Reinforcing Coal Mine Roof with Polyurethane Injection: 4 Case Studies

Gregory Molinda

Abstract NIOSH has recently completed a study of the interaction between polyurethane (PUR) and coal mine roof in order to determine the mechanism of reinforcement, in both highly fractured rock and unfractured rock. Four case studies of PUR reinforcement are presented. At a West Virginia site, a borehole camera revealed the location of roof voids and guided the PUR injection. By injecting polyurethane into a zone from 0.6 to 1.8 m (2–6 ft.) high in the roof, a roof beam was created and ongoing intersection falls were halted. In another highly fractured roof in a western Pennsylvania mine, a total of 5.8 cm (2.3 in.) of rubbleized rock was found in a zone up to 3 m (10 ft.) into the roof. Untargeted PUR injection filled approximately 1/2 of the fractures. These two case studies showed that it is not necessary to fill up 100% of the void space to create stability. In the other two field sites, polyurethane was injected into weak, but unfractured roof. Post-injection video monitoring showed that weak bedding planes were hydraulically wedged open and polyurethane injected along bedding. The reinforcement value of this injection method is limited because of the wafer-thin layer of PUR introduced along bedding, and the lack of a PUR "webbing" which would serve as a structural framework to provide strength. It was determined that video inspection prior to PUR injection can aid in identifying the fracture zones to target, and minimize "blind" pumping and loss of PUR.

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1 Background

Coal mine roof strata has been successfully reinforced with polyurethane (PUR) for over 40 years. Applications have included headgate stabilizations, rock consolidation over coal panels in advance of mining, and roof reinforcement for shield recovery. Polyurethane injection for ground stabilization in coal mines was first developed by the German coal mine research organization Bergbau-Forschung GmbH in the early 1960s (Jankowski 1972). It became a standard stabilization method in Germany after 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 US (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 over 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 0.05 mm (0.002 in.) 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 (Micon 2003). Finally, it does not obstruct roadways like standing support.

2 Current PUR Injection Design Process

Injection designs currently have a "one size fits all" approach, with drilling patterns and chemical grout volumes decided in advance, often for the sake of convenience rather than engineering design. A design process is needed to determine the optimum location for injecting polyurethane grout in order to maximize the reinforcement benefit and prevent wasting large volumes of chemical.

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 rubbleized zones, will indicate the permeability of the zone (Molinda 2004). Uphole mapping of fractures will help define permeability.
4. Injection pressures—Often the injection proceeds until a pre-determined injection pressure is achieved, indicating that the fractures are filled. If no back pressure is ever achieved the indication is that the fracture zone is infinitely large. Conversely, if a high back pressure is reached immediately or very quickly, then the roof is considered to be unfractured, and further pumping may hydrofracture the roof, which may loosen roof rocks.
5. Injection arrays—These pumping patterns can have a number of configurations. A typical injection pattern for an intersection will have injection holes angled over the rib on 3 m (10 ft.) centers spanning each crosscut in the intersection (Fig. 1). PUR may be injected over the rib on each side of the intersection. These injection holes will be packed off to the destabilized zone, and then PUR is injected to erect a "grout curtain" which will act as a barrier and permit infilling of the intersection. The holes are either pumped to a predetermined volume or pressure or injected to refusal. Then holes will be drilled and pumped in the center of the intersection to complete infilling of the pattern. The exact specifications of the design are often determined by the experience of the contractor.

3 Case Histories

Four case histories of polyurethane injection for coal mine roof stabilization are presented. Two of the histories were in highly fractured rock and two were in unfractured rock.

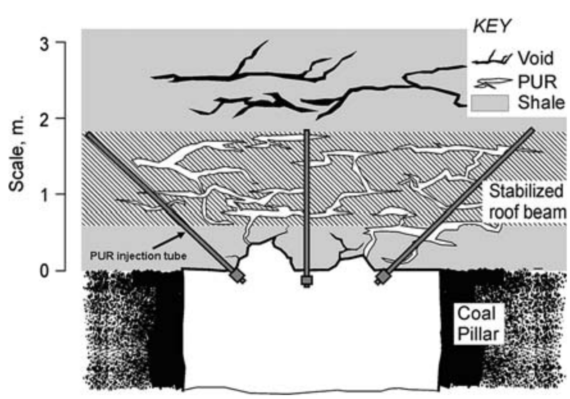


Fig. 1 Idealized PUR injection design

3.1 West Virginia Coal Mine—Fractured Roof

A coal mine in north-central 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 (Fig. 2). The 5.5 m (18 ft.) wide belt entry was averaging 2–3 roof falls per year which resulted in costly delays due to cleanup and rehabilitation. The roof rock was extremely weak and highly moisture-sensitive clay shale. August was the worst month, with roof falls occurring almost 2.5 times more frequently than the annual monthly average. In addition, it was suspected that frequent clay veins reacted to moisture, swelled, and applied bulking pressures on the roof sequence. The roof began to unravel between bolts soon after mining, 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 (Fig. 2).

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, building a false roof, moving the beltline, or polyurethane injection. Polyurethane injection was selected to stabilize all the unfallen intersections in the main beltway because, based on past experience, it had the greatest likelihood of success.

Beltway PUR pumping began using an injection pattern with 11 pump holes per intersection. It was difficult to build any pump pressure and questions immediately arose as to where the polyurethane was going. (It should be noted that this intersection was heavily supported with steel beams and posts). Cold air was blowing down the test hole indicating communication over the crosscut to the intake entry. During injection of two test intersections on the track, the job was stopped in order to evaluate the PUR reinforcement by using video monitoring.

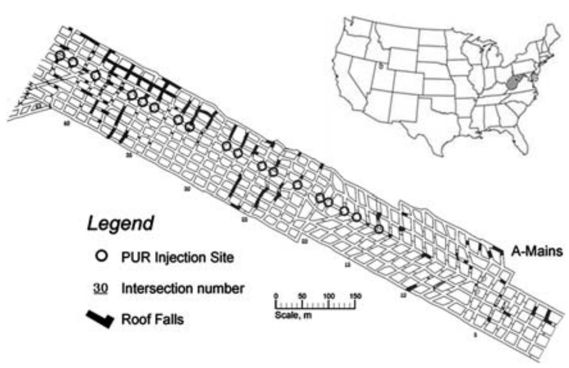


Fig. 2 Roof falls and PUR injection sites in West Virginia mine

3.1.1 Video Diagnostics

A total of 16 video logs from 15 intersections were used in the analysis. Monitoring holes were drilled on the walkway side of the belt in the middle of the intersection crosscut and approximately 0.9 m (3 ft.) from the rib.

Video monitoring of the first PUR injection test intersection on the track (intersection No. 26) detected large voids at 2.9–3.7 m (9.5–12 ft.) up into the roof (Fig. 3). A large void (27.9 cm (11 in.)) was detected in two test holes in the intersection at 3.4 m (11 ft.) above the roof line. A total of 48 cm (19 in.) of void space was observed in the roof. From these observations, and the lack of pump pressure, it appeared that large volumes of PUR were being lost into the voids. Video logs also revealed the condition of the roof in selected intersections along the Mains project area. Pre-pumping video logs showed significant voids in the roof at two intersections (No. 23 and No. 32) (Fig. 4). At No. 32, highly fractured roof rock was loading standing support and falling between supports (Fig. 5). Three-3.7 m (10–12 in.) of deflection on the steel beam in this intersection indicates the sum of separate fracture voids up in the roof and can be used as a de facto roof extensometer.

3.1.2 PUR Injection into the Beltway Roof

Because of the large separations detected in the roof, it would be impossible to fill all the voids with the full strength non-foaming PUR. After considering cavity-filling foam, a decision was made to target zones for reinforcement with non-foaming PUR. The concept was that if the lower beam could be reinforced, it would be unnecessary to fill all the voids. It was decided to concentrate the PUR injection on reinforcing the roof beam from 0.6–1.8 m (2–6 ft.) up into the roof. An injection procedure was designed which would target two isolated zones for PUR injection, creating a reinforced beam. The reinforced beam in A-Mains was created by pumping PUR in an isolated

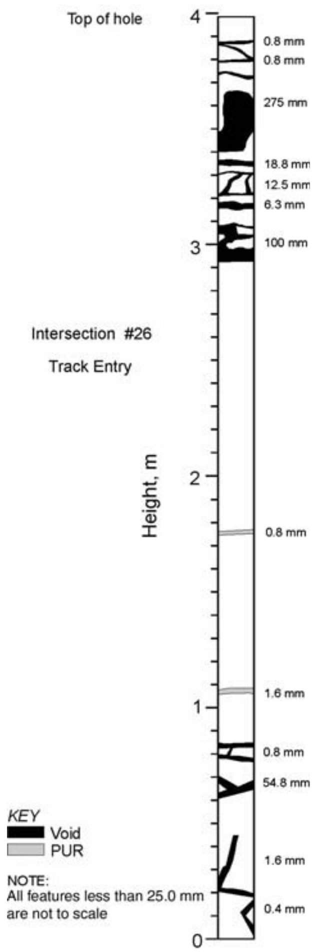


Fig. 3 Large voids detected by videoscope above bolt anchorage

zone from 1.2–1.8 m (4–6 ft.). The chemical was allowed to harden (30 s set time). A packer was then set and PUR was pumped from 0.6–1.2 m (2–4 ft.). Each intersection averaged 12 injection holes and these holes averaged 1.8–2.1 m (6–7 ft.) long. The average amount of PUR injected per intersection was 1,608 l (425 gal). This volume was calculated to allow 2.2–207.9 l (55 gal) drums of PUR mix to pump three holes. Injection pressures ranged from 0–13.8 MPa (0–2,000 psi) and averaged about 2.8–3.5 MPa (400–500 psi). The injection pattern was typically four angled holes on each side of the beltway in the intersection, and four holes along the middle of the intersection.

All intersections that had not fallen in the beltway were treated with PUR injection stabilization (Fig. 2). A total of 27 intersections had PUR injected.

3.1.3 Location of PUR After Injection into the Beltway Roof

Video logging was available at 16 post-injection test holes at 15 intersections. The test holes showed PUR successfully injected into numerous void spaces in the target zone in each of 15 intersections. Individual cracks ranging from paper thin up to 1.9 cm (0.75 in.) wide, and rubbleized zones up to 1.5 in. (3.8 cm) were filled with PUR (Fig. 6). This information allowed for an intersection-by-intersection evaluation of the PUR injection performance.

In five 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 (Figs. 4, 6). In intersections No. 21 and 23, all of the pre-existing fractures, in the zone of reinforcement, were filled with PUR.

In intersection No. 20 and 22 pre-injection holes showed solid roof and no voids or even separations (Fig. 4). After injection, a video log revealed that PUR was injected into a zone at 0.5 m (1.7 ft.) and from 1.1–1.2 m (3.5–3.8 ft.) into the roof in hole No. 20 (Fig. 6). It seems that in these holes PUR was injected either into weak, unseparated bedding planes or that it hydrofractured the bedding planes with injection pressures up to 12.4 MPa (1,800 psi.) Hole No. 22 showed similar evidence of hydrofracturing.

At intersection No. 32 PUR injection was less successful. PUR injection was stopped because no back pressures could be built up indicating flow out of the intersection. Several centimeters of void space was measured in the pre-injection pump zone .6–2.1 m (2–7 ft.) into the roof) (Fig. 4). No PUR was observed in one post-injection monitoring hole (Fig. 6, No. 32a), indicating loss of PUR into voids. The other post injection test hole in the intersection showed much less severe fracturing in the target zone at 0.6–2.1 m (2–7 ft.), with some PUR showing at 1.2 m (4 ft.). Several fractures in a zone from 0–0.2 m (0–1 ft.) had PUR shows. PUR shows in this zone, below the packed injection zone, indicated the extreme fracturing in this intersection. The PUR found fracture conduits below the packed zone and was seen dripping from the roof. In intersection No. 32 the one pre-injection hole and two post injection holes showed large variations in fracture location in the intersection. This indicates that additional

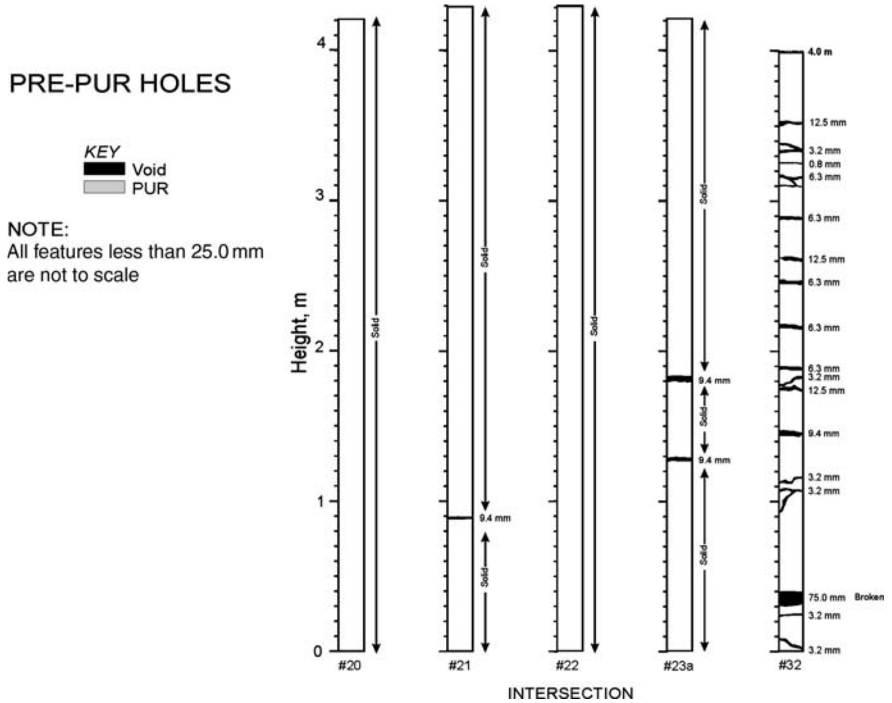


Fig. 4 Video logs of roof holes in selected intersections before PUR injection

Fig. 5 Heavily loaded standing support and roof damage in intersection

monitoring holes may be necessary to delineate the variation in highly fractured intersections.

Table 1 summarizes the PUR injection history of the remaining intersections. It shows the amount of void space filled by PUR in monitoring zone (the injection zone was from 0.6–1.8 m (2–6 ft.)) and the amount of PUR pumped.

Of the 16 holes that were video logged in 15 intersections, 9 had 100% of the void space in the monitoring zone 0.6–2.1 m (2–7 ft.) filled with PUR. 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 four test holes in the intersection showed voids ranging from 0–3.8 cm (0–1.5 in.) wide. The variation in void space over short distances may explain the partial filling of voids 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 three intersections (Nos. 32, 29, 26) monitoring holes detected 0, 1 and 9% of the voids filled, indicating loss of the pumped PUR into the mine opening or away from the intersection monitoring hole. Monitoring holes in each of these intersections revealed large void spaces above the bolted horizon 1.9–15.2 cm (0.75–6 in. wide voids). PUR injection was unsuccessful in these instances. The intersections are currently controlled by heavy standing support.

The amount of PUR pumped into each intersection was also recorded. The volume ranged from 880–2,642 l (233–699 gal) (Table 1). 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. If PUR is injected too low, roof

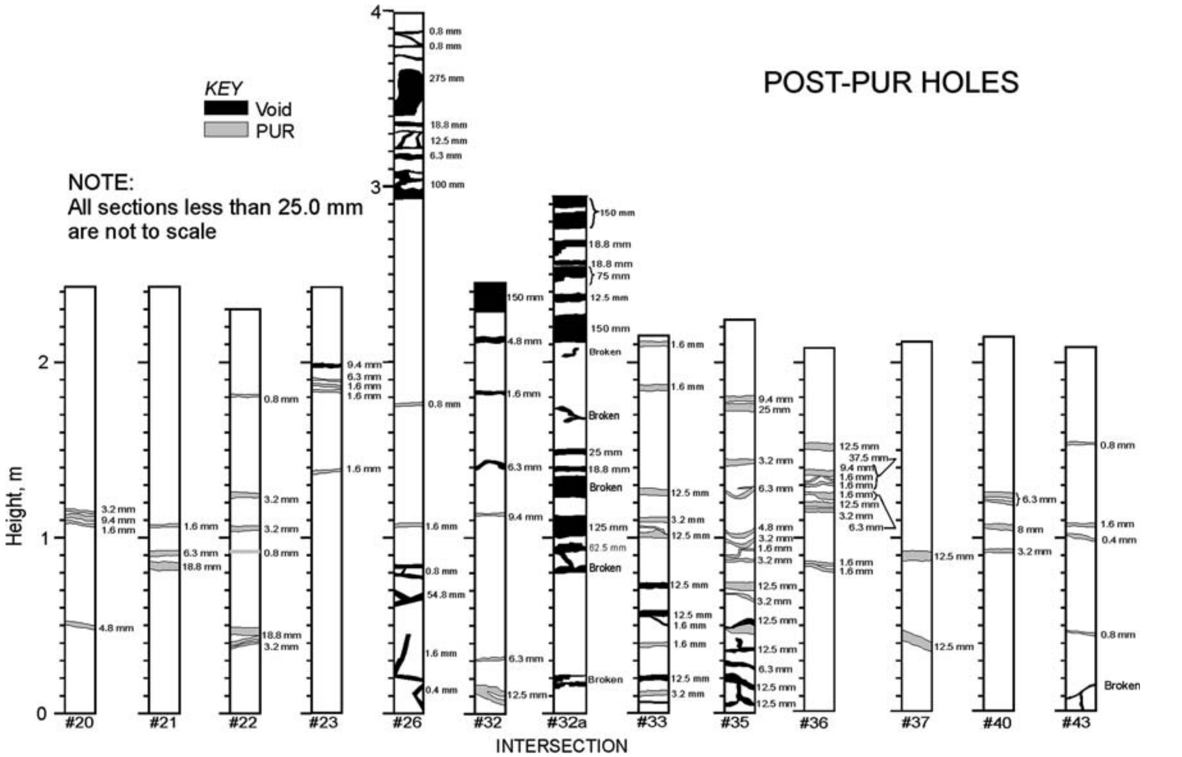


Fig. 6 Fractures filled with PUR in selected intersections after PUR injection

Table 1 Void space filled by PUR in the monitoring zone (0.6-2.1 m (2–7 ft.))

Intersection no/hole	PUR pumped l (gal)	Total void space cm (in.) 0.6–2.1 m (2–7 ft.) zone	No. of injection holes	Void space filled (%) in test hole 0.6–2.1 m (2–7 ft. zone)
43	2,642 (699)	0.28 (0.11)	21	100
42	2,010 (532)	3.8 (1.50)	16	100
40	2,139 (566)	1.8 (0.69)	17	100
37	2,517 (666)	1.3 (0.50)	20	100
36	2,388 (632)	7.7 (3.0)	19	100
35	2,642 (699)	7.4 (2.9)	21	100
33	1,761 (466)	4.6 (1.8)	12	71
32	880 (233)	2.2 (0.87)	8	43
32a	880 (233)	6.3 (11.8)	8	0
29	2,268 (600)	10.5 (4.1)	No data	1
28	No data	0.69 (0.27)	No data	93
26	2,268 (600)	6.23 (2.43)	No data	9
23	1,508 (399)	2.0 (0.81)	12	54
22	1,436 (380)	0.79 (0.31)	12	100
21	1,508 (399)	2.7 (1.06)	12	100
20	1,632 (432)	1.4 (0.56)	14	100

blocks may be dislodged. Additionally, if PUR is injected into large voids it may migrate away from the intersection and be of little value. Void spaces open 2.54 cm (1 in.) 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 3.0–4.0 m (10–13 ft.) into the roof, a stable beam has been created from 0.6–1.8 m (2–6 ft.) in the roof. In 2.5 years of monitoring since the injection project, 26 of the 27 reinforced intersections were stable.

3.2 Western Pennsylvania Coal Mine—Fractured Roof

A longwall mine in southwestern Pennsylvania was experiencing heavy roof conditions in surrounding rooms after a roof fall in the headgate of a future longwall panel. It was decided to inject PUR into the roof in order to stabilize several hundred feet of headgate entry in preparation of the upcoming longwall. An opportunity was presented to observe the fracture condition of the roof before injection and then after PUR injection. Additionally, heavy roof conditions were observed in the center track entry and this entry was chosen as a test site for PUR injection. Figure 7 shows the intersection where PUR injection and monitoring took place. Five pre-injection monitoring holes revealed the lithology and fractured condition of the roof (Fig. 8). The roof consisted of approximately 0.6 m (2 ft.) of roof coal, followed by gray shale from 0.6–2.1 m (2–7 ft.), followed by a coarse sandstone with coal streaks.

Hole No. 2 showed a total of 2.8 cm (1.1 in.) of open void or rubbleized zones of fractured rock up in the monitoring holes which were drilled to 3.0 m (10 ft.). The individual cracks ranged from 0.15–1.28 cm (0.06–0.5 in.), in bedding separations and zones of rubble. In holes 1, 2, 3 most fractures occurred above 1.5 m (5 ft.) and in holes 4, 5 most fractures occurred below 1.2 m (4 ft.), indicating some variability across the intersection. Polyurethane was injected into five vertical holes adjacent (30–60 cm (1–2 ft.) away) to the observation holes in the intersection. The holes were packed at approximately 30 cm (1 ft.) above the roof line.

Figure 9 shows the logs of test holes drilled after PUR injection. Approximately 50% of the total

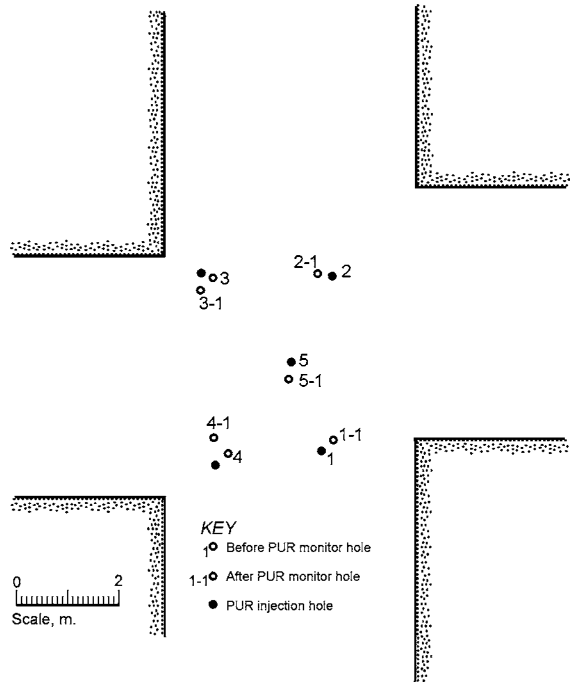


Fig. 7 Intersection holes monitored before and after PUR injection

fractures were filled with PUR, while the other 50% remained open. Figure 10 shows one of the glue-filled fractures after PUR injection. Since the holes were packed at the bottom, the PUR was free to find the path of least resistance up hole. Due to the tortuous nature of the fracture permeability the PUR found pathways which filled some fracture zones and bypassed others, as observed in the post-PUR monitoring holes. From experience at the mine in West Virginia this amount of void space filling should be enough to stabilize the intersection. The mine was closed shortly after the project and no assessment of the success of the PUR stabilization project was possible. By using multiple packed zones, as was the case in the West Virginia project, the chances of targeting particular zones of significant fracturing can be greatly increased.

3.3 Bruceton Safety Research Coal Mine—Unfractured Roof

The previous two case studies illustrate the reinforcement mechanism of PUR in highly fractured

Fig. 8 Pre-injection monitoring holes in the intersection

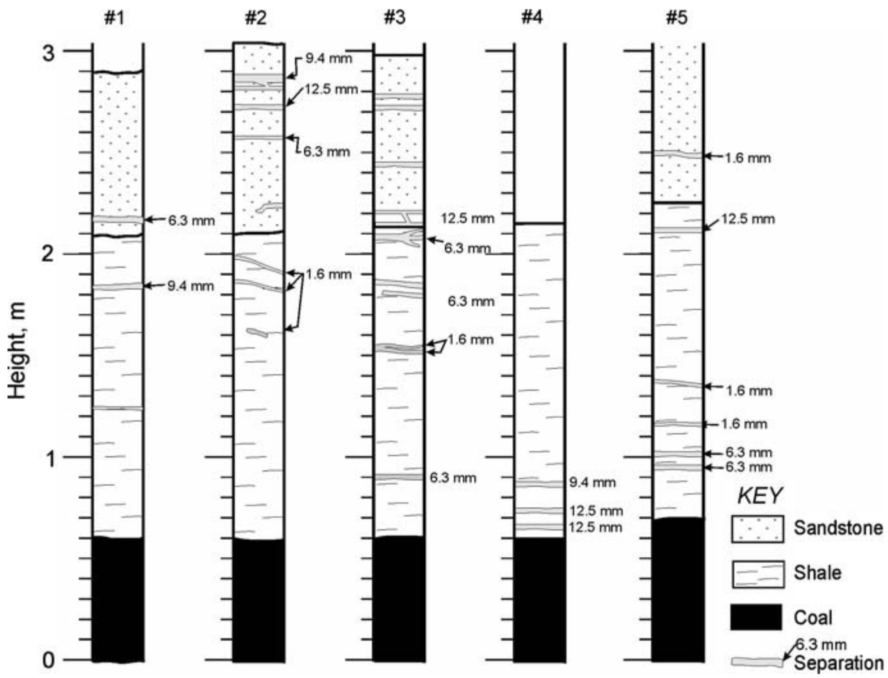
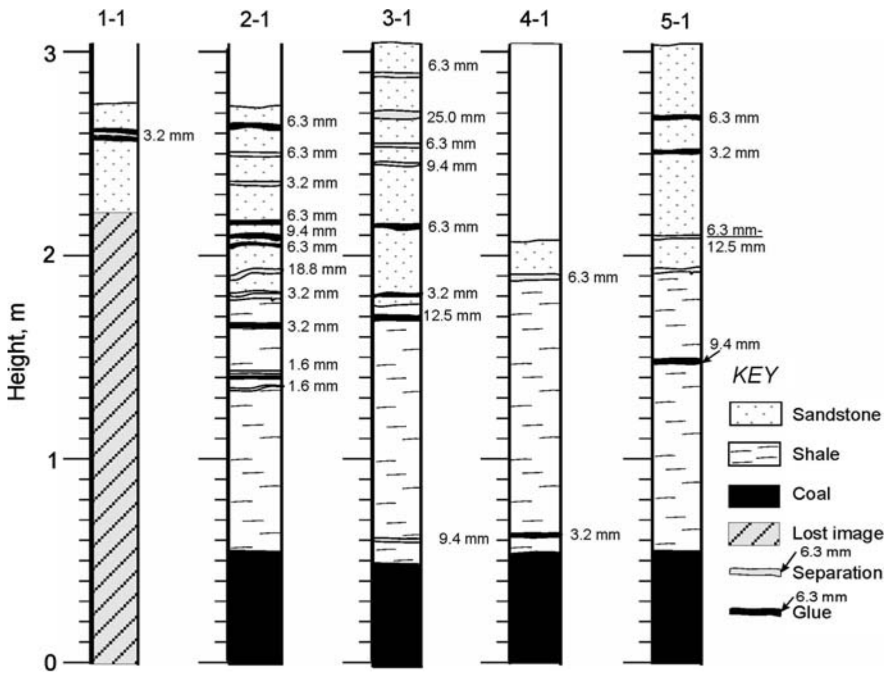


Fig. 9 Post-injection monitoring holes in the intersection



rock. The remaining two cases show the behavior of PUR when injected into unfractured rock. A test of PUR injection was undertaken at the NIOSH Bruceton Safety Research Coal Mine in southwestern Pa. The mine is located in the Pittsburgh coal bed with an immediate roof that consists of a sequence of rider coals and shale (Fig. 11). Six 2.4 m (8 ft.) long injection holes were drilled in one intersection (Fig. 12) into which a total of 477 kg (1,050 lbs) (397 l (105 gal)) of polyurethane was injected. The holes were isolated with packers located at 0.9 m (3 ft.) up in the hole, and PUR was pumped into open

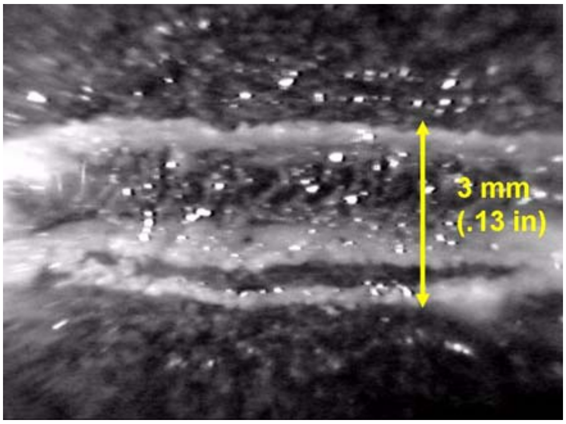


Fig. 10 Glue-filled fractures after PUR injection into hole 2-1

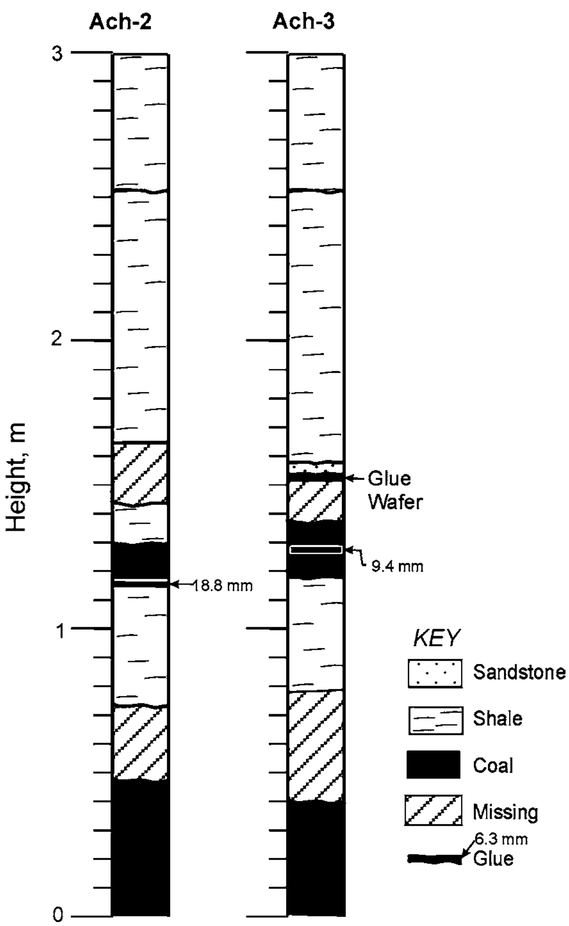


Fig. 11 Core holes drilled after PUR injection show glue injected at $\approx$1.2 m

hole from 0.9–2.4 m (3–8 ft.). Injection pressures went as high as 8.3 MPa (1,200 psi) and averaged about 3.5 MPa (500) psi.

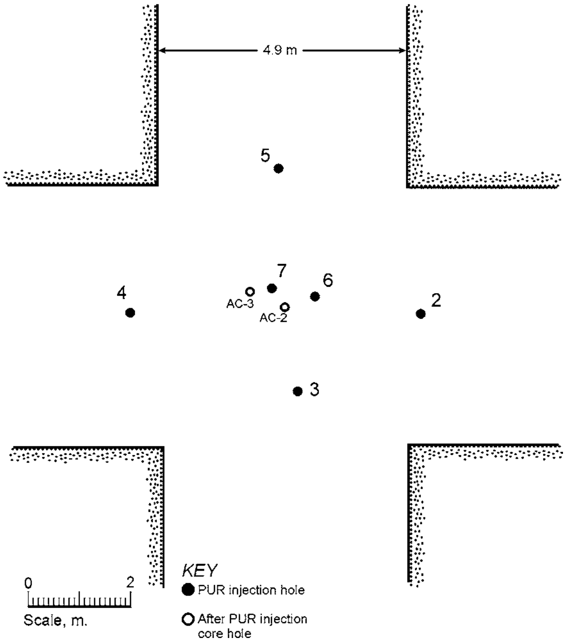


Fig. 12 Injection and monitoring holes at the Safety Research Coal Mine

Two coreholes were drilled after injection to determine the location of the polyurethane (Fig. 11). PUR was found injected along bedding at 1.2 m (3.9 ft.) in corehole ACH-2 and at 1.3 m (4.2 ft.) and 1.6 m (5.2 ft.) in ACH-3. This is essentially the same horizon due to small variables in the roof line. The PUR had hydrofractured the weak bedding in the second rider coalbed and left a 1.9 cm (0.75 in.) thick plug along bedding (Fig. 13). PUR was pumped into 1.5 m (5 ft.) of open hole at six locations around the intersection and the path of least resistance was the weak bedding found in the second rider coalbed (Fig. 11).

The results from this site indicate that, in unfractured ground, multiple horizons may not be hydrofractured and reinforced, but that only one reinforced zone can be expected. The support value of this zone containing a 1.9 cm (0.75 in.) layer of PUR is questionable. If multiple zones of reinforcement are desired, it will be necessary to isolate each such zone with a packer and pump the zone until failure and injection. This may be done from several injection holes packed at different heights or from the same hole with multiple packers.

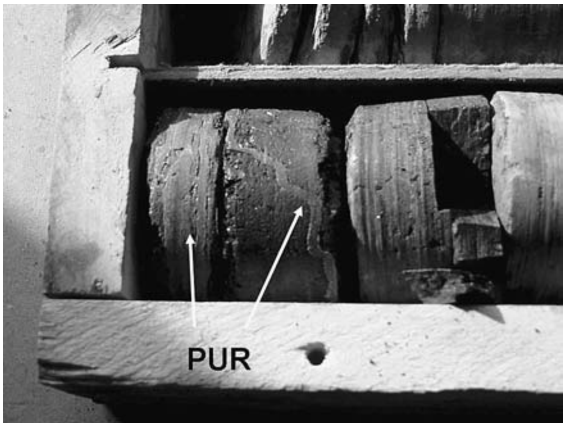


Fig. 13 Polyurethane injected into roof core Ach-2 at 1.2 m Bruceton Research Safety Coal Mine

Fig. 14 PUR injected into solid roof over longwall panel migrated back to the recovery room through a cutter

3.4 Western Pennsylvania Coal Mine—Unfractured Roof

A western PA longwall mine was using a pre-driven entry for longwall recovery. The entry was heavily supported including 2.4 m (8 ft.) combination bolts, 3.7 m (12 ft.) cable bolts, double channels every row of bolts, screen, and pumpable cribs. This heavy support is necessary to resist the front abutment load which will come on the room as the shearer approaches and cuts into the room. In addition, from the recovery room, the mine injected PUR over the panel and also over the opposite rib side of the entry. This was an attempt to reinforce the rock mass above the final panel cutout prior to the longwall pass. This rock mass would be subjected to front abutment loading when the shearer cut into the recovery room. Often, in weak ground, emergency PUR stabilization is needed in the final cut-through before longwall recovery. It was hoped that pre-grouting the roof would head off the need for an emergency PUR injection.

Ten feet angled "forepole" holes were drilled on 3.0 m (10 ft.) centers and PUR was injected in a zone from 0.6–3.0 m (2–10 ft.) into the roof rock at 45° over the panel. High pressures were built up and it was extremely difficult to force PUR into the tight, unfractured rock. PUR migrated back towards the recovery room and was observed leaking into the room via a cutter developed on the panel side of the room during development (Fig. 14). No observation was possible over the panel, but it is clear that PUR could not migrate over the solid panel as originally planned, but hydrofractured a weak bedding plane and followed the path of least resistance back into the entry. Two adjacent recovery chutes off of the recovery room were also selected for a test of the injection of PUR into unfractured, but undermined, roof rock. Chutes C and D were injected with PUR and the results monitored via videoscope (Figs. 15, 16). Figure 17 shows the lithology and final location of the PUR in the immediate roof after the injection in room C. No open separations occurred in the immediate 3.0 m (10 ft.) of roof rock prior to the injection. In room C one hole (PH-1) was drilled to 2.4 m (8 ft.), packed at 1.5 m (5 ft.), and injected with 4.0 l (15 gal) of PUR (Fig. 15). Then the hole was re-packed at 0.6 m (2 ft.) and injected with another 4.0 l (15 gal) of PUR. A number of cable and combination bolt holes experienced leaks as the PUR migrated through the entry roof. Five monitor holes were videoscoped after the PUR injection (Fig. 17). The first PUR injection zone was isolated at 1.5–2.1 m (5–7 ft.). This was the contact between the sandstone and the underlying shale. This was done to see if the PUR could hydrofracture the coarse sandstone with coal spars. No PUR was observed in the sandstone in any of the monitoring holes (Fig. 17). It appears that the bedding in the sandstone was too strong to be hydrofractured and the PUR must have found some other conduit for relief. The other injection zone was isolated at 0.6 m (2 ft.) (PH-1). PUR was injected from 0.6–1.5 m (2–5 ft.). A thin 0.08–0.64 cm (0.03–0.25 in.) PUR wafer was observed at 42.7–57.9 cm

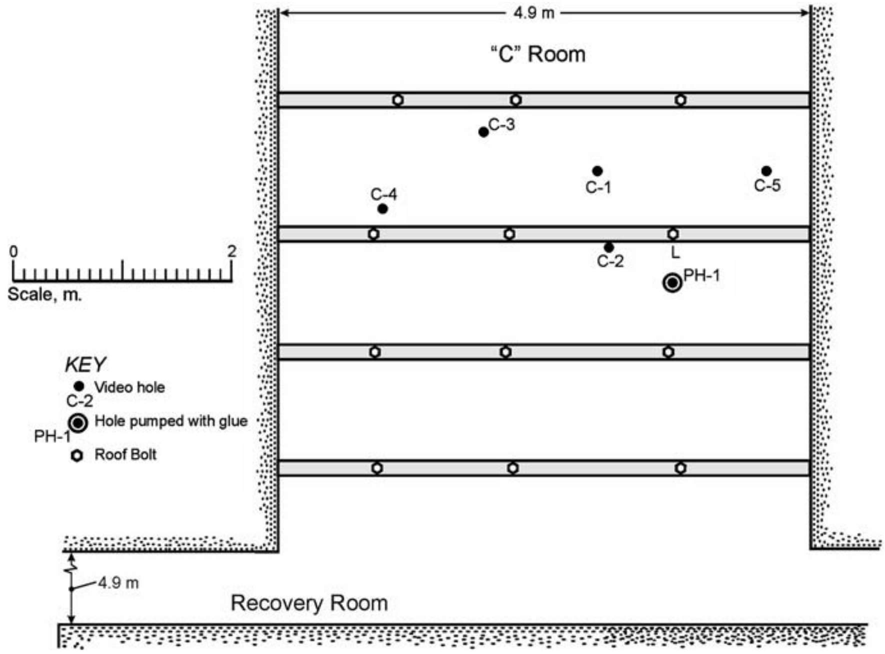


Fig. 15 First recovery chute with PUR injection and monitoring holes

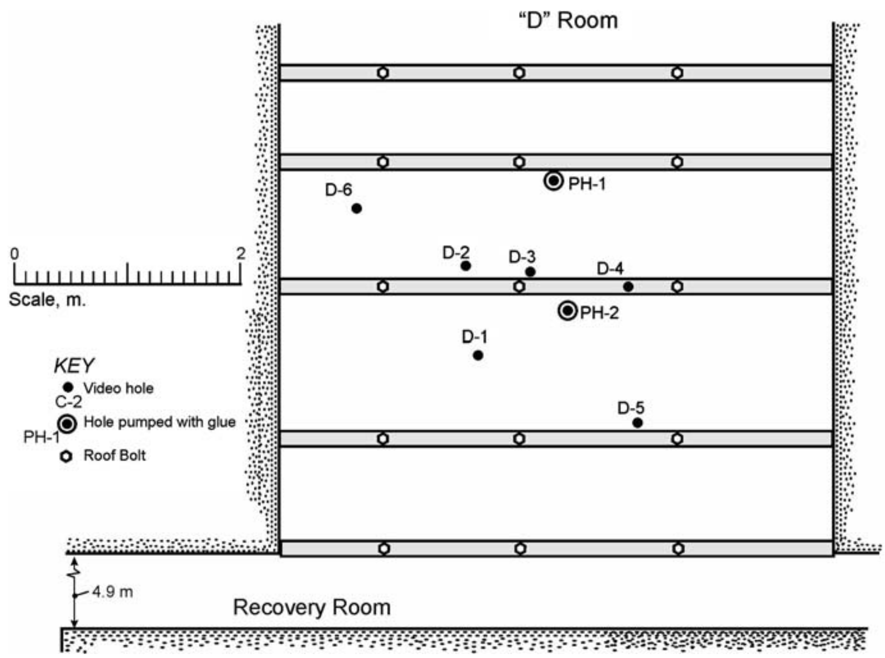


Fig. 16 Second recovery chute with PUR injection and monitoring holes

(1.4–1.9 ft.) up in the roof in two of the video holes (C-3, 5). These shows were below the packer at 0.6 m (2 ft.). This indicates that PUR migrated below the packer and found weak bedding planes at 42.7–57.9 cm (1.4 and 1.9 ft.). Similar to the Bruceton unfractured roof case, only one zone was hydrofractured and reinforced.

The adjacent chute (D) roof was also injected with PUR and videomonitored to locate the PUR (Fig. 16). Injection hole PH-1 was packed at 30 cm (1 ft.) and pumped with 62.7 l (16.6 gal) of PUR Injection hole PH-2 was packed at 90 cm (3 ft.) and pumped with 62.7 l (16.6 gal) of PUR. Video monitor holes D-1 thru 6 recorded the results (Fig. 18). The sandstone/

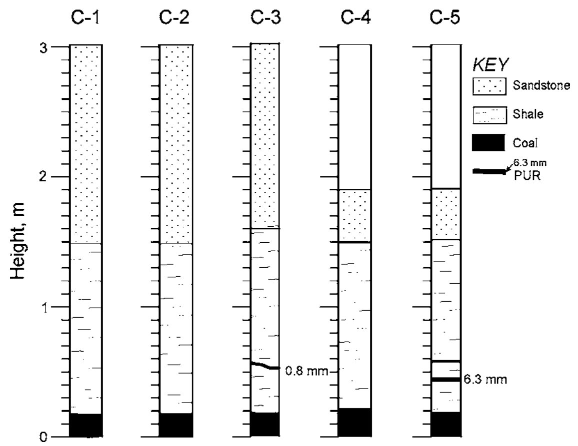


Fig. 17 Location of PUR after injection

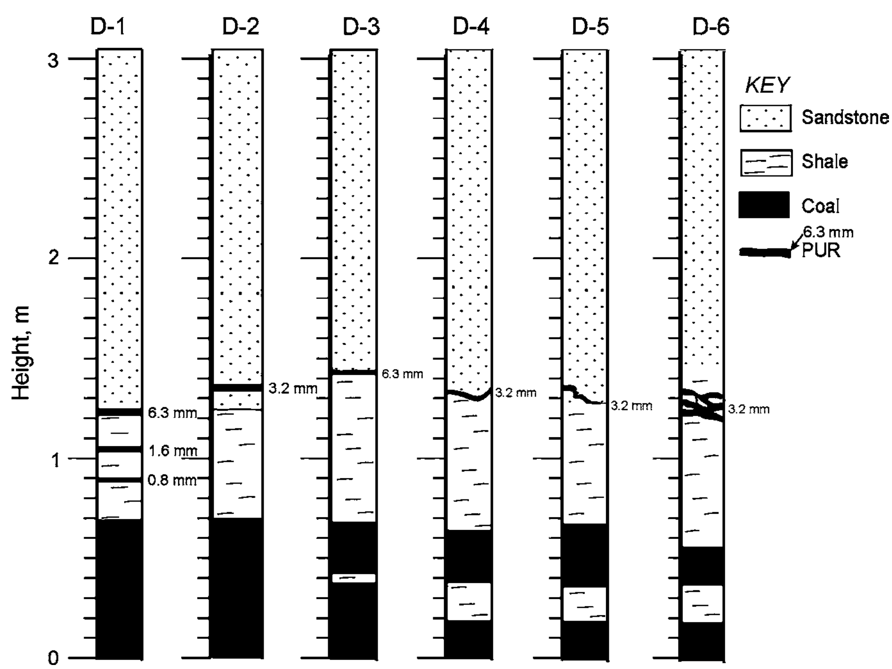
shale contact occurred at 1.1 m (3.5 ft.). All six monitor holes showed PUR layers ranging from 0.08–0.64 cm (0.03–0.25 in.) thick right near the contact of the sandstone and shale. Clearly the weakest bedding contact was this shale/sandstone contact. The PUR that was injected into the roof of both test rooms found the bedding horizon that was the weakest and wedged it open. In only one monitor hole (D-1) was there evidence of multiple injection zones over a 0.45 m (1.5 ft.) zone.

4 Discussion

The design and performance of a roof stabilization using PUR injection depends greatly on the condition of the rock mass. Typically, highly fractured rock masses benefit the most from the chemical bonding and inherent strength of PUR. PUR injection is more suitable for reinforcing highly fractured rock masses where fractures propagate across bedding resulting in isolated key blocks. In the two fractured roof cases described above, large voids and rubbleized zones allowed easy access for PUR, permitting a webbing structure of PUR-supported key blocks to form a beam in the roof. If the beam is significant enough to support the overlying dead load of detached rock, then this detached zone does not have to be reinforced.

The two case histories in unfractured ground indicate that significant reinforcement is unlikely. More likely PUR will hydrofracture the bedding and remain only on that one bedding plane. Monitoring data of the two test sites in unfractured ground indicate that injecting PUR "on the solid" will not reinforce the ground in any significant way because open fractures are not available. While the pressures realized (13.8 MPa (2,000 psi)) when injecting PUR are certainly enough to hydrofracture weak bedding

Fig. 18 Location of PUR after injection



planes, the resulting thin layers of PUR do not form a significant reinforcing web.

The 1.9 cm (0.75 in.) thick layer of polyurethane injected into the Pittsburgh roof bedding at the Bruceton site cannot be considered a consistent and continuous layer, considering the variability of bedding strength. The most likely occurrence, seen at both test sites, is that the PUR will be injected on only one horizon. Similarly, in the second site at the longwall recovery chute, only one horizon was hydrofractured. This single layer cannot be expected to provide substantial resistance to thick, overlying, detached roof blocks. These results are consistent with results obtained by using the hydrofracture method to measure in situ stress (Enever et al. 1990). In this procedure, only one bedding fracture is obtained in weak rock, indicating the path of least resistance for the fluid. Once the fracture has been created and the PUR is being injected, large volumes may be pumped into the single bedding plane fracture. This additional PUR will provide little additional reinforcement as it is usually a thin wafer confined to only one horizon. If substantial reinforcement is desired in unfractured rock, that goal must be accomplished by specific design. Multiple injection zones must be isolated with packers and the reinforcement will be obtained by the sum of the strength of several layers of PUR injected into weak bedding planes.

In reinforcing intersections, current designs utilize holes drilled in the corner of an entry angled up over the ribline. The idea is to create a "grout curtain" which could act to contain the polyurethane which then sets up and forms a barrier over the entry shoulder. The experience in the unfractured rock injection in the recovery room shows that this "over-the-rib grout curtain" is unlikely to be successful because PUR will migrate towards the undermined entry and not over the solid rib. Additionally, the polyurethane is thought to resist shearing of roof layers along the ribline. From the experience in unfractured rock, a single layer of PUR injected along bedding is unlikely to provide much resistance to shearing.

In extremely fractured rock, difficulty was encountered in getting the PUR into the zone targeted for beam reinforcement. This problem may be addressed when designing the "grout curtain" to prevent unwanted PUR loss into voids. This is a barrier established by injecting PUR around the perimeter of the intersection, and allowing it to set up before any subsequent round of PUR injection. Injection holes, pumping a set volume of PUR, may be drilled in concentric circles around an intersection, working towards the center of the intersection. With a 30 s set time, the PUR will have enough time to form a barrier before the next injection hole is started. This method will help to avoid pumping large volumes into large void spaces.

The study also demonstrated the value of using video monitoring of fractures prior to PUR injection. In the West Virginia case, the presence of large open voids, some as large as 28.2 cm (11 in.) wide, became the path of least resistance for PUR. Large volumes of PUR were being pumped into big voids resulting in wasted resin and little reinforcement. Video data showed that a reinforced beam from 0.6–1.8 m (2–6 ft.) could be created which would support the overlying broken rock. In many intersections video logs revealed that the roof was extremely broken up from 0–0.6 m (0–2 ft.) into the roof. Without this information attempts to inject PUR under pressure into this zone could result in hazards from dislodged roof blocks.

5 Conclusions

When using polyurethane injection to stabilize a rock mass, an understanding of the fracture condition of the rock mass in advance can help in the design of the injection. By knowing the location and extent of the fracture permeability, design parameters; including volume and expansion properties of chemical grout, target horizon, and density/geometry of injection holes, the injection of polyurethane can be optimized. Pre and post video-monitoring can provide valuable fracture information for both designing the injection parameters and evaluating the success of the PUR stabilization.

In designing a polyurethane stabilization, the goal should not necessarily be to fill all the fractures in the roof. Complete void-filling may not be achievable, except with expanding foam. In extremely fractured roof, an alternative is a beam-building design where 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. The concept is similar to beam building with roof bolts. If the rock beam can be maintained intact it can transfer the load of its own weight to the pillars and act to support the weight of a limited amount of fractured rock above. Mechanically, the polyurethane forms a beam out of rock that has been separated along bedding or is broken into key blocks. It is the size and strength of this beam which determines the stability of the roof.

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