DEVELOPMENTS IN SEALANT SUPPORT SYSTEMS FOR GROUND CONTROL

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ABSTRACT

During the past few years, the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH) has been evaluating developments in sealant support systems from a ground control perspective. The proper selection and use of a sealant material can significantly enhance ground control which may result in a decrease in worker related injuries due to ground falls. The purpose of this paper is threefold: to briefly review the current state-of-the-art technology in shotcrete and membrane developments, to evaluate the preliminary findings of a long-term underground study of various types of sealant materials, and to examine installation practices that are critical for an effective sealant material. The underground study utilizes NIOSH's Lake Lynn Laboratory Experimental Mine to evaluate the long-term performance of several types of shotcrete and membrane materials. Sealant performance to date have been evaluated on a regular basis over a two year period. Although the study is still ongoing, critical mining practices were identified that may seriously effect the bond of the sealant materials to the mine roof and rib; most notably, the importance of scaling and thorough cleaning of the rib prior to application. Also, results from an extensive series of Schmidt Hammer tests found that the shotcrete increased in strength by 70% during the humid summer months.

INTRODUCTION

Most underground mines in the United States are composed of deteriorated rock of some degree. When this rock is exposed to the cyclical weathering process, it often accelerates the deterioration of the mine roof or rib. This presents a stability problem and potential safety hazard for underground workers. In underground coal mines for instance, it is estimated that over 400 injuries occur annually due to skin failure of the roof or rib in permanently supported areas of the mine (1). Critical and long-life areas in the mine, such as the shafts, shops, beltways, haulage ways, and overcasts, can often experience weathering over time which may require remedial support to arrest this process. These support methods include additional bolting, wire meshing, or sealing the weathered rock with sealant material such as shotcrete. Shotcrete, or pneumatically sprayed concrete, offers the benefits of being low cost, exhibits high compressive strength, performs well under wet conditions, and has a good long-term performance record.

The newest generation of sealants are materials known as membrane or sprayable liner materials. Membranes can generically be classified as multi-component polymeric material and offer these advantages: fast application rates, fast setting times, reduced material handling underground, good tensile strength, excellent elongation properties, and good bond strength. Although shotcrete offers excellent rigid support, most membrane materials can provide active support where the elastic membrane supplies resistance as it deforms due to failure of the rock. Membrane materials are considered an emerging technology and are gaining favor in an increasing number of mines.

The paper presents a brief summary of shotcrete and membrane developments, preliminary results of a 2-year comparison study of several types of sealants in a underground environment, and reviews critical practices in effectively using sealant materials.

SHOTCRETE DEVELOPMENTS

Shotcrete was first developed in the early 1900's and the technology was eventually extended to underground mines. Currently, it is estimated that 7 million cubic feet of shotcrete is used annually in North American mining operations (2). Thicker applications of shotcrete (greater than 3 in) is typically used to provide structural support to a critical underground location whereas, thinner applications (less than 3 in) are used to seal and protect the rock from weathering and unraveling. Currently, shotcrete is used at the face and as part of the mining development cycle at several underground metal mines in Canada (3). Often shotcrete is used in conjunction with bolts to eliminate wire mesh and to permit wider bolt spacing (4). Use of synthetic and steel fiber reinforced shotcrete can increase the tensile strength of the shotcrete and provide the necessary ground support for a wide range of ground conditions. Current trends indicate that increasing numbers of metal mines are relying on shotcrete as an integral ground support component during the mining development cycle (5).

According to Rispin et al. (2, 5), a mine has recently experimented with automated shotcrete equipment, using a computer controlled, laser driven system for mapping headings to be sprayed and the computer regulating part or all of the shotcrete spraying process. Some of the benefits of this state-of-the-art technology may provide a reduction in material rebound, a more precise control over application thickness, and the capability to map the applied concrete. Inco's North Mine (nickel and copper) in Copper Cliffs, Ontario (5) is integrating this technology with tele-operation. Tele-operation is an innovative process where the face development is operated from a remote surface location. Shotcrete is used as a ground control component in their plan to tele-operate the mining development cycle. This remote mining process may eventually remove underground workers from dangerous ground fall conditions that occur during face advancement.

MEMBRANE DEVELOPMENTS

According to the Rand Institute's publication *New Workforce at Work in Mining* (4), spray-on coatings have been identified as one of the top three emerging ground support technologies for underground mining. Membrane materials have been found to be an effective tool to seal the rib from weathering, to prevent the rib from unraveling, and will gradually deform with any rock movements. According to Archibald and DeGagne (6), membranes have demonstrated exceptionally high installation rates, quick set times (within minutes to hours of application), easy handling procedures, and improved rock reinforcement than traditional support methods.

Although membranes do not provide as much structural support as shotcrete, in situations where large rock deformations occur, the more flexible membrane materials may provide better support over the full range of deformations (7). Large deformation may not be a problem so long as the confined rock deforms the membrane in a uniform manner.

Most application of membranes in the U.S. are used for repairing critical underground locations that have severely weathered; however, in Canada some progress has been made in using membrane materials during face development and other applications. Significant membrane research studies have been conducted at Inco's Research Mine in Copper Cliff, Ontario where these ground support roles for membranes were identified by Espley et al. (8):

- membranes may be used during mine development, instead of wire meshing, as a secondary means of support along with bolting
- membrane materials may be sprayed over mesh and bolts which prohibits rusting and also provides significant improvements in the support capabilities of the overall system
- membrane materials may be sprayed over shotcrete to form a tough composite super liner that is able to withstand severe ground bursting conditions
- high-strength membrane materials may be used for stand alone support with delayed and wide-spaced bolting, this is a long-term goal.

Based on Inco's experience at their research copper mine (8), a membrane material for replacing bolts and screens (stand alone support) should have a tensile strength greater than 700 psi, as well as a quick set time. Development of high tensile strength membrane material may not be too far off in the future. According to Lacerda and Rispin (9), most membrane materials under development may generate tensile strengths over 2,200 psi in 15 minutes and should become a reality within the next few years. This would be quite a breakthrough considering most membrane materials (excluding polyurethanes) have tensile strengths of 100-700 psi. In addition, the application of high strength membranes have the potential of being automated and integrated with tele-remote mining techniques from a surface control room, so that exposure of mine personnel to hazardous ground conditions during the mining cycle may be significantly reduced.

LAKE LYNN EXPERIMENTAL MINE STUDY

Background

The sealant study was conducted at the NIOSH, Pittsburgh Research Laboratory's Lake Lynn Laboratory (10). Developed in 1979, the Lake Lynn Laboratory is one of the world's foremost facilities for conducting mining safety and health research. Located at the site of a former underground limestone mine and quarry, Lake Lynn is a multipurpose research lab designed to provide a modern, full-scale, realistic environment for performing research in mining safety and health technology. The Lake Lynn Experimental Mine (LLEM) is located in the Greenbrier limestone formation which has three to five shale bands horizontally bedded in the limestone throughout the mine (figure 1). Large seasonal variations of the temperature and humidity have caused the shale bands to weather and degrade. Frequent explosion tests generating over pressures as high as 100 psi have accelerated the degradation process by dislodging the loose rib and roof rock onto the mine floor and thereby exposing fresh rock to weathering. This continual degradation process presents long-term structural degradation issues for the rib lines and pillars as well as a potential safety concern. Additionally, each year significant worker hours are committed to facility maintenance for the removal of the spalled and loose material. To alleviate this problem, a long-term maintenance solution of sealing the mine ribs and roof with shotcrete was initiated. This provided an ideal opportunity to initiate a research study to evaluate various types of sealant materials in conditions typically encountered in underground mine environments.

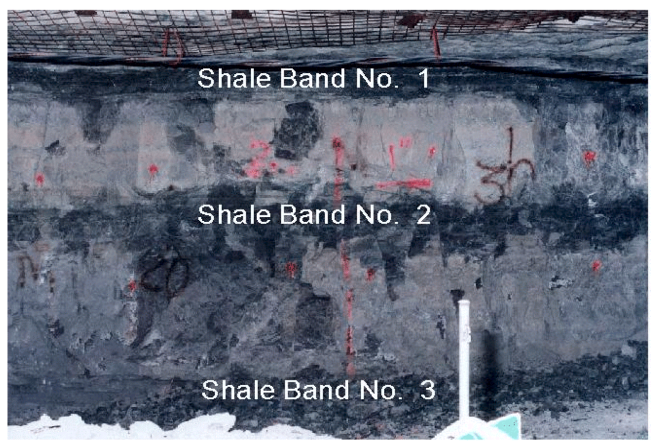

Figure 1. Shale bands dividing the limestone formation at LLEM.

The goal of this study is to evaluate the long-term performance of various types of shotcrete and membrane materials at critical mine locations (predominately on mine ribs). The LLEM offers the advantages of an underground mine environment without the constraints of a production mine. The uniform presence of shale bands throughout the mine provides a good opportunity to evaluate sealant adherence to weathered rock. The mine setting also allows the sealant materials to be equally exposed to cyclical changes in temperature, humidity, vibration, stress conditions, and other factors. These variable conditions may help identify those materials that are most effective under different underground environments.

Study Methodology

The comparison evaluation conducted at the LLEM is a very basic observational study.

Before a study site is sealed, the rib is mechanically scaled, washed with water at pressures ranging from 100 to 150 psi, and photographed. The photographs are taken in sequential order to record any structural defects that may affect the sealant's performance after application. A second sequential series of photographs are taken to record the appearance of sealed rib after application. This series of photographs provide a baseline of the rib's appearance for future comparisons.

In an attempt to examine various mine factors more prevalent in certain areas of the mine, most of the study sites are clustered in areas of the mine that are more prone to weathering, vibration effects, and high stress conditions. The weather effects are most severe near the entrance portal (e.g., study site M in figure 2), the vibration effects are more intense near where the explosion tests are initiated (e.g., study sites R, S, and X in figure 2), and the high stress conditions are more pronounced where the mine pillars have spalled in the old mine workings near the hydrostatic chamber area of the mine (e.g., study sites A and C in figure 2). Shotcrete parameters being examined include: shotcrete thicknesses, bedded shale effects, and debonded shotcrete. These factors were quantified and evaluated with a Schmidt Hammer tool to estimate the compressive strength of the applied shotcrete.

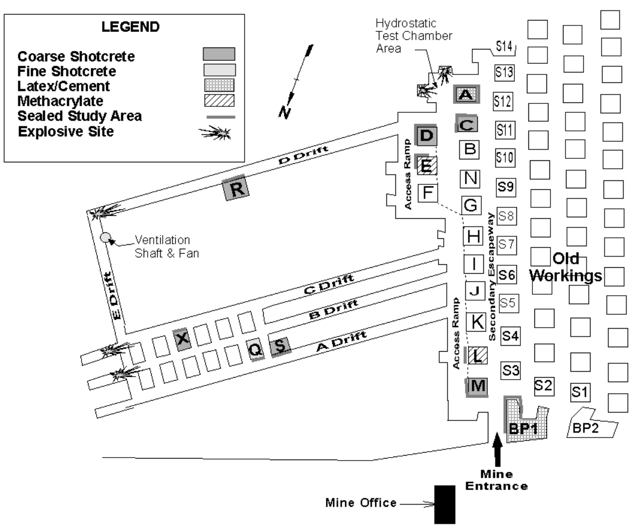

Figure 2. Diagram of LLEM.

<u>Schmidt Rebound Hammer</u>. According to Beaupre (11), the rebounding Schmidt Hammer was found to be an effective tool to determine shotcrete hardness and correlates well with compressive strength. Each shotcrete site has 4-6 test areas upon which each area has 10 hammer tests conducted on a bimonthly or monthly basis. Each test surface area is first smoothed with a grinder to provide a uniform test surface. A wide range of solid and non-solid areas are selected to equitably sample the estimated compressive strength of the shotcrete. The Schmidt Hammer contains a spring-loaded mass that is released against a plunger when the hammer is pressed against the shotcrete. Once the plunger impacts the shotcrete and the mass recoils, the rebound value of the mass is measured by a gauge on the hammer's side. Testing is done according to ASTM C 805 (12), which requires 10 readings at each site. If any of the readings exceed the average by 6 units, those readings are removed and a new average is determined. This average is then multiplied by an average calibration correction factor based on a series of 10 tests using a calibration anvil before and after each mine visit. Based on a series of calibration curves provided by the Schmidt Hammer manufacturer, the estimated compressive strength can be interpolated based on the calibrated average value and the angle of the hammer with regards to the horizontal.

Since the Schmidt Hammer provides only an estimate of the shotcrete compressive strength, a verification test was conducted to compare the Schmidt Hammer results with laboratory unconfined compressive strength test results of shotcrete samples. The shotcrete was poured into a test mold , cured for 8 months, cut into two inch cubes, a surface grinding machine was used to finish the cube surfaces at the required tolerances and unconfined compressive strength tests were run on the shotcrete cube samples. The Schmidt Hammer results produced an estimated compressive strength of 6,900 psi while the laboratory unconfined compressive strength of the shotcrete was 7,275 psi (both shotcrete series were cured more than 8 months). From these results, it appears that the Schmidt Hammer produces a fairly reasonable estimate of the actual compressive strength.

The non-shotcrete materials cannot be tested with the Schmidt Hammer due to the non-rigid behavior of those materials.

<u>Other Monitoring Techniques</u>. Weather data loggers are stationed in the vicinity of the study sites to track the temperature and humidity every hour. When explosion tests are conducted in C and D drifts and at the hydrostatic chamber, they are documented including the date and the corresponding maximum over pressure generated. Defining the stress conditions is a more difficult task. Future plans include the use of the boundary element model LAMODEL to estimate the stress conditions in the hydrostatic chamber area of the mine.

Sealant Materials Studied

Two types of commonly used shotcrete materials and three types of promising membrane materials were selected to be evaluated in this long-term study. The materials will be referred to by their generic names to avoid any appearance of NIOSH endorsement of one product over another.

- Coarse shotcrete - contains cement, sand, "BB-sized" gravel aggregate, micro silica fume and 0.5-in acid resistant glass fibers. The shotcrete is applied using dry process equipment primarily composed of a large rotary barrel gun. As with all dry process shotcrete machines, the shotcrete is conveyed dry through the hose and water is added to the dry shotcrete at the nozzle. The nozzleman controls the amount of water to obtain the proper consistency which can vary depending on the particular application. Due to the LLEM entry size (6.5 ft high by 18-20 ft wide), the compressed air valve on the pneumatic gun is set at a lower adjustment level to minimize rebound. The coarse shotcrete was installed at sites C, D, M, R, S, and X as shown in figure 2.
- Fine shotcrete - contains cement, well graded silica aggregate, micro silica fume and 0.5-in acid resistant glass fibers. The same dry process shotcrete machine used to apply the coarse shotcrete was used to apply the fine shotcrete. The fine shotcrete was installed at site Q as shown in figure 2.
- Latex/cement membrane - contains two separate components, a liquid polymer latex and hydraulic cement powder. The two components are mixed in a single bin and an air compressor

provides a nozzle pressure of 100 psi to apply the membrane. This membrane was installed at sites BP1 and A.

- Methacrylate membrane - contains two separate liquid components, a methacrylate resin and an initiator (epoxy resin). The two components are mixed in separate bins and pumped to the nozzle in separate hoses. At the nozzle they are combined under a pressure of 60-100 psi. This membrane was installed at sites E and L. The liquid methacrylate component contains graphite chips to extinguish flames.

Table 1 shows a summary of some of the properties of the materials chosen for the study. Most of the membrane properties were obtained from an extensive study by Archibald at Queen's University (13). After a decade of study, Archibald and DeGagne (6) found that membranes offer significant ground support potential and, from a health and safety perspective, the majority of membranes were found t be acceptable for underground use.

The two shotcrete materials evaluated at the LLEM have high compressive strengths but no ability to elongate. This makes the shotcrete behave as a rigid restraint whereas, the more elastic membrane materials deform and confine the pillar which probably increases the overall pillar strength. The Material Safety Data Sheets (MSDS) of the materials indicate that they are either nonflammable or self extinguishing. Set (cure) times for the membrane materials are much shorter than for the shotcrete materials. Although the Mine Safety and Health Administration (MSHA) does not require certification of ground support membrane materials, MSHA has developed flammability guidelines for polyurethane foams.

Preliminary Study Results

Most of the quantitative data compiled for this study is associated with the Schmidt Hammer results on the coarse shotcrete which have been evaluated on a regular basis for the past 2 years. The study observations of the other membrane and shotcrete materials will be discussed in the later section. Table 2 lists some of the study results of the shotcretes and membrane materials.

Table 1. Summary of sealant material properties.

Sealant type	Manufacturer's compressive strength[1] (psi)	Estimated tensile strength[1] (psi)	Percent elongation (%)	Set time (Minutes)	Flammability	Health issues
Coarse Shotcrete	8,000	1,000	0	45-60[2]	Nonflamable	Dust
Fine Shotcrete	8,200	950	0	45-60[2]	Nonflamable	Dust
Latex/Cement	-	>145	12-30	<3	Self Extinguishing	Respiration
Methacrylate	-	>290	>100	<3	Self Extinguishing	Respiration

[1]Strength in 28 days.
[2]Initial set time.
Portions of this table are taken from laboratory studies conducted by Archibald (13).

Tabl111e 2 - Summary of sealant material study information.

Sealant type	Sites	Thickness (inch)	Date installed	Estimated cost[1] ($/ft^2)	Material loss[2] (%)	In situ compressive strength[3] (psi)
Coarse Shotcrete	R,X C,D,M,S,R,X C,M,R,X	0.5 1.0 2.0	11/99 11/99-6/00 11/99-6/00	0.66 1.24 2.01	14.9 15.0 15.0	6,425 5,911 6,618
Fine Shotcrete	Q Q Q	0.5 1.0 2.0	9/01 9/01 9/01	0.48 0.74 1.74	17.6 15.3 14.9	2,938 3,972 4,526
Latex/Cement	A BP1	0.3 0.15-0.30	10/99 10/99	1.63 0.98	n/a	n/a
Methacrylate	L,E E	0.08 0.12-0.20	1/01-3/01 9/01	2.28 n/a	n/a	n/a

[1]Material cost.
[2]Loss due to rebound and overspray combined.
[3] Estimated (based on Schmidt Hammer results) and most recent data (January 2002).
n/a = not available

Coarse Shotcrete

The coarse shotcrete was first installed in November 1999 at sites S, M, X and R followed by sites C and D in February and June 2000, respectively. None of the coarse shotcrete sites have shown any signs of failure or deterioration. Site M has shown a few hairline cracks but no signs of failure. Over the years some of the Schmidt Hammer test sites have deteriorated from the repeated hammer blows and were required to be re-ground to provide a smooth test surface. The hammer test results provide a good quantitative indicator of the shotcrete's performance. The most noticeable problem with shotcrete is the loss of material due to overspray and rebound during installation. During application, 15% of the mixed shotcrete fell on to the mine floor (table 2). According to Browning (14), shotcrete (with silica fume) applied to the rib using the dry method will experience a material loss of 5%, while overhead application to the roof is about 8% loss. The higher loss of shotcrete at the LLEM may be due to irregular rib surfaces. Sometimes the horizontal ledges make it nearly impossible to apply the shotcrete perpendicular to the surface. Other contributing factors could be attributed to the age of the equipment and the infrequent replacement of the nozzle.

Figure 3 shows a 70% increase in the coarse shotcrete average compressive strength over the two year period. Technically shotcrete reaches its design strength in 28 days but may increase in strength another 5-10% after 56 days (14). The coarse shotcrete was installed between November 1999 and early February 2000, so the shotcrete should have reached at least its 56 days strength by the time the hammer tests were started. Consequently, most of the strength increase may be attributed to other factors, perhaps the high humidity levels present during the time in question. Typically, the humidity levels at the LLEM during the summer months are 100% which produces condensation on the rib and roof of the mine. Possibly the continual presence of moisture, prolonged the curing process of the shotcrete and resulted in the large increase in shotcrete strength. This seems to indicate that spraying the shotcrete with water, in dry mines or dry winter months, may help cure the shotcrete and allow it to reach its full strength.

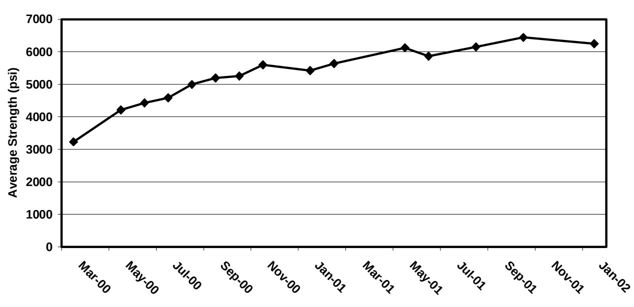

Figure 3. Schmidt Hammer averaged coarse shotcrete results - time versus estimated compressive strength.

Weather Effects. There appears to be a considerable lag time in reaching the maximum strength of the in situ coarse shotcrete. Examining the cumulative rate of strength increase from the averaged hammer test results for all the test sites, as shown in figure 4, indicates a higher rate of strength increase during the spring and summer of 2000. However, by the fall of 2000, the rate of increase had lessened. Further analyses of the data by test sites (figure 5) shows that study sites C, M, and R had the greatest cumulative increase in strength, especially during the spring and summer of 2000. Weather data from these sites (figures 6-8), shows that during the late spring and early summer the humidity levels rapidly increase and reach a 100% saturation level by mid summer. Perhaps the added moisture at these sites may have assisted in fully curing the shotcrete on the mine ribs. Site M is located near the entrance portal where there are frequent changes in temperature and humidity which mirror the exterior daily weather cycles. However, site C is located 1,000 ft from the portal where the temperature and humidity cycles are significantly less than Site M, although humidity is still high. Site R is located in the D drift near the ventilation fan. Frequently the fan is operating during the night, in the blowing mode, to ventilate the mine after fire or explosion experiments. During this mode, the D drift experiences frequent temperature and humidity cycles due to exterior climate changes.

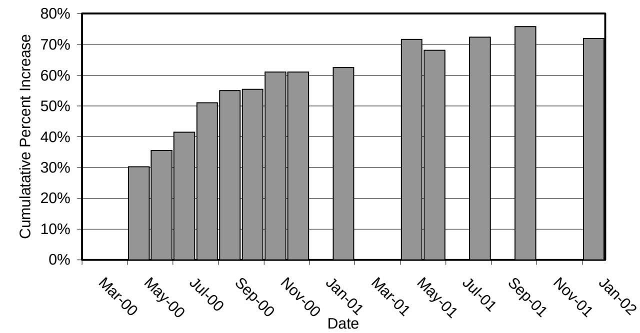

Figure 4. Schmidt Hammer coarse shotcrete results - time versus cumulative percent increase in strength.

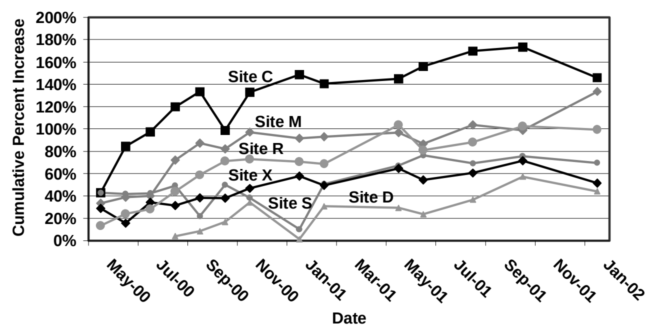

Figure 5. Schmidt Hammer coarse shotcrete results - time versus cumulative percent increase in strength by test site.

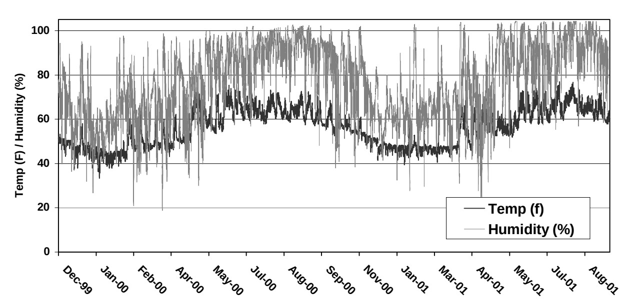

Figure 6. Weather station data at BP-1 site -temperature and humidity versus time.

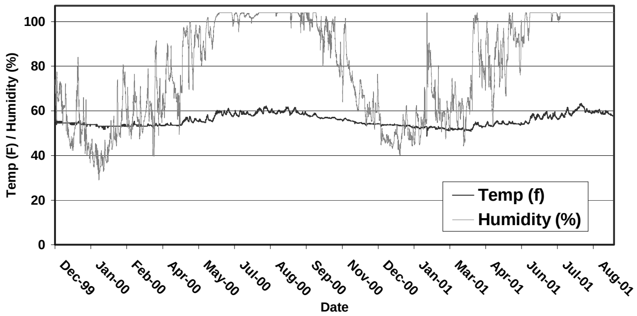

Figure 7. Weather station data near Pillar C site - temperature and humidity versus time.

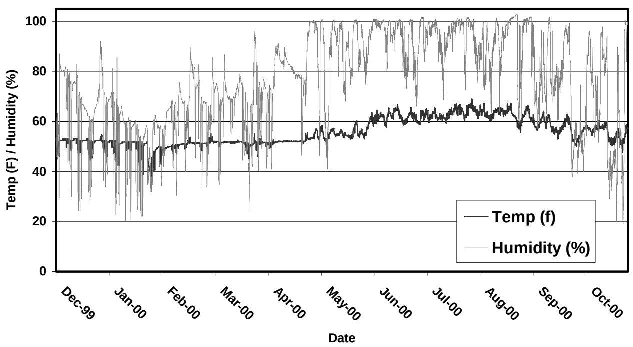

Figure 8. Weather station data near R site - temperature and humidity versus time.

Explosion Effects. The effects of the frequent mine explosion tests conducted within the LLEM were evaluated by comparing the average hammer strength of the shotcrete before and after each test. As can be seen in figure 9, there is no significant decrease in the shotcrete strength. In addition, examinations of the sites before and after each mine explosion test did not reveal any effects on the physical integrity of the shotcrete. Increases in the shotcrete strength after the mine tests is probably due to the long-term curing of the shotcrete. It was apparent after the explosion tests, that the shotcrete had maintained its integrity and stayed completely intact. No fallen roof or rib debris was detected in the areas that were shotcreted.

Bedded Shale Effects. The limestone strata within the LLEM is divided by several bedded shale layers and these shale layers were significantly susceptible to the original weathering problem. To determine if there is a change in shotcrete strengths between the shale and limestone sites, a representative sample of hammer sites that had shotcrete applied were located in the shale and limestone areas. The preliminary short-term results, as shown in figure 10, do not reveal any significant difference in the shotcrete strength, which appears to indicate that the shotcrete adheres equally well to the bedded shale as it does to the limestone. If the shale binder did not provide a good bond or had detached from the shotcrete, the hammer results would have been significantly lower.

Thickness Effects. Although it is difficult to maintain a consistent thickness with shotcrete, three thickness variations were evaluated. Protruding nails were used as a guide by the nozzleman to measure the desired shotcrete thickness during the application process. Since

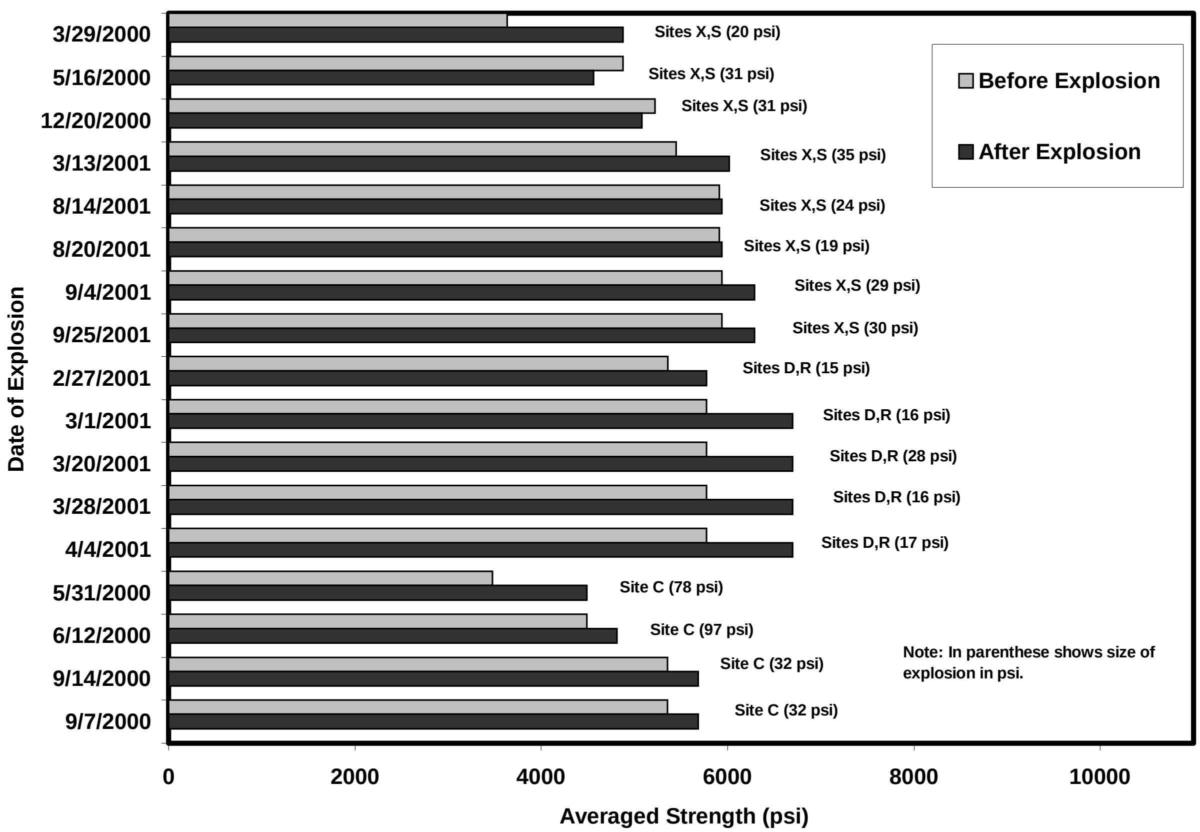

Figure 9. Comparison of coarse shotcrete strength before and after explosion tests - estimated compressive strength versus time.

one inch is a common thickness for non-structural shotcrete, half the common thickness (½ in) and twice the common thickness (2 in) were selected along with the 1 in thickness for this study. A series of hammer tests were conducted at each of the sites with the three different shotcrete thicknesses to evaluate the strength of the shotcrete as a function of thickness. The data shown in figure 11 indicates that there are some differences in the shotcrete compressive strength based on its thickness, however, these differences are random and not consistent. Technically the thickness of the shotcrete should not produce different strengths. However, the differences may have been related to test variability and effects of the hammer blows penetrating the thin shotcrete layers into the rock.

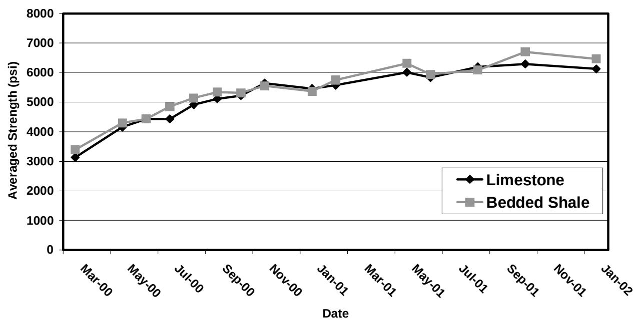

Figure 10. Comparison of coarse shotcrete strength in the limestone and bedded shale - time versus estimated compressive strength.

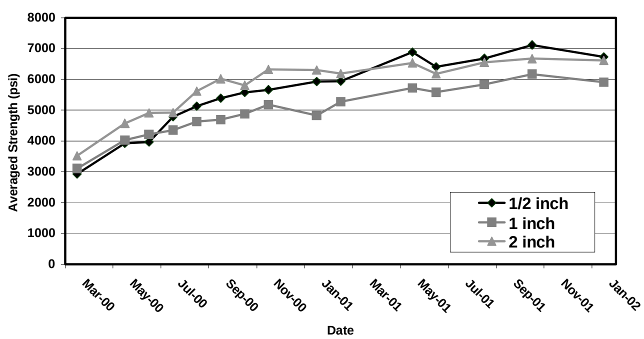

Figure 11. Comparison of coarse shotcrete strength by thickness - time versus estimated compressive strength.

Bonding Effects. Following the shotcrete cure period (greater than 56 days), the shotcrete was sounded with a geologist's hammer to indicate isolated areas in the shotcrete that produced a hollow sound compared to the solid sound elsewhere. This hollow sound may be the result of an air cavity behind the shotcrete, probably due to the shotcrete not properly bonding to the underlying rock. To determine if cavities behind the shotcrete effects its strength, a representative sample of hollow and solid sounding areas were evaluated. Figure 12 shows that the hollow cavity areas have 25% lower strength than the solid areas. This trend is fairly consistent through the two year study period.

Fine Shotcrete

Fine shotcrete was installed in September 2001 at site Q in A drift. As listed in table 2, a 16% overspray/rebound rate was estimated with the fine shotcrete which was comparable to the coarse shotcrete rate. After five months of monitoring its strength using the Schmidt Hammer results, the compressive strengths of the fine shotcrete had increased 19% compared to 52% for the coarse shotcrete for the same time period. It is conceivable that seasonal factors affected the rate of curing, as the coarse shotcrete was first cured in the winter/spring and the fine shotcrete initial curing was in the fall/winter. In the fall and winter, the humidity levels are decreasing and in spring the humidity levels are increasing. To date, fine shotcrete has not shown any signs of deterioration. Due to its recent application minimal data is available for analysis. Future components of this study may include evaluating the performance of a fine shotcrete with polyproylene fibers compared to the glass fibers contained in this current type of shotcrete.

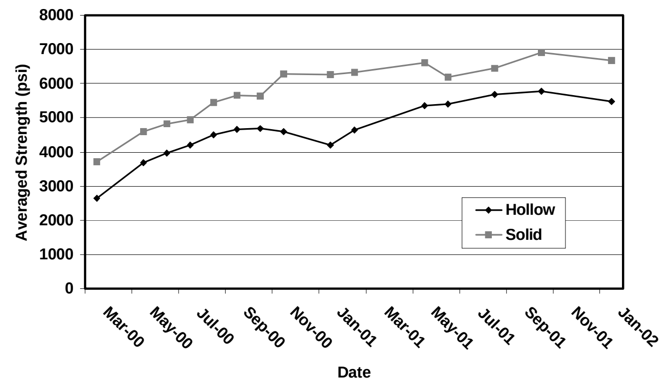

Figure 12. Comparison of coarse shotcrete strength by bond effects - time versus estimated compressive strength.

L
atex/Cement Membrane

The latex/cement membrane has been the longest standing material in the study. It was applied in October 1999 and has performed favorably. A double thickness of 0.31 in (8 mm) sealant was applied on pillar A in the hydrostatic test chamber area (figure 2) of the mine. In this area, ventilation control structures such as stoppings, seals, and bulkheads are frequently evaluated through explosion testing to study failure mechanisms. These explosion tests generate considerable blast vibrations in the area. Over the past 40 years, the pillars have also spalled considerably due to weathering as described earlier and more recently due to damage caused by block and other debris propelled at the pillar as the result of the seal explosion evaluations. Added stress conditions due to the greater overburden at this site may also be influencing the pillar spalling in this area. To date it appears that the latex/cement membrane has effectively sealed the pillar from additional weathering mechanisms. No rock spalling has occurred since application of the membrane. Although the membrane does not contribute significant structural support (tables 1-2) it may provide some additional confinement to the pillar which, in turn, may increase its load carrying capacity.

The latex/cement membrane was also applied on a 250 ft section of the large barrier pillar (BP1) near the entrance portal (figure 2). This area of the mine is subject to frequent freeze thaw cycles and large changes in temperature and humidity (figure 6). A double coating of sealant 0.31 in (8 mm) thick was applied around a corner area and on the unmeshed areas of the adjacent roof. The membrane at this site has also performed well, with the exception of three small patches (approximately 36 ft^2 total area) that have detached from the rib. These patches represent less than 1% of the total area covered. Upon close observation, it appeared the cause of failure was more related to the failure of the rock than failure of the membrane. In two of the cases, the area was located at the bedded shale material near the rib/roof corner. Most likely, the fractured shale was degraded when initially sealed. Close examination of the detached membrane indicates that the dominate failure mechanism was the rock failing and not the membrane. However, the weight of the loose rib eventually exceeded the strength of the membrane (which in both cases was a single thickness of 0.15 in (4 mm)), allowing a section to detach and fall from the rib. Probably, if this site was properly scaled and the damaged rock was removed, the latex/cement membrane would not have detached.

Methacrylate Membrane

The methacrylate membrane was installed at sites L and E (figure 2) in January, March and September 2001. Pump problems produced incorrect mixing ratios and viscosity which resulted in inadequate application thickness and material composition. Possibly, operator inexperience may have also contributed to the improper application. The inadequate thickness and the improper mixing resulted in not generating sufficient exotherm to cure the membrane. Consequently, the material did not set properly or bond to the limestone, and after several months it began to split and peel off the rib and roof. However, the sealant appeared to bond adequately in the areas where both the pump was providing the correct mixing ratios and the operator applied the sealant at the required coating thickness. Unfortunately, during this particular application at the LLEM the combination of correct mixing ratios and proper sealant thickness was only achieved over a very limited area.

The previous applications were removed in September 2001 and a reformulated methacrylate was applied with a thickness of about 0.15 in (4 mm) on Pillar E using a different type of pump. Observations over several months appear to indicate that the reformulated sealant is bonding better than the previous material. However, during this period, about 5% of the sealed area has separated from the rib. Particular bonding problems have been observed along the horizontal rock ledges. Although the pillars were washed (100-150 psi water pressure) prior to sealing, perhaps moisture collected on these ledges resulting in a poor bond. Discussions are ongoing with the manufacturer to resolve these application issues, as well as to evaluate other innovative membrane materials that were recently developed.

CRITICAL PRACTICES

The membrane and shotcrete materials are only as strong as their weakest link. The physical properties of these materials are severely diminished if they are not properly installed. After direct experience with working with these materials as well as numerous discussions with manufacturers (14, 15, 16) and mining personnel (3, 8), the following critical practices should be carefully considered before using any type of shotcrete or membrane sealant material.

Surface Preparation

Probably the most critical and most overlooked component that may hinder the successful application of a shotcrete or membrane material is the surface preparation prior to application. For the LLEM study, the rib and roof were scaled the day before application and washed (100-150 psi water pressure) the day of application. The scaling removes most of the loose material and provides a clean surface for the shotcrete to adhere. Washing the site with water removes most of the smaller size broken rock and dust that coats the rib and horizontal ledges. A recent study by Kuchta (17) found an increase in the shotcrete adhesion strength by a factor of four on a concrete wall cleaned with water at 3,000 psi as compared to surface cleaned at 100 psi. If diesel equipment is operated in the area, a high water pressure cleaning may be capable of removing the slick diesel soot or any oil that may have accumulated on the rib and roof. In the upcoming year, the Colorado School of Mines will include LLEM in their field study of high pressure water treatment of shotcrete.

Mine Conditions

In the selection of an effective sealant material, several questions need to be considered to fit the needs of the mine. How long must the sealant material perform; i.e., what is the anticipated life of the site? Generally, if it is a temporary site, a lower strength membrane material can be used with a minimum thickness. If it is a critical site that may play a long-term role in the life of the mine, for example the main beltway, a high strength material with a greater thickness than is typically used may be appropriate.

If shotcrete is being installed during the drier winter months, it appears to be beneficial to spray water on the shotcrete on a consistent basis after application. According to the preliminary results from the LLEM study, shotcrete applied during the winter months increased in strength by 70% during the following summer possibly due to the high humidity that may prolong the curing process and result in the added shotcrete strength. Humidity levels at the LLEM during the summer months are typically over 100% which produces condensation on the rib and roof of the mine. This seems to indicate that spraying the shotcrete with water may help cure the shotcrete to reach its full strength.

None of the membrane or shotcrete materials will perform adequately when applied under flowing water conditions. Flowing water will prevent the material from properly curing and adhering to the rock. The source of the water should be identified, diverted, drained, and dried before any membrane or shotcrete applications.

Logistical Issues

Critical logistical issues that may hinder the effectiveness of the sealant material include the proper conditions for storing and applying the material. Most of the membrane materials specify a storage temperature range of 40-110° F, but some polyurethane materials require a minimum storage temperature of 68° F. In addition, all of the materials specify dry storage conditions, especially the shotcrete. Maintaining dry conditions may be difficult, especially if the materials are stored underground. In mines of limited mining extent, there may be large fluctuations in humidity (as shown in the humidity charts, figures 6-8), which can result in condensation. The material should be stored in heated warehouses until required underground and then tarps and shrink wrap should be used to protect the material from condensation.

Another critical factor is tracking the shelf life of the materials. Most membrane materials have a shelf life of 3 to 6 months, while shotcretes have an indefinite shelf life if kept in a warm and dry location. Materials that exceed the shelf life may have a reduced strength.

Finally, the project conditions may affect its curing and bonding to the rock surface. Some specifications for shotcrete require the surface temperature of the rock be greater than 48^{o} F. In addition, the shotcrete should not be exposed to temperatures below 48^{o} F for a minimum of 96 hours after application. During some of the summer months, areas in close proximity to intake air in many mines experience nearly 100% humidity which may seriously affect the curing and bonding of some membrane materials. The temperature and humidity levels of the application site need to be considered when scheduling the membrane and shotcrete work.

Human Factors

Also critical to the performance of the shotcrete is the experience and technique of the nozzleman installing the material. The basic technique for the LLEM application involved keeping the nozzle perpendicular and maintaining the nozzle approximately 3 ft distance from the rock surface. According to Browning (14), the art of shotcreting is building up the proper thickness of shotcrete on the rock fast enough that it adheres but not too fast so that it starts to rebound. Applying shotcrete to the roof is even more difficult due to overspray and rebound of the shotcrete. Rispin (2) mentions that there are industry wide training programs for nozzleman, as well as other associated positions, that offer a blend of practical and theoretical knowledge and the importance of proper placement of the shotcrete. Usually application of membrane material is not quite as challenging as shotcrete, due to shotcrete's denser consistency and sensitive application process. Critical issues for membrane application are maintaining a proper thickness so that the membrane will cure properly and obtaining the proper pump mixing ratios of the two components.

Some other factors that may indirectly benefit the nozzleman's performance include:

- providing the optimal airflow to minimize dust;
- using additional lighting to enhance visual attention to ensure proper material adherence and thickness;
- using the required personal protective equipment including a fitted respirator (according to MSDS specifications);
- providing hearing protection;
- providing disposable water/chemical resistance coveralls, gloves, and boots, and;
- following the recommended maintenance and replacement schedules for the nozzle and other parts of the sealant equipment.

CONCLUSIONS

An ongoing study of various types of membrane and shotcrete materials at NIOSH's LLEM is providing a unique forum for evaluating the long-term behavior of the sealants in an underground environment. Preliminary results indicate that the latex/cement performed favorably, with less than 1% of the material surface area debonded from the mine rib two years after application. The coarse shotcrete also has performed favorably over the two year study period. Although no observations of shotcrete failure occurred to date during the study, several areas indicated an incomplete bond with the rock according to the results obtained from the Schmidt Hammer tests. The hollow sounding areas resulted in 25% lower compressive strengths. Hammer test results indicate that the shotcrete strength does not seem to be affected by the bedded shale or vibrations induced by the experimental explosion tests. However, a delay in the full curing process appeared to have occurred for the shotcrete applied during the drier winter months; full curing was not achieved until the humid summer months. During the summer months, a 70% increase in the shotcrete strength was achieved as documented by the Schmidt Hammer test results. Humidity levels at the LLEM during the summer months are typically over 100% which produces condensation on the rib and roof of the mine which may promote the shotcrete reaction and additional strength.

Other critical practices that need to be addressed specifically include proper surface preparation of the mine strata prior to application. A clean surface that is devoid of loose rocks, dust, or diesel soot helps ensure a good bond with the membrane or shotcrete. Additional critical practices are related to the mine conditions, logistical issues, and human factors.

With the emerging technology of mine membrane materials, more U.S. mines are starting to use these materials to rehabilitate critical underground locations afflicted with weathering and unraveling ground conditions. The use of these sealant materials is expected to reduce the occurrence of groundfalls which will provide an additional tool to enhance worker safety and extend the longevity of the underground pillars. Several Canadian metal mines are using shotcrete at the face during face development. They are also starting to experiment with membranes during face development as a substitute for wire meshing used for secondary support along with bolting. In the not too distant future, both shotcrete and membrane materials may be used in the underground metal mines as a primary ground control component in the remote mining development cycle. Perhaps segments of this technology may be applied to underground coal mines and provide a partial solution to reducing roof and rib fall injuries during face development.

REFERENCES

1. Molinda, G.M., Dolinar, D.R. and Robertson, S.B. Reducing Injuries from the Fall of Roof in U.S. Coal Mines. Unpublished paper presented at the Society for Mining, Metallurgy, and Exploration, Inc. (SME), Annual Meeting and Exhibit, Phoenix, AZ, February 25-27, 2002.

2. Rispin, M. and Brooks, J. Shotcrete in North American Underground Mines: Yesterday, Today and Tomorrow. CIM Bulletin, Vol. 94, No. 1052, 2001, pp. 76-79.

3. Espley, S., Malek, F. and O'Donnell, J. INCO's Experience with Shotcrete for Ground Support. Australian Center for Geomechanics, International Seminar on Mine Surface Support Liners 2001, Membrane, Shotcrete and Mesh, Perth, Australia, 2001, Sec. 9, pp. 1-22.

4. Peterson, D., LaTourrette, T. and Bartis, J. New Forces at Work in Mining: Industry Views of Critical Technologies. RAND Institute Publication, Santa Monica, CA, 2001, pp. 26-27.

5. Rispin, M., Runciman, N. and Knight, B. Shotcrete Research and Development at INCO's Test Mine. Proceedings, 3rd International Symposium on Sprayed Concrete: Modern Use. Oslo, Norway, 1999, pp. 430-438.

6. Archibald, J. and DeGagne, D. Spay-On Lining Support in Canadian Underground Mining- A Research Summary. CIM Bulletin, Vol. 94, No.1050, 2001, pp. 49-56.

7. Tannant, D. Thin Spray-On Liners for Underground Rock Support Testing and Design Issues. Australian Center for Geomechanics, International Seminar on Mine Surface Support Liners 2001, Membrane, Shotcrete and Mesh, Perth, Australia, 2001, Sec. 27, pp. 1-22.

8. Espley, S., Gustas, R., Heilig, H. and Moreau, L. Thin Spray-On Liner Research and Field Trials at INCO. Australian Center for Geomechanics, International Seminar on Mine Surface Support Liners 2001, Membrane, Shotcrete and Mesh, Perth, Australia, 2001, Sec. 25, pp. 1-23.

9. Lacerda, L. and Rispin, M. Current Ground Support Membrane Applications in North American Underground Mines. SME Annual Meeting, Phoenix, AZ, SME Preprint 02-091, 2002, 7 pp.

10. Triebsch, G. and Sapko, M.J. Lake Lynn Laboratory: A State-of-the-Art Mining Research Facility. Proceedings, International Symposium on Unique Underground Structures, Denver, CO, June 12-15, 1990, CSM Press, Vol. 2, 1990, pp. 75-1 to 75-21.

11. Beaupre, D. Underground Shotcrete Quality Assessment. Centre de Recherche Interuniversitaire Sur Le Beton. Laval University, Montreal, Quebec, December 1994, 21 pp.

12. American Society for Testing and Materials. Standard Test Method for Rebound Number of Hardened Concrete. C 805-97 in 2001 in Annual Book of ASTM Standards, Section 4, Vol. 04.02, Concrete and Aggregates, Philadelphia, PA, 2001, pp. 416-418.

13. Archibald, J. Canadian Laboratory and Field Testing. Australian Center for Geomechanics. Australian Center for Geomechanics, International Seminar on Mine Surface Support Liners 2001, Membrane, Shotcrete and Mesh, Perth, Australia, 2001, Sec. 23, pp. 1-31.

14. Browning, A. Personal Conversation 2002.

15. Spearing, A. and Champa, J. Superskins - The Present and the Future. Australian Center for Geomechanics. Australian Center for Geomechanics, International Seminar on Mine Surface Support Liners 2001, Membrane, Shotcrete and Mesh, Perth, Australia, 2001, Sec. 16, pp. 1-11.

16. Degville, D. Personal Conversation 2002.

17. Kuchta, M. Quantifying the Increase in Adhesion Strength of Shotcrete Applied to Surfaces Treated with High Pressure Water. SME Annual Meeting, Phoenix, AZ, SME Preprint 02-035, 2002, 4 pp.