EVALUATION OF POLYURETHANE INJECTION FOR BELTWAY ROOF STABILIZATION IN A WEST VIRGINIA COAL MINE

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ABSTRACT

Extremely difficult ground conditions were encountered in the main belt entry in a room and pillar mine in West Virginia. Several generations of supplemental support, including cable bolts, cribbing, and Heintzmann jacks and beams failed to halt roof falls that threatened workers safety and the life of the mine. Polyurethane (PUR) was injected into 27 intersections in the roof and the results were monitored by borehole video camera. The mine had averaged 2-3 falls in the beltway per year and, since the roof injection, no roof falls have occurred. Pre- and post injection monitoring of test holes showed that stability can be achieved without filling all of the existing void spaces. Video logging showed that the project goal of building a beam from 2-6 ft into the roof was successful. Pre-injection monitoring of roof fractures uphole can delineate the zones to target for reinforcement, and avoid pumping PUR into large voids to little effect. Multiple-injection zones can be identified, and the entire intersection drill hole array can be optimized based on knowledge of the fractured zones. In addition, pre-monitoring can prevent excessive hydrofracturing in solid zones. Polyurethane injection is a proven method of rock stabilization in even the weakest, most broken ground. Optimization of the injection design by pre-injection video diagnostics can greatly contribute to the successful and efficient roof stabilization.

BACKGROUND

Polyurethane injection for ground stabilization in coal mines was first developed by the German coal mine research organization Bergbau-Forschung GmbH in the early 1960's (Stewart and Hesse, 1985). It became a standard stabilization method in Germany since its commercial introduction in 1971 (Knoblauch, 1994). With the introduction of the RokLok binder system in 1977, polyurethane stabilization, particularly in longwall recovery, has become common in the U.S. (Stewart and Hesse, 1985).

Polyurethane injection in coal mines is most commonly used in difficult ground conditions including fractured rock in headgates and tailgates, and as a stabilization remedy to prevent longwall face caving. It may also be used as a replacement for roof meshing in shield recovery, and as a sealant to prevent groundwater inflow, but often it is applied as a last resort where conventional roof reinforcement and support has failed.

Polyurethane is typically a two component system that has several advantages to conventional support. It has the ability to chemically bond to the rock, unlike other supports which rely on frictional contact. Because it is injected under pressure, it inherently "targets" fractures, which are the paths of least resistance. It also has a low viscosity which allows it to penetrate cracks as small as 0.04 mm wide (Knoblauch, 1994). It has engineered expansion properties (1:1 to 1:12) which also allow for penetration (Shaller and Russell, 1986). It is both strong and plastic, preserving its' integrity under load and racking-type deformations. Finally, it does not present the obstacle of standing support.

In designing a polyurethane stabilization the goal is to reinforce the fractured rock to the point where it can support its own weight and the weight of unconsolidated rock above it. Mechanically, the polyurethane forms a beam with rock that has been separated along bedding or is broken into key blocks. It is the size and strength of this beam which enhances the stability of the roof.

There are a number of variables which must be considered:

1. The location of fractures – This information will help determine the zone to target for polyurethane injection.
2. The extent of the fracture zone – An estimation of the total void space could be used to calculate the volume of PUR needed. In highly fractured roof, more test holes may be required.
3. Character of the fractures – A determination of the nature of fractures, whether they are bedding separations or a rubbleized zone, will indicate the permeability of the zone.

PUR injection arrays can have a number of configurations. A typical injection pattern for an intersection will have four injection holes angled over the rib on 10 ft centers spanning each crosscut in the intersection (Figure 1). PUR may be injected over the rib on each side of the intersection to erect a "grout curtain" which will act as a barrier and permit infilling of the intersection. These injection holes will be packed off to the destabilized zone, and then PUR is injected. The holes will be pumped to a predetermined volume or pressure or they may be injected to refusal. Then holes will be drilled and pumped in the center of the intersection to complete the beam. The exact specifications of the design are often determined by the experience of the contractor.

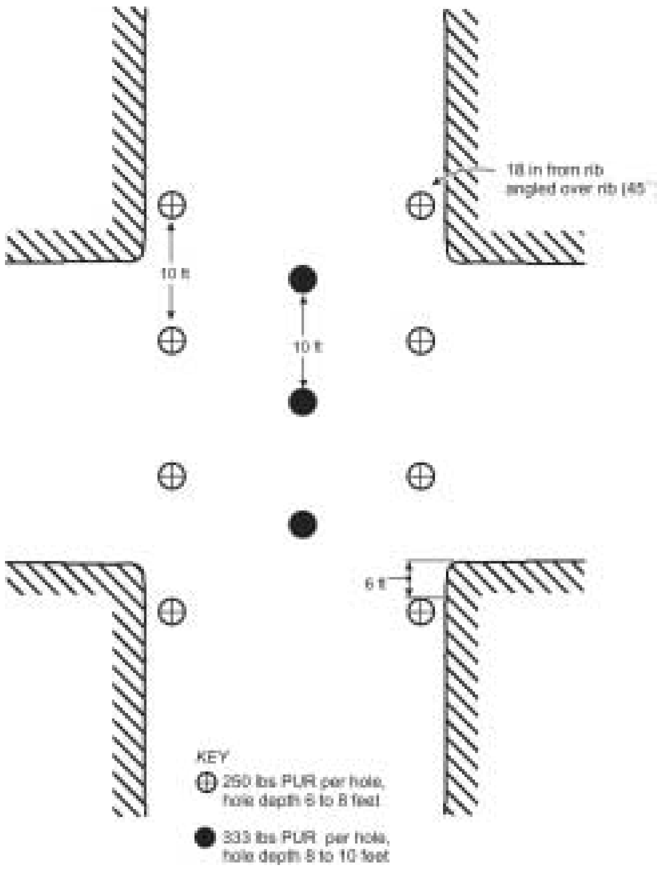

Figure 1. Idealized PUR injection array.

BELTWAY STABILIZATION

A coal mine in West Virginia was experiencing extremely difficult roof conditions in its main beltway throughout the life of the mine leading up to the autumn of 2002 (figure 2). The 18 ft wide belt entry was averaging 2-3 falls per year which threatened workers safety and resulted in costly delays due to cleanup and rehabilitation. The roof rock is an extremely weak clay shale which is highly moisture-sensitive. In August, roof falls occur almost 2.5 times more frequently than the annual monthly average. In addition, it is suspected that frequent clay veins also react to moisture, swell, and apply bulking pressures on the roof sequence. The roof begins to unravel between bolts in a relatively short time, leading to a progressive upward failure and finally a roof fall. Mine-wide, 63% of roof falls occurred in intersections. In the beltway from the portal to the first submains, 15 of 43 intersections had fallen (figure 2). The project goal was to stabilize all the unfallen intersections by polyurethane injection.

In the beltway several generations of supplemental support including cable bolts, roof screen, pizza pans, posts and beams, and cribs were beginning to restrict travel. At this point options included adding additional support, moving the beltline, or polyurethane injection. Polyurethane injection was selected because, based on past experience, it had the greatest likelihood of success.

Using an injection design pattern with 11 pumped holes per intersection, the project began (figure 1). After injection of two test intersections on the track, the job was stopped in order to evaluate the PUR reinforcement by using video monitoring. It had been difficult to build any pump pressure and questions arose as to where the polyurethane was going. Large voids were detected at 10-12 ft up into the roof. (It should be noted that this intersection was heavily supported with steel beams and posts). From these observations it was decided to concentrate the PUR injection on reinforcing the roof beam from 2-6 ft up into the roof. It would be impossible to fill the large void spaces in the roof and, in fact, would be unnecessary if the lower beam could be reinforced.

Testing Method

Because of its demonstrated value, it was decided to continue video monitoring through the project, and to use the information to refine the design of the PUR injection. Figure 2 shows the Mains and the beltway, and intersections selected for polyurethane stabilization. All intersections that had not fallen in the beltway were selected for PUR-injection stabilization. A total of 27 intersections had PUR injected for stabilization. The reinforced beam in the Mains was created by pumping PUR in a zone from 2-6 ft. Two pump zones were isolated. PUR was pumped first from 4-6 ft, allowed to set, and then was pumped from 2-4 ft. Each intersection averaged 12 injection holes and these holes averaged 6-7 ft long. The average amount of PUR injected per intersection was 425 gal. This volume was calculated to allow 2 - 55 gal drums of PUR mix to pump 3 holes. Injection pressures ranged from 0-2,000 psi and averaged about 400-500 psi.

The injection pattern was typically 4 angled holes on each side of the beltway across the intersection, and 4 holes along the middle of the intersection. A total of 17 video logs from 11 intersections were used in the analysis. Five intersections had both pre-injection and post-injection, and 6 intersections had only post-injection videos. Monitoring holes were drilled on the walkway side of the belt in the middle of the intersection crosscut, and approximately 3 ft from the rib.

PRE AND POST INJECTION MONITORING OF FRACTURES IN THE BELTWAY ROOF

Video logs, some pre-and post injection, revealed the condition of the roof in selected intersections along the Mains project area (figures 3a and b). Pre-pumping video logs showed significant voids in the roof at two intersections (No. 23 and. 32) (figure 3a). At No. 32, highly fractured roof rock was loading standing support and falling between supports. Using the design plan of reinforcing a roof beam from 2-6 ft into the roof, PUR injection continued. Video logging was available at 16 post-injection test holes at 11 intersections. The test holes showed PUR successfully injected into numerous void spaces in the target zone in each of 11 intersections. Individual cracks ranging from paper thin up to ¾ in wide, and rubbleized zones up to 1.5 in were filled with PUR (figures 4a and 4b). This information allowed for an intersection-by-intersection evaluation of the PUR injection performance.

In 5 intersections (Nos. 20, 21, 22, 23, 32) both pre and post-injection test holes were video-logged in order to determine which pre-existing fractures were filled with PUR (figures 3a and 3b). Intersection No. 21 had a rubble zone 3/8 in thick at 2.9 ft into the roof prior to PUR injection (figure 3a). Twelve injection holes pumped 399 gal of PUR into the intersection in two isolated zones (4 ft and 2 ft) (table 1.). In a post-injection test hole (figure 3b), there are three prominent PUR “shows” from 2.7-3.5 ft. effectively filling the rubble zone (figure 5). 100% of the void space at this hole location in the intersection was filled with PUR (figure 3b, No. 21 post-injection hole).

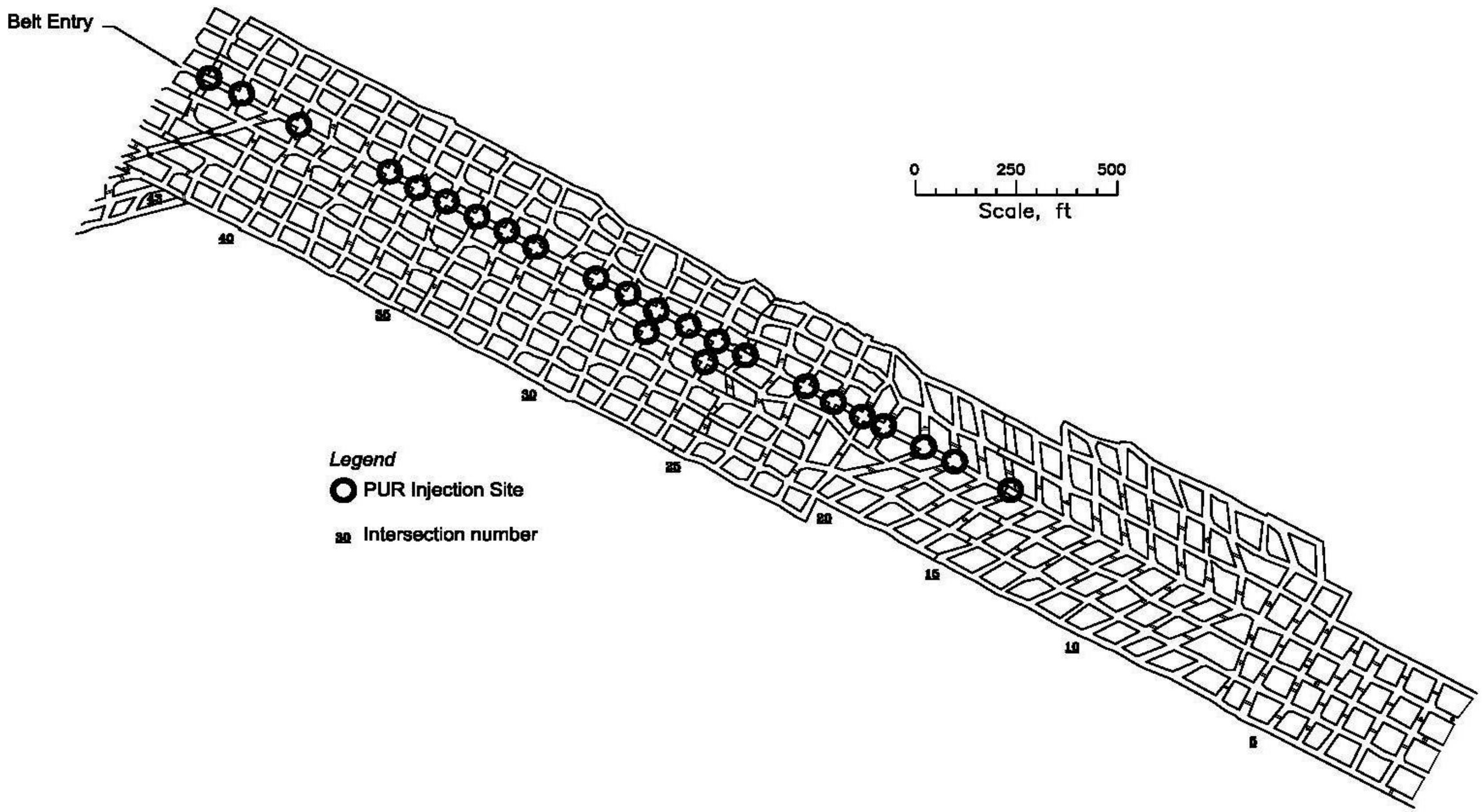

Figure 2. Intersections stabilized with polyurethane.

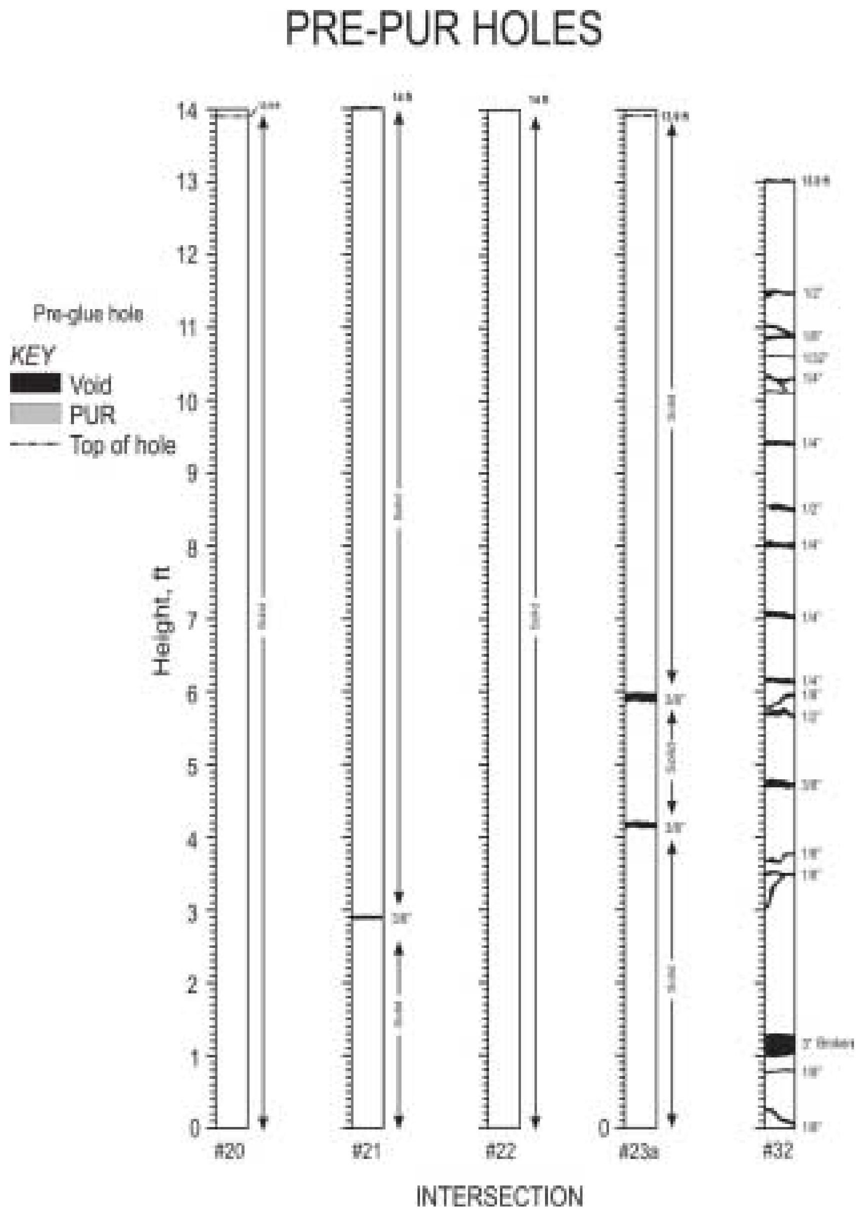

Figure 3a. Borehole camera logs of monitoring holes prior to PUR injection. (These are the only pre-injection logs available.)

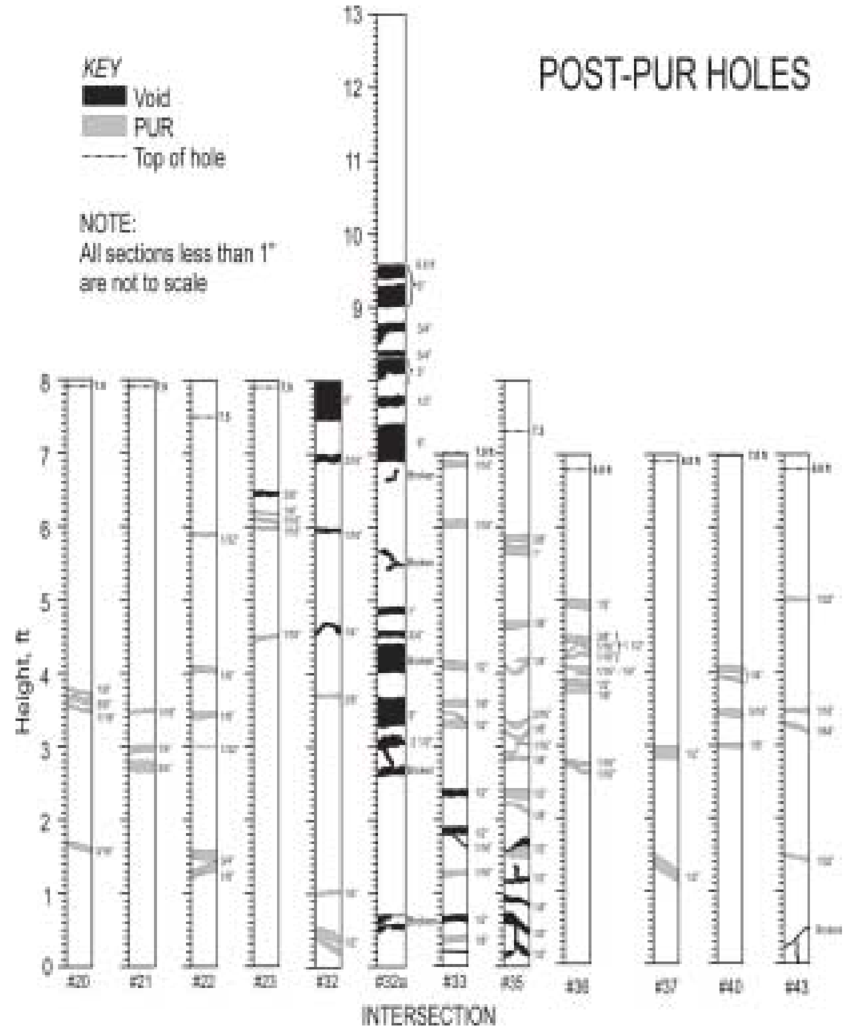

Figure 3b. Borehole camera logs of monitoring holes after PUR injection. (Some intersections listed here do not have pre-injection logs available.)

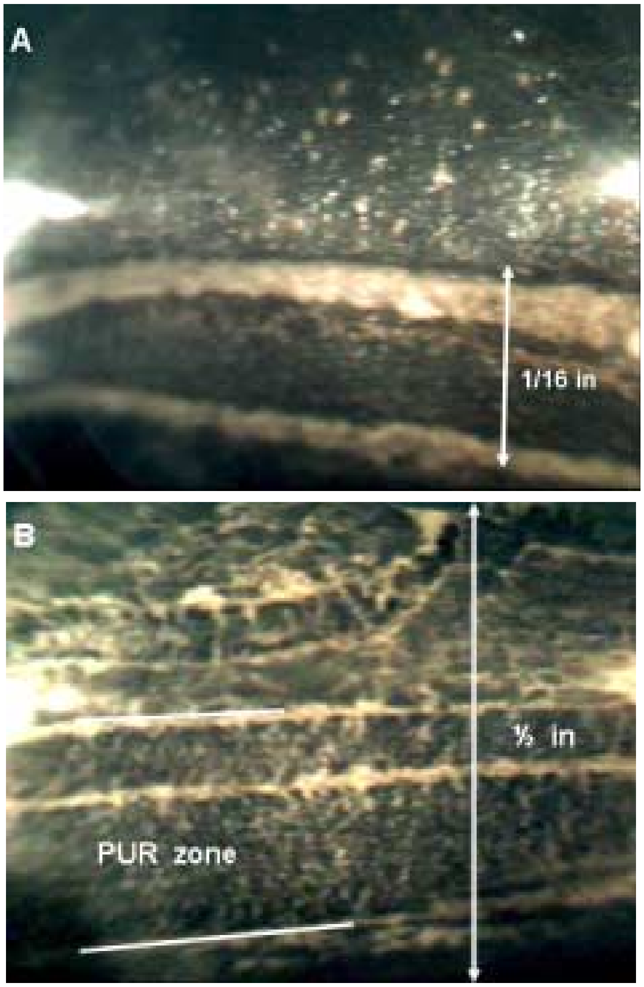

Figure 4. Borehole camera images showing PUR zones in the roof.

Table 1. Void Space Filled by PUR in 7 ft high monitoring zone.

Intersection no.	Void space filled (%) in test hole (2-7 ft zone)	Total void space (in) 2-7 ft zone	No. of injection holes	PUR pumped (gal)
43	100	0.11	21	699
42	100	1.5	16	532
40	100	0.69	17	566
37	100	0.5	20	666
36	100	3.0	19	632
35	100	2.87	21	699
33	71	1.75	12	466
32	43	0.87	8	233
	0	11.75	8	233
29	1	4.10	No data	600
28	93	0.27	No data	No data
26	9	2.43	No data	600
23	54	0.81	12	399
22	100	0.31	12	380
21	100	1.06	12	399
20	100	0.56	14	432

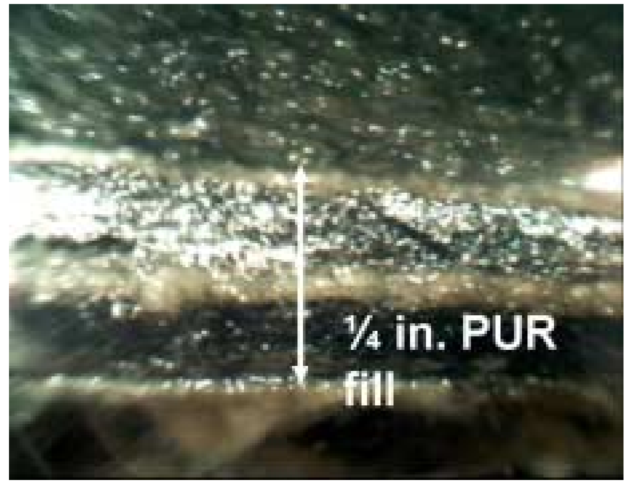

Figure 5. PUR-filled separations at intersection No. 21.

In intersection No. 23, two fractures existed at 4.2 ft (3/8 in wide) and 6.0 ft (3/8 in wide) prior to injection into the roof (figure 3a, test hole No. 23a). One-hundred ten gal of PUR was pumped into a zone packed at 4 ft and 289 gal of PUR was pumped into a zone packed at 2 ft (table 1). Both zones were filled with PUR, with another 3/8 in void left unfilled at 6.5 ft (figure 3b). This void was above the height of the injection holes.

In intersection No. 20 the pre-injection hole showed solid roof and no voids or even separations (figure 3a). Fourteen holes were drilled and approximately 432 gal of PUR was pumped (table 1). After injection, a video log revealed that PUR was injected into a zone at 1.7 ft and from 3.5-3.8 ft into the roof (figure 3b). It is assumed that PUR was injected into weak, unseparated bedding planes or that the bedding may have been hydrofractured with injection pressures up to 1,800 psi. Another possibility is that fractures were present that were not revealed by the pre-injection test hole. PUR could have been injected into these zones.

At intersection No. 22 pre-injection video monitoring again showed a solid roof with no voids or separations (figure 3a). Twelve injection holes were pumped. At 4 ft of each hole a packer was set and 110 gal total was pumped between all holes. The hole was repacked at 2 ft and 271 gal was pumped, between 2 and 4 ft. The post-injection video monitoring hole showed significant PUR injected into 6 zones from 1.2 ft to 6 ft (figure 3b). These zones may have been hydrofractured. It is also possible that PUR was injected into tight bedding plane separations not visible in the pre-injection videos. In this case, PUR may still have some reinforcing value, especially when roof movement begins. In tight roof, pre-monitoring can indicate that lesser volumes of PUR should be pumped.

The last intersection with both pre and post injection monitoring was No. 32. At this intersection PUR injection was less successful. Several inches of void space was measured in the pre-injection zone (2-7 ft into the roof) (figure 3a and 6). At 8 injection holes a total of 233 gal of PUR was pumped (table 1). Two holes were video monitored after injection (figure 3b, holes nos. 32, 32a). No PUR was observed in one post-injection monitoring hole. But in the other test hole, several fractures in a zone from 0-1 ft had PUR shows (figure 7). PUR shows below the packed injection zone highlight the extreme fracturing in the intersection. The PUR found fracture conduits below the packed zone and was seen dripping from the roof. The one pre injection hole and two post injection holes show large variations in fracture location in the intersection. This indicates that additional monitoring holes may be necessary to delineate the variation in highly fractured intersections.

Figure 6. Large void at 6 ft into the roof at intersection No. 32 prior to PUR injection.

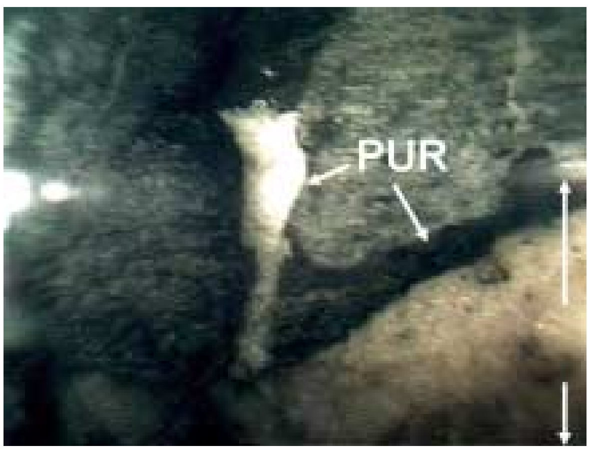

Figure 7. PUR filling fractures at 1 ft into the roof at intersection No. 32.

Six other intersections (Nos. 43, 40, 37, 36, 35, 33) had only post-injection video logs available (figure 3b). Table 1 summarizes the PUR injection history of the remaining intersections. It shows the amount of void space filled by PUR in the 7 ft monitoring zone (the injection zone was from 2-6 ft.).

Of the 16 holes that were video logged (15 intersections) 9 had 100% of the void space in the monitoring zone (2-7 ft) filled. That is, there was no remaining void. Six of the holes had voids filled ranging from 1-93%, and one had no observed PUR "shows." In some intersections with multiple test holes, large differences in void space were seen across the intersection (No. 32 intersection and No. 28). In No. 28 intersection 4 test holes in the intersection spanning one crosscut showed voids ranging from 0 – 1.5 in. The variation in void space over short distances may explain the partial filling of void in some test holes. Even though test holes are near injection holes, PUR may follow a circuitous route depending on the fracture permeability of the intersection. In two intersections (Nos. 32 and 29) monitoring holes detected 0 and 1% of the voids filled, indicating loss of the pumped PUR into the mine opening or away from the intersection monitoring hole. Monitoring holes in both of these intersections revealed large void spaces above the bolted horizon (3/4 in – 6 in wide) (figure 3b). These intersections are currently controlled by heavy standing support.

The amount of PUR pumped into each intersection was also recorded. The volume ranged from 233 to 699 gal (table 1). Several intersections that were injected with large volumes (600 gal) of PUR (Nos. 29 and 26) were still left with a large percent of the void spaces unfilled. The location of the PUR injection up in the roof, in regards to building a stable roof beam, appears to be just as important as the volume of PUR pumped per hole. If the beam is constructed too high in the roof then fractured rock below it may fall. Additionally, if PUR is injected into large voids it may migrate away from the intersection and be of little value. Void spaces open an inch or more may be difficult to completely fill with PUR. A better strategy in the beltway was to concentrate PUR injection to building a stable beam below these large openings. At intersection No. 26, even though large voids exist from 10-13 ft into the roof, a stable beam has been created from 2-6 ft in the roof.

DISCUSSION

The design of a PUR stabilization site necessarily requires an estimate of the amount of chemical to inject. Current estimates are based on calculations of area (ft^2) of roof to be stabilized and the contractors' experience. The polyurethane grout used at the site was rated at 70 lbs/ft^3 and not intended to expand, although some expansion may occur if water is encountered. By using pre-pumping video monitoring the condition of the roof can be assessed and the zone of beam reinforcement can be determined. In the Mains beltway, in most of the intersections, a stable beam was created at 2-6 ft into the roof. Eleven of 12 post-gluing monitor holes showed PUR in the targeted beam zone, with 10 of 12 monitoring holes showing no open fractures in the target zone. Some of the intersections had large voids above the reinforced zone indicating that the reinforced beam was strong enough to hold at least 7 ft of fractured rock.

The reinforced beam in the Mains was created by pumping PUR in a zone from 2-6 ft. Two pump zones were isolated. PUR was pumped first from 4-6 ft, allowed to set, and then was pumped from 2-4 ft. The roof is highly fractured from 0-2 ft and it would be very difficult to saturate this zone with PUR because most of the chemical would leak out of the roof. In addition, high pumping pressures may dislodge roof blocks. Therefore, PUR is not typically designed for skin control but meant to prevent massive roof falls.

One method to estimate the volume of PUR needed for stabilization is to do a volume calculation based on the void space detected in a pre injection test hole. Void volume calculations were done for all injected intersections. When comparing the amount of voids filled with the amount of pumped PUR, the results were highly varied. Some intersections showed more PUR pumped than required, and some test holes showed less PUR was required to fill 100% of the void space than calculated. The discrepancy appears to lie in the monitoring. In highly fractured rock, fracture permeability requires more test holes to correctly delineate the void space and permeability of the target beam.

A void volume calculation was also done on intersection No. 35. In this highly fractured intersection, a total of 2.87 in of void space was measured in the target zone (2-6 ft). At 379 gal/in of void space, it would take 1,087 gal of PUR to fill the voids space of the entire intersection. Six-hundred ninety-nine gallons were pumped into 21 holes at that intersection, filling 100% of the void space detected at the test hole site. While 100% of the void space at the test hole was filled with PUR, more unfilled void space may possibly exist throughout the remainder of the intersection. In this case stability was achieved with less than complete filling of the theoretical void space. More test holes are required to completely delineate the extent of PUR infiltration throughout the intersection.

The determination of how much PUR to pump into each intersection is a function of roof condition and experience. The use of pre-injection monitoring can:

1. Locate the position of the zone requiring reinforcement.

2. Provide void separation data for a preliminary estimate of the necessary PUR volume.

In highly fractured roof it may be impossible to fill all available void space. An estimate of void space in the target zone will provide a starting point for a PUR volume calculation.

In tight roof (no open voids) less PUR is needed. In intersection 16, a total of 3/8 in of total void space was found in the target zone in a pre-injection hole, amounting to 142 gal of PUR necessary to fill the intersection roof void space (no post-injection hole was available for analysis). 765 gal of PUR were injected into the intersection. The additional PUR may be injected above the target zone, lost to the mine opening, or injected into weak bedding planes in the roof. Once again, a third possibility is that PUR was injected into existing fractures not detected by the monitoring hole. More monitoring holes would more accurately delineate the permeability of the target zone and provide a more accurate starting point for a PUR injection volume estimate.

PERMEABILITY

The permeability of the fractured rock plays an important role in designing the number and location of injection holes. Unfortunately, permeability in highly fractured rock can vary tremendously even in short distances. Two monitor holes in intersection No. 32 separated by 10 feet showed 0.68 in roof void and 11 in of roof void, respectively, in the target zone (2-6 ft). Schaller and Russell (1986) found that after injecting one roof hole in an intersection, PUR was found distributed over 20 m^2. This was in roof with voids up to 4 in wide. Rather than pumping PUR to refusal, contractors may often pump a predetermined amount of PUR around the perimeter of the intersection, allow it to set up (25 seconds set time in this instance), and fill in the intersection with holes along the center line. Pumping to refusal happened rarely in the Mains beltway indicating that it was not possible (or necessary) to fill all the existing voids to achieve stabilization. The path of PUR migration in the highly fractured rock is difficult to predict. At intersection No. 32, 3 injection holes were within 1-5 ft of a monitor hole (32a) and no PUR was detected. For this reason more injection holes, more closely spaced, would enhance PUR distribution.

In the more highly fractured intersections more difficulty was encountered in getting the PUR into the zone intended for beam reinforcement. This problem may be addressed when designing the grout curtain to act as a barrier to subsequent PUR injections. It may be necessary to install several layers of grout curtain to ensure an effective barrier to PUR loss. More injection holes in 2 or more concentric layers around the perimeter of the intersection may be necessary before infilling of the interior of the intersection. Along the same lines, shorter packed zones (1 ft) within the beam zone would allow the beam to be reinforced in several lifts. Instead of two injection zones from 4-6 and 2-4 ft, four zones (2-3, 3-4, 4-5 and 5-6 ft) may provide more effective infill.

Fundamental questions remain about the optimal volume and location of PUR needed to stabilize an intersection. Numerical modeling studies may shed light on the mechanics of PUR stabilization and provide answers to these questions.

SUMMARY

Polyurethane injection in the Mains beltway appears to have successfully stabilized the remaining unfallen intersections. This is demonstrated by the fact that no roof falls have occurred through April, 2004 when 2-3 falls per year previously occurred. Video monitoring of PUR injection results have shown that polyurethane was contained in the target zone in 11 of 12 cases. This containment depends on the extent of fracturing and permeability of the roof strata. In highly fractured roof more injection holes may be needed. Additional monitoring holes may also be needed to verify the location of the polyurethane.

The PUR injection strategy of building a roof beam from 2-6 ft in the roof appears to have successfully supported up to 7 ft + of fractured rock load height above the injection zone. In 9 of 16 video monitoring holes (15 intersections, some logs not presented), PUR filled 100% of void spaces, 5 holes showed partial filling of voids (ranging from 1-93% void filling), and 2 monitoring holes in intersections showed little or no PUR. From these data and the success in stopping roof falls, it was determined that it is not necessary to fill all of the void spaces in the roof strata. It is sufficient to concentrate on stabilizing a target roof beam which can then carry dead load from unconsolidated strata above.

Pre-injection monitoring holes showed where voids occurred in the roof and can be used to guide the target zones for PUR injection, thereby avoiding losing PUR into vast voids and costly over-pumping into tight roof. Post-injection video monitoring can also be used to assess the success of the injection by calculating the amount and location of void space filled. Video monitoring of roof holes also showed rapid changes in permeability in short distances can occur in intersections, thus affecting the zone of influence of the injection holes. The accuracy of estimates of the injection volumes needed to stabilize the intersection is dependent on the number of test holes available for void calculations. More test holes will allow more accurate estimates of void space and permeability in the target zone.

It is concluded that pre and post-monitoring of roof void space can help to optimize the design of PUR injection for roof stabilization.

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