CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the three case studies using PUR product for stabilization of rock slopes and dry-stack walls, the following should be considered when designing the PUR mitigation system:

- Applicability of PUR for the Site Conditions
- Preliminary PUR Volume Estimation
- PUR Product Requirements
- PUR Placement Considerations
- Site Monitoring Considerations
- Clean Up and Disposal Requirements

APPLICABILITY OF PUR FOR THE SITE CONDITIONS

Rock Mass Stabilization

The case studies involved injecting PUR product into a rock mass with open fracture apertures larger than approximately 2 mm (1/8 in). The PUR product migrated into fractures and fracture orientations that were interconnected and resin flowed from one set of fractures into adjacent fractured sets. The rock mass joint and fracture sets varied from 0.5 to 3 m (1.5 to 9 ft) apart. PUR product was visibly flowing out from the joint sets at distances in excess of 1.5 m (5 ft) adjacent to the point of injection.

The two case studies in this report focused on rock mass stabilization in hard metamorphic gneisses and schists; however, based on extensive use in underground coal mining applications, PUR is also applicable in bedded, jointed sedimentary formations. It should be noted that if the joint sets are not interconnected PUR placement volumes and uniform dispersion through the rock mass may decrease significantly resulting in unsatisfactory stabilization of the rock mass.

Due to the nature of the work, crane baskets or man-lifts were necessary to access the rockslopes, requiring traffic control during construction on roadway projects. Man-lifts are typically limited to approximately 30 m (100 ft) above the roadway section. Cranes could also be used for the installation of PUR product; however, it may not be cost effective to mobilize a large crane to a remote site and may require roadway closures to reach sections that cannot be accessed with man-lifts significantly impacting traffic.

Until PUR is more fully evaluated for the mitigation of unstable rock slopes, PUR is not recommended to replace tensioned or non-tensioned rock bolting. However, PUR can be effectively used to optimize required bolting, and may mitigate the need for other types of surface treatments (for example, plates, straps, and mesh). If only a small percentage of PUR is successfully injected into a fracture plane, it will substantially increase the cohesion between the opposing sides of the fracture. For example, it can be shown that an increase in 1 kPa (20 psf) will dramatically increase the overall factor of safety of the joint set.

Visually the PUR product may blend into the rock background depending on the rock type. If aesthetics are important, it will be imperative to remove product overruns during placement to minimize the effort required to peel it off the rock face. Fully hardened PUR product can be chipped from the rock face, but requires greater effort. Removal of exposed PUR product immediately after injection facilitates the removal process.

Dry-stack Wall Stabilization

Based on the successful outcome of the case study for the dry-stack wall stabilization, the PUR product was injected behind a failing wall system with soft, open-voided sections. The PUR product provided the following advantages to cement grouts by providing:

- Greater viscosity which limited product migration keeping product behind the wall system and out of the nearby sensitive areas.
- Provided very fast adhesion between the dry-stack boulders.
- Provided greater tensile strength to the wall system that would not have been achievable with cement based grouts.

The PUR product in the case study migrated behind the dry-stack walls since the materials behind the walls were very loose to loose with open-void sections behind the boulder facing which made it possible to insert small diameter jam-rods behind the wall sections. Tight or very dense materials behind dry-stack walls may have required other methods of placing the injection ports behind the wall such as mechanical drilling (i.e. core or auger) to create ports in which to inject the product.

The case study had easy access to the wall structure in order to inject the PUR product from a central point. Long pumping distances were not required in the case studies. Long pumping distances may affect the temperature of the component products causing accelerated or reduced set times depending on the ambient temperature and heating or cooling of the delivery hoses.

PRELIMINARY PUR VOLUME ESTIMATION

As discussed in this report, the presence or absence of moisture will greatly affect the strength, viscosity and foaming aspects of the PUR product. Pre-injection volume estimation is difficult. Dry conditions will require more PUR product to be placed and will result in a greater bonding and strength set-up, but may require a more labor intensive effort to clean-up material overruns. Wet conditions will require less PUR product to be placed, since the material will foam in the presence of water and may migrate much shorter distances. Clean-up will be much easier with a foamed or slightly foamed product.

Rock Mass Stabilization

Based on the case studies in fractured rock applications, which were drilled to depths ranging from 2.5 to 3.6 m (8 to 12 ft), approximately 450 kg (1,000 lb) of product was injected per day. As a daily average based on the two field demonstration sites, the amount of PUR injected per hole ranged from 22 to 450 kg (50 lb to 1000 lb) and the time of injection ranged from 20 to 60 minutes. At the Poudre Canyon Site, approximately 80 m^2 (850 ft^2) of portal area was treated to an estimated average depth of 3 m (10 ft), for a total approximate PUR grouted rock volume of 240 m^3 (8,500 ft^3), however, it is was not possible to determine the total depth that the product actually migrated. The preceding volume estimations are provided as a general observation of the case study. It was determined that a measurable volume of PUR product was injected into a fracture pathway which will qualitatively increase the stability of the rock mass, but it was not possible to determine the exact extent of the product migration or the quantitative increase in factor of safety.

The case studies for the rock mass stabilization were generally moist to dry. Foaming was observed at each location, but the majority of the product placement occurred in dry fracture pathways. If wet or very moist conditions were encountered the volume placement of product would be estimated to be half or even one quarter of what was placed under dry conditions.

Dry-stack Wall Stabilization

Based on the case study for placement of PUR product in the dry-stack wall, where injection portals could be hand driven, approximately 900 kg (2,000 lb) of PUR was injected daily. The amount of PUR injected per hole ranged from 22 to 225 kg (50 lb to 500 lb), with injection times ranging from 20 to 60 minutes. Approximately 135 kg (300 lb) of PUR product per injection hole/jam-rod installation was observed for the dry-stack wall. Over the course of three days, 18 m (60 ft) of wall, averaging 2.7 m (9 ft) in height was injected with 1,800 kg (4,000 lb) of PUR. It is estimated that approximately 57 m^3 (2,000 ft^3) of wall structure was treated, and of this volume, approximately 11 m^3 (400 ft^3) was estimated to be open voids within the backfill and behind the dry-stack boulders. In addition approximately 1.7 m^3 (60 ft^3) of non-foamed resin was injected, likely filling approximately 20% to 25% volume of open void space within the wall. Note, in a classical soil context, the open void space is not to be confused with soil void space which is a ratio of volume of voids to volume of solids within a soil matrix. The PUR product does not readily permeate moist soils like a cement grout which migrates within the soil matrix. The PUR will typically foam and seal off in the presence of any moisture, but will migrate through the open void pathways behind the dry-stack boulders.

The case study for the dry-stack stabilization started in very moist conditions after several days of heavy precipitation, but then continued through a period of dryness. Extensive foaming occurred initially since the PUR product was coming into contact with soil moisture, but then as the subsurface dried out, foaming ceased and non-foaming PUR product was migrating from the wall face.

Due to the presence of large open-space features within and behind the wall facing, the PUR placed volumes were not significantly governed by the moisture content of the soil. It was possible to place product that foamed or did not foam since the product could find large pathways to migrate and was generally not confined to a particular pathway as with the rock mass case studies. The main aspect that did govern product placement was the potential to move and outwardly deflect the wall system.

PUR PRODUCT REQUIREMENTS

A special contract requirement (SCR) specification has been provided in Appendix A. This specification was developed as a general guideline for referencing PUR products for rock mass and dry-stack wall stabilization. Overall, the PUR product is sensitive to water and temperature. Water will reduce the strength of the product and create foaming and reduce volume takes, but will still be greater than the in-situ rock mass strengths or cohesions. Low or high temperatures outside the working range of the particular product may render the product difficult to use, since it will not be possible to inject the product due to rapid set times (hot temperatures) or poor mixing and slow set times (cold temperatures).

PUR PLACEMENT CONSIDERATIONS

Rock Mass Stabilization

Planning the efficient progression of work is essential to a successful installation. On rock slopes, work should progress from the bottom up. This ensures that staged pumping is always working against a well-filled and mostly sealed volume of rock as the PUR migrates upward through the rock mass. Drill holes should be located to intersect rock fractures to maximize the injection potential of the PUR product. The orientation, persistence, aperture and condition of the fractures and joints should be considered prior to PUR injection to maximize rock mass stabilization.

Drilling and PUR injection should be conducted sequentially – completing resin injection immediately following drilling before moving to the next drilling/injection location. The contractor may elect to pre-drill several holes prior to injection operations; however, this practice risks premature sealing of open holes adjacent to injection operations if holes are spaced too closely together. In highly fractured rock masses, or rock units with persistent jointing, it is prudent to drill and then inject PUR sequentially to accommodate unexpected resin migration patterns within the injection plan.

Although not observed during the demonstration projects described in this manual, the potential for complete rock mass sealing in wet or periodically wet environments should be considered when planning PUR injection operations. At the demonstration sites, observations indicate that sufficient jointing and fracturing remained open following resin injection to allow for the dissipation of groundwater pressures during seasonal runoff. However, consideration should be given to the installation of permanent drainage (e.g., horizontal drains, weep holes) in areas particularly susceptible to hydrostatic pressures.

Dry-stack Wall Stabilization

For rock retaining structures, it is recommended to treat the top of the wall first to stabilize loose, unconfined blocks before proceeding with interior wall injection. Injection rods placed several ft behind the wall face, on approximate 1.5-m (5-ft) centers along the wall, and to within 1.5 m (5 ft) of the bottom of the wall, should then be injected, taking care not to create conditions within the wall where expanding resin is pressuring against prior sealed sections of the structure. Direct face injection can be done to stabilize facing rock. Drilling was not required for PUR applications based on the demonstration at South Fork. The jam-rod technology was sufficient for effective PUR delivery behind and within the wall mass.

SITE MONITORING CONSIDERATIONS

Controlling pressure and volume is critical to a successful project outcome. Too much pressure or too much quantity at once may topple a dry-stack wall or peel an unstable rock flake off a rock slope. Staged pumping of relatively small volumes of PUR at very low pump pressures appears to work well for the progressive stabilization of both rock and retaining structures. Higher volume, high-pressure pumping should be limited to the mining industry where isolated rock failure during injection (intentional hydrofracturing of the rock mass) can be tolerated. Staged pumping, coupled with fast set times, ensures that loads from hydrostatic injection pressures are isolated and of short duration. Based on the case studies, pumping pressures should be closely monitored during installation, as pressures more than 1,800 kPa (250 psi) would likely have initiated movement within the rock mass. In the case studies, pumping pressures were kept to a minimum to minimize rock displacement.

Monitoring for either the dry-stack walls or rock slopes typically relies on continual visual inspection, but may employ simple "tell-tales" consisting of rocks or wedges placed in fractures and discontinuities that can quickly indicate potentially adverse rock mass displacements during PUR injection. More elaborate systems, such as crackmeters and extensometers, could also be used on projects particularly sensitive to rock mass or wall displacements.

There does not appear to be a need for drainage pipe installation when treating porous retaining walls. PUR coverage is neither continuous within the wall mass or sufficient to fill entire voids for either dry-stack walls or rock slopes. Although only a fraction of the existing open void space may be filled, the strength increase achieved by bonding wall elements together and/or consolidating wet sections with foaming PUR appears to greatly enhance wall stability.

CLEAN UP AND DISPOSAL REQUIREMENTS

The majority of the cleanup effort should be done within 1 to 2 minutes of PUR overrun, before early set. Hand tools are effective at chipping and peeling drips and runs from rock surfaces, but cannot remove all of the resin overrun. The PUR RokLok product was dark brown and blended well with most surfaces, making it difficult to see from more than 3 to 5 m (10 to 15 ft) away. The foaming product is a much lighter color, and may be readily visible from a short distance against darker rock units. Fortunately, foamed PUR is much easier to remove than dense, non-foamed PUR, limiting its visibility on most projects.