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Mitigation of an open shaft at a legacy mine site in British Columbia, Canada using polyurethane foam

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Abstract

Legacy underground mining sites may include the presence of unsecured openings to surface, such as shafts, vent raises, and portals that pose a risk to public and animal safety. This paper presents a case study of the design methodology and use of a polyurethane foam (PUF) plug for the mitigation of an open shaft at a legacy mine site in British Columbia, Canada.

Common methods of securing openings to surface include the design and construction of concrete caps or plugs, installation of steel grates, and/or placement of backfill. The method chosen depends on the remediation objectives, desired lifespan, and project setting. Openings in remote locations may require special considerations to optimise cost and reduce impacts on the environment due to the increased difficulty in transporting equipment and materials to the project site.

The shaft that is the subject of this paper had previously been backfilled several times with rockfill by the site Owner, but the backfill had either migrated and/or settled over time, eventually resulting in an expression of surface subsidence. The shaft location is within steep terrain and only accessible from an unsanctioned foot and bike trail which limits access with mobile equipment. The use of PUF was advantageous in this situation due to its portability and ability to be hand-mixed and hand-poured into the opening, reducing the need to transport equipment to the project site which would have impacted the surrounding forest terrain.

The PUF plug was constructed to prevent further subsidence and seal off access to the shaft to provide a long-term mitigative solution. The plug was required to have sufficient density, strength, and thickness to resist anticipated natural loads, and was designed to incorporate cementitious grout and backfill layers to provide ultraviolet (UV) and fire protection, respectively. An inspection port was also included in the design to facilitate long-term performance monitoring.

Technical specifications and a work methodology for mitigating the open shaft with PUF were developed to meet the design basis. A quality assurance program consisting of on-site observations and monitoring of site conditions, as well as sampling of the PUF material for third-party density and strength testing was also carried out. A post-construction monitoring program will be implemented beginning in summer 2023, following snow melt, and will consist of visual monitoring at surface and at depth through the installed inspection port.

Keywords: *mitigation, shaft, polyurethane foam, backfill, remote, opening to surface*

1 Introduction

The project site (the Site), a legacy gold/copper mine, is located in southern British Columbia and partially located within the jurisdictional boundary of a municipality. Mining at the Site occurred between the late 19th to early 20th centuries and consists of a major mining property and multiple neighbouring claims. Exploration and mining activities during the Site's history resulted in the creation of many features which include surface mining (e.g., prospects), underground shafts, stopes, portals and adits, and surface subsidence above underground mining (i.e., stopes and tunnels). Many surface features are accessible from public areas, including roadways and a vast trail network system. The Owner has mitigated many of the features in the past, generally with placement of rockfill; however, fill has potential to migrate into the underground workings or settle over time, which can result in subsidence or re-opening of the features.

Since 2006, work completed at the Site has included routine surface reconnaissance of the mining property and nearby claims to identify new features related to historical mining, assess visible changes to previously identified features, and assign relative hazard ratings to each feature to aid in closure prioritization. In addition, geotechnical investigations and mitigation recommendations and remediation designs have been developed for select features based on hazard prioritization considering factors such as accessibility, fall from height risk, and underground connectivity (Nikl et al. 2023). The goal of this continued work is to mitigate the hazard posed to the public and wildlife from historical mining activities.

The feature that is the subject of this paper is an open shaft outside of the main mining property that had previously been backfilled several times with rockfill by the site Owner. This shaft has been observed as part of the routine surface reconnaissance programs conducted at the Site. Between 2006 and 2018, a minor surface depression (approximately 0.30 m deep) was observed at the shaft location. When the shaft was visited during the 2019 surface reconnaissance program, a large opening was observed to have developed measuring (visually) approximately 3.5 m by 5.0 m at surface and up to approximately 10 m deep (depth estimated from a camera affixed to a pole). It was interpreted that the previously placed backfill had either migrated and/or settled over time, eventually resulting in an expression of surface subsidence. Due to the size of the opening and its location off an unsanctioned, yet accessible to the public, foot and bike trail, it was recommended that the shaft be guarded with signage and fencing as an interim measure while a long-term mitigation solution was developed. The shaft remained in similar condition until September 2022 when the mitigation that is the subject of this paper was implemented (Figure 1).

Figure 1 Photograph of open shaft taken during 2022 surface monitoring program

For a vertical opening such as a shaft, potential mitigation measures can include concrete caps, plugs, and/or placement of backfill. The method chosen depends on the remediation objectives, desired lifespan, and project setting. Openings in remote locations may require special considerations to optimise cost, reduce impacts to the environment due to the increased difficulty in transporting equipment and materials to the project site, and limit accessibility to the public by not developing a road or trail network. The location of the open shaft on the Site is within steep terrain and is only accessible from an unsanctioned foot and bike trail, limiting the potential for access with mobile equipment.

To provide a long-term mitigation solution, the following design basis goals were identified for mitigation of the shaft:

- Prevent further subsidence at the shaft location.
- Prevent access by humans and wildlife.
- Require minimal equipment and quantities of material that could preferably be mobilized to the shaft via trail access.
- Be able to support anticipated natural vertical loads (e.g., from snow cover).
- Provide a long-term mitigative solution.

The key constraint in identifying a mitigation measure to proceed with for the shaft was the access constraint for mobilization of equipment and materials to the shaft location. This was due both to the steep terrain and difficult access, as well as the sensitive surrounding forest terrain. Mitigation measures such as concrete caps, cemented rock backfill plugs, or placement of rockfill would not meet this constraint. Therefore, an alternative solution was required.

2 Methodology

2.1 Polyurethane foam (PUF) in mine closure

Polyurethane foam (PUF) is a rigid plastic that is formed by mixing two components together, an isocyanate and a polyol resin (Priscu et al. 2010). The use of PUF to plug mine openings has been in practice in the United States since the 1980's (Burghardt 1994). It was identified that a PUF plug could be a possible mitigation solution for the open shaft, however as the use of PUF in mine closure applications is not as widespread in Canada, a desktop study was carried out to confirm the feasibility of implementing such a solution in this case and whether it could address the project constraints. Several case studies, both in Canada and in the United States, were reviewed including Charney et al. (1992), Miller et al. (2019), Munoz et al. (1999), and Priscu et al. (2010).

Review of the case studies indicated that the use of PUF in remote applications is advantageous, due to its portability and the ability to prepare and install the PUF plug without heavy equipment or extensive site preparation. PUF may be mixed by hand and placed by hand-pouring, reducing the need to transport equipment to the project site or to have workers enter the potentially hazardous mine opening. Further, PUF expands after mixing, which reduces the amount of material that needs to be brought to the site – the typical expansion ratio of PUF being in the range of 25 to 30:1 (Munoz et al. 1999, Priscu et al. 2010).

Review of bench- and large-scale testing completed by Charney et al. (1992) and Munoz et al. (1999) on PUF plugs provided insight into its behaviour under loading. The tests indicate that when subjected to a downward vertical load, PUF will initially fail adjacent to the walls of the shaft in the uppermost portion of foam. Additional load is required to continue pushing the foam downward after the initial failure, as the load applied to the PUF is re-distributed to other parts of the foam and the shaft walls, resulting in a residual strength. Results of the large-scale testing conducted by Munoz et al. (1999) indicated that PUF could withstand vertical loading of greater magnitude than the natural loading anticipated at the shaft location on the Site.

A disadvantage to using PUF as a mitigation measure was found to be that it is susceptible to damage from ultraviolet (UV) radiation, heat, and fire. It can also easily be cut and removed (Burghardt 1994, Priscu et al. 2010). For this reason, plug designs generally incorporate a layer of backfill and/or cementitious grout placed on top of the PUF plug to protect it from sunlight and direct heat.

An additional limitation found was the uncertainty in the design life of PUF. As PUF has only been in use in mine closure applications since the 1980's, there is no demonstration of its ability to perform beyond roughly 40 years. In the case of the open shaft on the Site, this was determined, in conjunction with the site Owner, to be an adequate timeframe as there are no regulatory requirements or limitations associated with risk management and mine closure at the Site.

2.2 Characterization of shaft

Observations of the shaft during the annual surface reconnaissance programs provided approximate visual estimates of shaft dimensions, from a safe setback distance from the shaft collar. To better estimate the dimensions of the shaft to plan for the implementation of the PUF plug, a camera survey was carried out in July 2021. A HERO5 GoPro™ camera was used to create a three-dimensional (3-D) photogrammetry model of the shaft (Figure 2) that could be used to characterize the size, orientation, and volume of the shaft opening. The GoPro was GPS enabled and set-up to take photographs at 0.5 second intervals.

Two methods were used to collect photographs of the opening:

1. The GoPro was affixed to a cantilever made up of eight sections of polyvinyl chloride (PVC) pipe (1 m lengths) threaded together. Two personnel standing a safe distance from the opening moved the cantilever back and forth over the opening, while rotating the camera to image the shaft walls. A third person acted as a spotter for the two camera personnel.

2. The GoPro was affixed to a telescoping monopod which was then attached to two short, 1 m lengths of PVC pipe threaded together. One person standing a safe distance from the shaft collar raised the GoPro over the opening to capture images of the shaft. This was repeated from seven stations around the perimeter of the opening. A second person acted as a spotter for the person holding the camera.

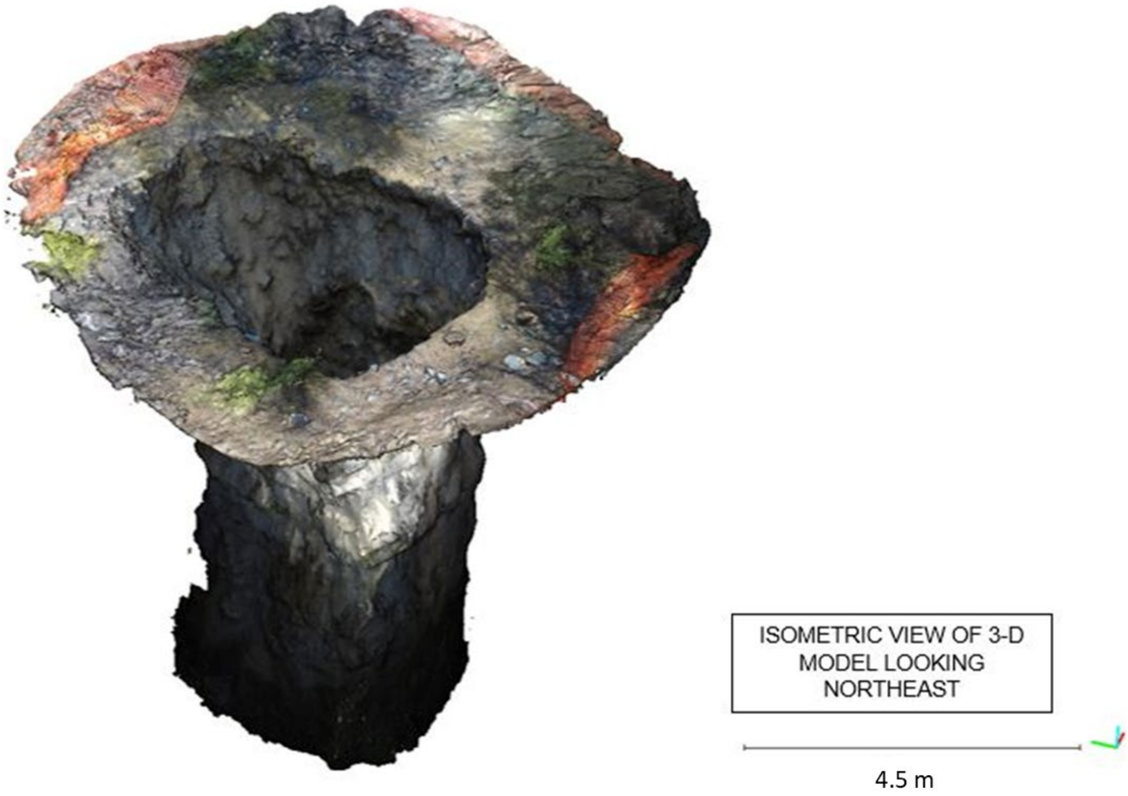

Figure 2 3-D photogrammetry model of shaft opening

The photographs resulting from the camera survey were reviewed and the best images (i.e., determined by lighting, clarity, and visibility of the opening) were chosen to build a 3-D photogrammetry model of the shaft. A total of 203 images from both survey methods were used to build the 3-D model using the Agisoft Metashape Professional software (Agisoft LLC 2021).

The GPS readings from the GoPro were used to initially orient and scale the model. Plumb-bob measurements of the opening were taken to provide additional scale information. Two plumb-bob measurements of depth and two measurements of the dimensions at surface were recorded.

Table 1 gives the approximate dimensions of the shaft as measured from the 3-D photogrammetry model. Values are rounded to the nearest 0.5 m.

Table 1 Approximate dimensions of shaft

Depth (m)	Side Lengths at Surface (Collar)		Average Side Lengths at Depth		Volume (m^3)
	Short Side (m)	Long Side (m)	Short Side (m)	Long Side (m)	
7.5	4.0	5.0	2.5	3.5	69.0

The following additional observations of the shaft were made during the camera survey and from the 3-D model:

- The shaft is near vertical, with the long-axis of the opening oriented approximately northeast-southwest.
- The shaft is in the shape of a wedge, with the opening at surface being larger than the dimensions at depth.
- The base of the shaft is formed by rockfill material and is uneven. An average depth of approximately 7.5 m was measured from the model.
- No evidence of further opening to the underground below was noted.
- The vertical depth of overburden cover was estimated using observations from the images of the shaft and measurements from the 3-D model. The measured overburden depth was found to vary from approximately 1.0 to 2.5 m, with the largest depth of cover being on the north wall.
- The sides of the shaft below the overburden cover are rough and moderately fractured.
- No water flow was noted at the time of the camera survey.
- No evidence of animal access to the opening was noted during the site work or in the photographs.

The above-mentioned observations allowed for the design of a PUF plug to be developed, with the intent of satisfying the design basis.

2.3 Development of design and technical specifications

A design and a set of technical specifications were developed to meet the design basis. The plug design incorporated four main components: the PUF Plug, a Cementitious Grout Cover, Backfill cover and an Inspection Port through the centre of the plug. The existing rockfill in the shaft served as the foundation floor (or Formwork) to pour the PUF Plug onto.

Details of, and key specifications for, components of the plug construction are summarized below:

- PUF Plug:
  - The PUF Plug is the primary component of the plug construction.
  - The PUF density was required to be between 28.8 kg/m^3 to 48.1 kg/m^3 and the PUF Plug thickness was required to be a minimum of 5.5 m. The required height and density were calculated using recommended formulas from Charney et al. (1992) under assumed natural loading conditions specific to the Site. These calculations assume that the plug behaves independently of the rockfill Formwork at the base of the plug. Section 4.2 discusses the calculated bearing capacity of the plug in further detail.
  - Required to be placed in continuous lifts of no more than 0.5 m expanded thickness (manufacturer's instructions due to the exothermic reaction of PUF). Any observed cracks and/or voids in lifts of PUF required to be repaired.
  - Required to be free of unauthorized foreign material.
  - Not to be placed if water inflow in shaft opening observed, or during periods of heavy precipitation.
- Cementitious Grout Cover:
  - Intended to provide UV protection for the PUF Plug.
  - Cementitious grout mixed at a water-to-cement ratio of 0.5 to 1.
  - Mixed and placed when the final lift PUF was determined to be cooled and tack-free (no longer sticky to the touch).

  - Required to have a minimum thickness of 0.05 m.
  - Required to cure in temperatures above 0°C for a period of at least 12 hours.
- Backfill layer:
  - Intended to provide fire protection for the PUF Plug.
  - Required to consist of clean, granular rockfill.
  - Placed when Cementitious Grout layer was determined to be cured.
  - Placed to existing ground surface and graded to promote surface drainage away from shaft.
- Inspection Port:
  - Intended for long-term monitoring of the integrity of the PUF Plug and the condition of rockfill at the base of the plug.
  - Required to be made of material capable of withstanding temperatures greater than 100°C without deformation or changes to the inner or outer diameter of the pipe, due to the exothermic reaction of the two components of PUF.
  - Required to remain free of any gaps, holes, and obstructions that may compromise the integrity of the pipe, or the passable diameter of the pipe.
  - Installed from above ground surface, down to existing rockfill (Formwork).
  - Capped and locked to prevent unauthorized access to plug and to prevent potential ingress of water to base of plug that may promote further migration of the rockfill at the plug base.

3 On-site quality assurance

3.1 Plug construction overview

Construction of the plug was carried out in late-September to early-October 2022. A construction quality assurance (QA) program was implemented during the construction and included a PUF mix trial (Section 3.2), the observation of key components of the plug construction (Section 3.3), and PUF sampling for third-party laboratory testing (Section 3.4).

Mobilization of equipment and materials to the shaft location was completed with the assistance of two pack horses and one guide horse using the existing trails. Materials were carried up simultaneously while the PUF was being placed in the shaft to limit the amount of material stored on-site overnight.

The key steps of construction were:

1. Installation of the Inspection Port vertically in the approximate centre of the shaft. The Inspection Port consisted of a 0.15 m inside diameter galvanized steel pipe. The pipe was tethered in place to trees surrounding the shaft.
2. A PUF Plug was placed to approximately 0.76 m below ground surface, using hand-mixing and hand-pouring methods. The PUF was poured in lifts of targeted maximum 0.5 m thickness (Figures 3a and 3b). The initial lift of PUF was placed using the existing rockfill in the base of the shaft as the false floor Formwork for construction. A total of seventeen lifts of varying thickness were placed over the two-day duration PUF pour.
3. A Cementitious Grout Cover was placed to approximately 0.06 m thickness on top of the PUF Plug. The grout was mixed using a paddle mixer and placed into the shaft by hand. Prior to cementitious grout placement, the shaft collar was prepared by removing excess PUF that had adhered to the collar during the PUF pour. PUF is highly flammable and any inclusion of it in the Cementitious Grout

Cover and Backfill layers would have prevented these layers from acting as fire and UV protection for the plug.

4. A layer of Backfill was placed to approximately 0.70 m thickness on top of the Cementitious Grout Cover once cured. The Backfill consisted of rock from a waste rock pile adjacent to the shaft.
5. Following backfill placement, the Inspection Port was cut to approximately 0.5 m above ground surface and a lockable steel cap was installed.

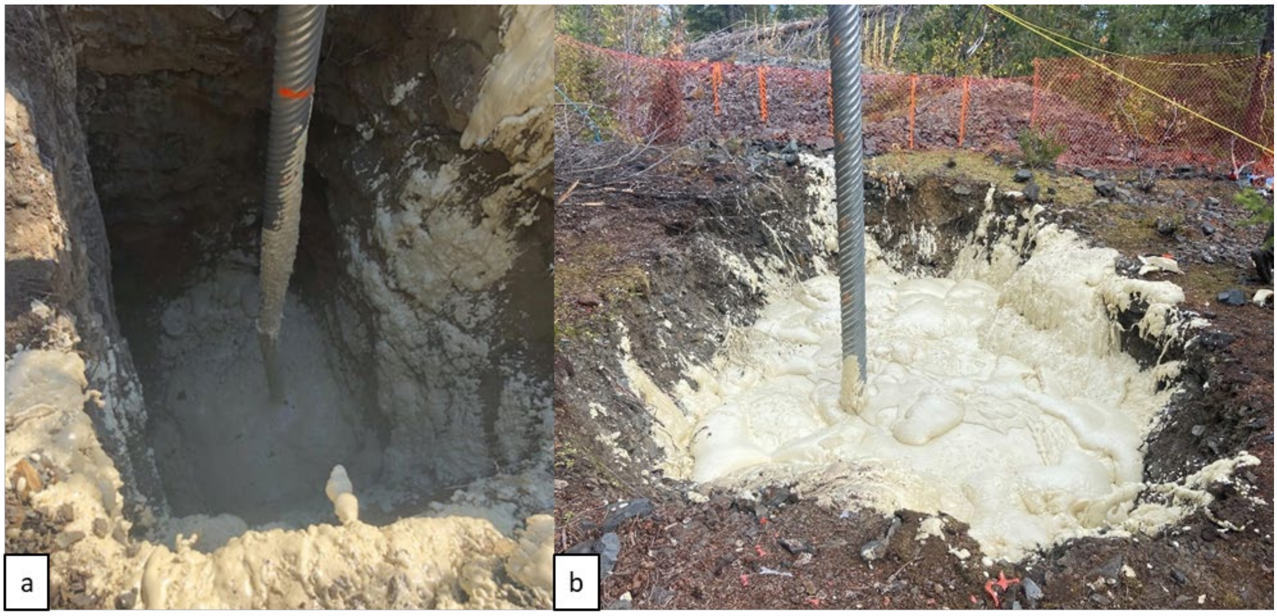

Figure 3 (a) Lift 1 following placement (b) Lift 17 following placement

3.2 Mix trial

Prior to PUF placement, a mix trial was performed to observe the behaviour of the PUF under potential site conditions. The PUF was hand-mixed and poured into an available container on-site, a 22 L galvanized steel pail. Ambient temperature, weather conditions, initial and final volume of PUF, as well as the time it took the PUF to reach different stages of its reaction and the temperatures at each stage of reaction, were recorded. Once the PUF had set, it was cut open and inspected for any voids, tears, or irregularities. The key parameters observed from the mix trial were the tack-free time as well as ambient and PUF surface temperature. These parameters were used during construction to estimate when each new lift of PUF could be placed.

3.3 Quality assurance observations

During the plug construction, the key components of the construction were observed and measurements of ambient temperature, lift thickness, and PUF appearance and consistency for each lift of PUF placed in the shaft were recorded. In addition, samples of the PUF material were collected for third-party laboratory testing (Section 3.4). These observations, along with the density and strength properties obtained from the samples collected, were used to confirm that the plug construction was in conformance with the technical and manufacturer's specifications, there were no concerns with the overall quality of the plug, and that the strength of the PUF would be sufficient to resist anticipated natural loads.

Temperatures of the PUF were recorded using an infrared digital temperature gun. Ambient temperatures during plug construction were measured using an outdoor thermometer. Initially, marks were made on the Inspection Port at approximately 0.5 m intervals to measure lift thickness; however, it was found to be difficult to control the speed and direction of the PUF liquid when poured from the bag, so the marks became covered due to PUF splatter. A laser distance meter was instead used to measure the distance to the PUF surface from a consistent location at the shaft collar. These measurements were approximate due to the variability of the PUF surface but acceptable for the construction of the plug.

Temperatures during the plug construction were observed to be above freezing, between approximately 12°C and 23°C. No precipitation was noted during the PUF Plug pour. Precipitation was observed during placement of the Cementitious Grout Cover and a tarp canopy was erected over the shaft at this point. The shaft was covered with a tarp overnight following each day of construction.

Minor cracking that was observed in the PUF during placement in the shaft was repaired with the pouring of the next lift.

The following minor deviations from the specifications were noted during construction:

- The Inspection Port experienced bending during the PUF plug pour. The Contractor made efforts to straighten it, however since no access was permitted inside the shaft some bending remained in the plug at completion.
- During placement of Lift 9, a Contractor personnel's hardhat fell into the shaft and was incorporated into the plug.

These deviations were not interpreted to have an impact on the ability of the plug to perform as intended.

3.4 Sampling of polyurethane foam

A total of eleven bulk PUF samples were collected for third-party laboratory testing of strength properties and density (Section 4.2). The samples were collected in 22 L galvanized steel pails concurrently with the pouring of a lift within the shaft so that the atmospheric conditions and sample preparation were consistent with that of the PUF Plug. The samples were allowed to rise and set within the pail after which a lid was placed on the pail to secure the sample.

4 Results

4.1 Plug completion

The PUF Plug construction was completed in general accordance with the specification and proposed design approach, with minor deviations that are not expected to impact the performance of the PUF Plug as intended.

Table 2 summarizes the quantity of material used and the completed dimension of each of the plug components at completion. The total approximate volume of material placed in the shaft at completion (82 m^3) was greater than the initially approximated volume of 69 m^3 from the 3-D photogrammetry model (Section 2.2). This was interpreted to be a result of the uncertainty associated with scaling the photogrammetry model from GPS data and plumb-bob measurements.

The final dimensions of the shaft collar prior to Backfill cover placement were measured to be approximately 4.1 m by 5.4 m and 0.7 m deep, using a laser distance meter. Figure 4 shows a photograph of the PUF Plug at project completion.

Table 2 Quantities and thickness of plug components at completion

Plug Component	Approximate Quantity Placed (m^3)	Approximate Completed Thickness/Height (m)
PUF Plug	52	Up to 6.4
Cementitious Grout Cover	14	0.06
Backfill	16	0.70
Inspection Port	Not applicable	0.50 (measured above ground surface)

Figure 4 Completed polyurethane foam plug

4.2 Laboratory testing

Bulk samples of PUF collected during the plug construction were shipped to a laboratory in Ontario, Canada. Samples were extracted from the pails and cut down to test specimen size at the laboratory. Laboratory testing was performed in accordance with ASTM International standards (2016, 2017, 2020a, 2020b).

PUF is anisotropic and has different strengths parallel and perpendicular to foam rise (Charney et al. 1992). As such, tests were completed in each of the two directions for strength testing (i.e., compressive, tensile, and shear testing).

Results of the laboratory testing are summarized in Table 3.

Table 3 Results of laboratory testing on sampled polyurethane foam

Test Type	Test Count	Minimum Value	Average Value	Maximum Value
Density (kg/m^3)	7	34.5	37.8	41.4
Compressive Strength Parallel (kPa)	6	185	201	222
Compressive Strength Perpendicular (kPa)	6	86	124	145
Tensile Strength Parallel (kPa)	3	364	391	423
Tensile Strength Perpendicular (kPa)	3	215	288	373
Shear Strength Parallel (kPa)	3	166	195	211
Shear Strength Perpendicular (kPa)	3	158	200	261

The laboratory testing results were compared with the manufacturer's specifications, as well as formulas from available literature to determine whether the PUF plug would be suitable to accommodate the anticipated natural loading conditions. The anticipated load for the Site was calculated based on the dead weight of the plug components and a surcharge load of 12 kPa per the *Health, Safety, and Reclamation Code for Mines in British Columbia* (Government of British Columbia 2021) requirement for securing of openings - which is expected to exceed any actual loading on the plug (e.g., from snow cover, applied load from pedestrian access).

Review of the laboratory testing resulted in the following conclusions:

- The density of the PUF sampled met the required range of density (28.8 kg/m^3 to 48.1 kg/m^3) from the specification.

- The strength properties of the sampled foam parallel and perpendicular to foam rise were consistent with documented trends (Charney et al. 1992). The results indicate that strength parallel to foam rise generally exceeds strength perpendicular to foam rise, except for shear strength, which is less sensitive to the direction of loading. The expected load direction on the PUF Plug is parallel to foam rise (vertically down with respect to the shaft).

- Specimens tested for tensile and shear strength experienced cohesive failure of the foam, rather than adhesive failure of the interfacial bond.

- The tensile strength of the sampled foam parallel to foam rise is sufficient to support the anticipated load on the PUF Plug. According to a rule of thumb established from bench-scale testing conducted by Charney et al. (1992), PUF can sustain net vertical downward pressures approximately equal to the strength of foam loaded in tension parallel to foam rise. Incorporating a load factor of 2, and a capacity reduction factor of 0.4 (recommended by Charney et al. 1992), the Factor of Safety (FoS) for the anticipated load was found to be 2.3.

- The length of the PUF Plug is sufficient to resist punching shear failure. Punching shear failure (Lang 1999) is the mechanism by which applied pressure causes a plug to move relative to rock by shearing either through the rock mass, the plug material, or along the rock-plug interface. Review of bench- and large-scale testing completed by Charney et al. (1992) and Munoz et al. (1999) during the desktop study indicated that the failure mechanism of PUF under vertical loading can be likened to punching shear failure. As it was not possible to verify the interface shear strength between rock and PUF through the laboratory testing program, a peak interface shear strength between PUF and timber was back calculated from large-scale load testing of PUF by Munoz et al. (1999). Based on the constructed length of the plug (approximately 6.4 m) and the required length of 1.3 m to resist punching shear using the back-calculated peak timber-to-PUF interface shear strength from Munoz et al. (1999), the FoS of the PUF plug was found to be 4.9.

5 Conclusion and path forward

The PUF Plug construction was completed in general accordance with the technical specifications. Laboratory testing indicated that the PUF material met the technical specifications for density and, based on anticipated loading conditions, and provided that the plug is not subjected to loading conditions beyond those anticipated, there are no concerns with the stability of the plug. The long-term stability of the plug is also dependent on the Backfill and Cementitious Grout layers remaining in place so that the PUF Plug is not subject to degradation from UV radiation and/or fire.

Long-term mitigation of the shaft is supported provided that early periodic monitoring of the PUF Plug does not indicate any concerns with the stability of the plug. As PUF has only been in use in mine closure applications since the 1980's, there is no demonstration of its ability to perform beyond roughly 40 years. Therefore, long-term mitigation in this context is defined by a period of no longer than 40 years. In the case of the open shaft on the Site, this was determined, in conjunction with the site Owner, to be an adequate timeframe as there are no regulatory requirements or limitations associated with risk management and mine closure at the Site.

The PUF plug will be monitored as part of the annual surface reconnaissance programs. Monitoring of the plug will be conducted annually for the first five years following plug construction, beginning in summer 2023. Depending on the observations made, the monitoring frequency may be reduced. Monitoring will focus on identifying any depressions or cracks at surface in proximity to the PUF Plug. Additionally, a borehole camera or plumb-bob will pass through the Inspection Port to determine if there is any change in the rockfill elevation beneath the PUF Plug, or warping of the Inspection Port which may indicate deformation (i.e., sagging) of the PUF Plug.

Signage and fencing will continue be placed in the area to warn of a mining hazard and will remain in place until such time that early periodic monitoring of the plug has shown no sign of plug degradation.

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