncoated areas. The areas sprayed with sealant yielded 2.9 and 3.8 lbs/ft^2 of roof rock collected during the first year of monitoring. The areas with no sealant yielded 9.2 and 15.5 lbs/ft^2 during that same period. The two uncoated areas showed at least 2.5 times and as much as 4.8 times the fallen rock of the two coated areas. The uncoated areas had varying roof rock falling rates throughout the study, whereas the coated areas had similar trends, as seen in figure 7. Some of the rocks collected from the uncoated areas were much larger than the rocks collected from the coated areas. There were two periods of increased roof rock fall amounts, December 2007 through March 2008 and December 2008 through February 2009.

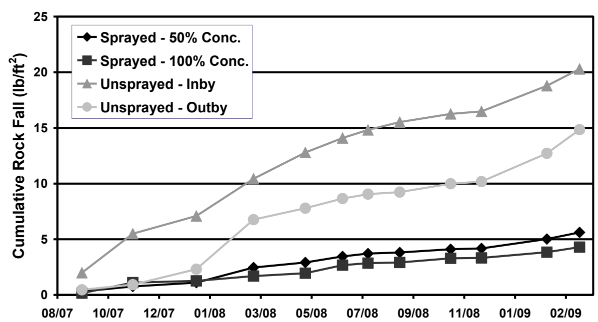

Figure 7. Cumulative roof rock collection results.

The results demonstrate the improvement expected from sealing roof rocks when compared to the areas that were not coated with the sealant. There does not appear to be any distinct seasonal trends associated with the falling roof rock. The results also indicate that this sealant can be diluted with 50% water and still maintain the same level of protection. Since the spray sealant has no strength, it should be applied as quickly after mining as possible for the greatest effect prior to roof sag. A photo of the roof rock collection area taken on March 3, 2008 prior to rock collection can be seen in Figure 8.

Convergence

The cumulative roof-to-floor convergence for the study site can be seen in Figure 9. The plot shows that the convergence is continually increasing with time. There are four distinct periods in the figure. Periods one and three have a much higher rate of convergence compared with periods two and four. The increase in

Figure 8. Photo of the rock collection area, looking inby from the intersection, taken on March 3, 2008.

the rate of convergence corresponds to the warmer humid months of April through September. This increase in humidity can cause swelling of the roof and floor leading to the increasing rate of convergence. Another possible factor in the changing rates is bed separation of the weakly bedded immediate roof and floor.

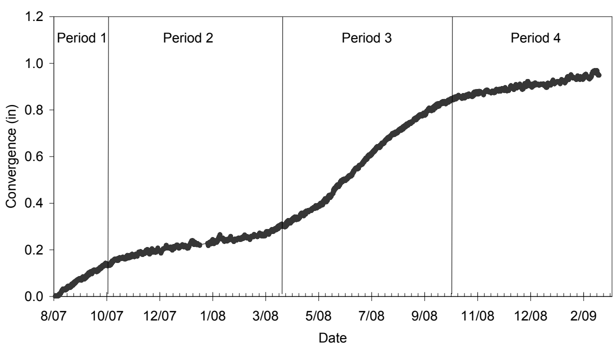

Figure 9. Convergence measurements in intersection of study mine.

Another instrument deployed at the study site was the 3-point mechanical extensometer intended to document the roof sag over the entire study period. The mechanical extensometer never measured any roof sag. With the extensometer showing no roof sag and the convergence rod measuring roof-to-floor convergence, swelling of the floor is probably the cause of the convergence.

Bolt Load

The bolt load cell shows an almost immediate reduction in load. The initial load loss is typical with a mechanical anchor bolt. This initial drop off was followed by a steady decline from September to January and a steady increase from January until mid July. In mid July there was a steep reduction in the bolt load. After this steep reduction, the bolt load has been gradually decreasing ever since. This trend, as seen in Figure 10, does not correspond to the trends of the convergence measurements. This steep reduction in July 2008 could be due to anchor slippage or roof deterioration around the bolt plate. It appears that the bolt loading is somewhat related to seasonal trends. The mechanical bolt appears unable to sustain the full design load in this roof.

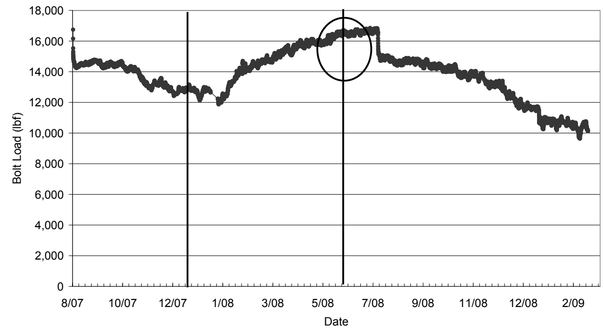

Figure 10. Bolt load in intersection of study mine.

Temperature and Humidity

The temperature and humidity sensors showed a constant relative humidity of 100% throughout the entire year on the sensors located in all three holes at 2-ft, 8-ft, and 12-ft horizons above the roof line. A single sensor was placed approximately 1 ft above the roof line in the open hole on 28 April 2009 and has maintained 100% relative humidity ever since. The sensors in the entry varied in relative humidity from less than 40% to 100% throughout the year, reflecting the ambient conditions. The constant relative humidity in the holes, including the open hole, shows that no air transfer is occurring between the entry and the hole. It indicates that the humidity is coming from the formation rather than the humidity in the entries' air. Thus, the roof is still subjected to moisture trapped in the formation which may still be damaging the roof. The relative humidity measurements up the hole are the overlapping lines at 100% in Figure 11.

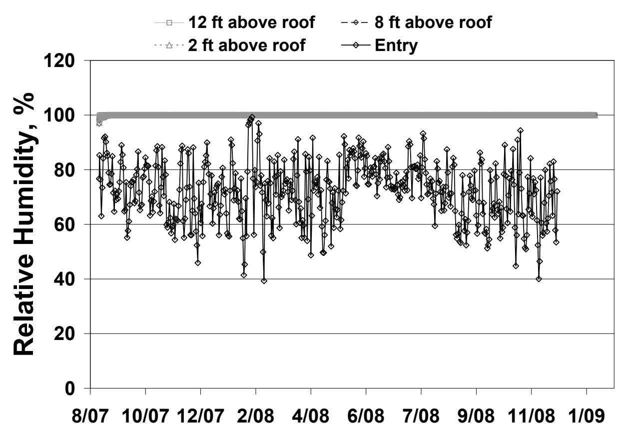

Figure 11. Open hole and entry humidity.

The temperature in the holes was also extremely constant on a daily basis compared with the entry measurements. The daily variation was typically less than one degree Fahrenheit in the hole sensors compared to an average of around seven degrees Fahrenheit for the entry sensors. There was also very little variation in the temperature and relative humidity measurements among the three open and sealed holes. A sample of the temperature results can be seen in Figure 12. The temperature measurements are thicker smoother lines for the sensor up the open hole. The thinner line represents the temperature in the entry.

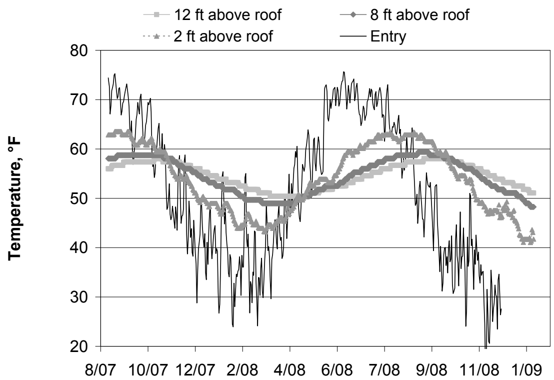

Figure 12. Open hole and entry temperature.

Visual Observation

The final method used in evaluating the deterioration of the roof was visual observation documented with photography. Several photographs were taken during each visit to document the time dependent deterioration of the roof. The locations of these photographs can be seen in Figure 5. The photograph in Figure 13 was taken on August 16, 2007, at onset of study, from the intersection in the study site looking inby, point 5 in figure 5. This photo shows minor roof deterioration and no roof rock on the tarps as would be expected at the beginning of the study. Figure 14 is a photo of the same location taken on June 25, 2008. Figure 14 depicts a much greater level of roof deterioration and roof rock on the tarp than that in Figure 13.

Figure 13. Photo taken 8-16-07 looking inby at study site, location 1.

In addition to the photographs demonstrating the changing conditions in the instrumented area, photographs of the adjacent entry were taken. This adjacent entry is also in intake air and the

Figure 14. Photo taken 6-25-08 looking inby at study site, location 1.

roof is screened. As seen in photo in Figure 15 taken during the 10th month of the study, the screen contained the roof rock and subsequently maintained better overall conditions. Several previous studies have shown the benefit to roof screening in moisture sensitive roof control (Molinda et al., 2003; Compton et al., 2007).

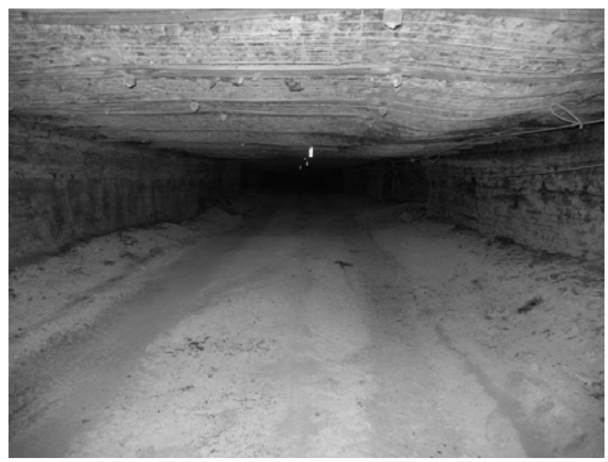

Figure 15. Photo taken 6-25-08 looking inby in adjacent entry with screen, location 15.

CONCLUSIONS

The roof rock volumes, along with several other measurements, demonstrated the importance of time to the deterioration of roof rock in coal mines. Seasonal changes appear to have some impact on the condition of the roof. Weak moisture-sensitive roof rock at the study mine began deteriorating within 1 year of the mine opening.

From the convergence measurements, it appears that the floor swells substantially during the hot humid months of the year and may continue moving slightly during the cold dry months. The extensometer also showed that the roof was either not acting as a beam or that the anchors are unable to maintain solid contact.

Since the extensometer showed no movement but the convergence rod did record displacement during the study period, the movement recorded is most likely due to floor heave. The floor heave appears to be related to seasonal temperature and humidity changes in the mine air. The bolt load has not regained its peak load since last summer, which may be related to anchor slippage or loss bolt tension due to creep yielding or deterioration of the roof rock most likely move the bolt plate.

The other interesting outcome from the instrumentation at the study site came from the humidity and temperature monitoring. The results showed that the intake air moisture does not affect moisture content in drill or bolt holes, one foot above the roof line. All three open and sealed tests holes maintained 100% humidity from two feet above the mine roof to the top of the hole and a single sensor maintained 100% relative humidity less than one foot above the roof line in the open hole. This lack of communication between the moisture in the entry and open holes indicates that if open bolt holes cause a problem, it is probably not due to penetration of the mine air as some have speculated, but rather to the effect of in situ groundwater. The temperature and relative humidity measurements do not explain the seasonal loading and increased rate of roof falls typically seen in mines with weak, moisture-sensitive roof rock during the summer. The exposed rock at the skin of the opening may well be affected by the seasonal temperature and humidity changes in the mine air through absorption of moisture from the mine air as proposed by Kot Unrug (1988).

As for the engineering controls, the sealant coated entry proved to limit the amount of roof rock falling substantially over the year long study. Through instrumentation, measurement and visual observation the emulsion coating appeared very beneficial, at least in the short term, for protecting moisture sensitive roof. Using the results from the roof rock collection, it is estimated that approximately 1 ton of rock will fall to the floor per 50 ft of drivage every year for the roof sprayed with sealant, assuming that the roof sealant maintains the same level of protection. For the roof without sealant, the amount of rock falling to the floor per 50 ft of drivage was approximately 4 tons per year. Additionally rocks collected from the floor of uncoated areas appeared to be larger than those from the coated areas. The difference in the roof condition of the instrumented unscreened entry and the adjacent entry, which was screened, can be seen through photographs and visual observations. The screened entry maintained its original condition much better than the entry with the sealant and the entry with neither screen nor sealant.

The findings from this study indicate that weak moisture-sensitive roof rock can deteriorate rapidly, as soon as six months. There is also evidence that these seasonal effects are related to the surface of the opening and in the short term do not affect the general stability of the roof based on the extensometer data. Screening may well be the single best engineering control available for controlling moisture deterioration in weak roof rock. For short lived panels, sealants appear capable of maintaining adequate protection from deterioration and may protect for longer periods if reapplied.

CURRENT SUPPORT DESIGN

After observing the progressive roof deterioration, the mine operator changed its support plan. Instead of installing screen in four entries, now the entire entry system is being screened. When the screen does not reach both ribs, along the rib where screen is not in contact, a 4-ft bolt is installed between the end of the screen and the rib. Along with the increase in screen, straps and one 10-ft cable bolt is being installed in every other row. They are also now installing six 10-ft-long cable bolts per intersection instead of four. To date this new support plan seems to be adequate and no subsequent roof falls have been reported.

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 agency determination or policy.

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