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Groundwater control in tunneling using injected polymer barriers

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ABSTRACT: Cementitious grouts, such as Ordinary Portland Cement (OPC) have historically been widely used for water control in underground structures such as mines and tunnels. Although cheap and readily available, OPC exhibits performance limitations without additives. Chemical (or solution) grouts such as polyurethanes and acrylamides present with health and safety concerns during the mixing and application process. There is a third category of grouting materials, Polymer-Based Emulsion (PBE) that provide a cost-effective, non-toxic option. PBE grout was developed in the 1970s and first used to seal high pressure, high-rate water inflows into deep subsurface South African mines. Since the 1980s, PBE has also been applied in mines in Namibia, the UK, Australia, Zimbabwe, Botswana, Zambia, the United States, Canada, Poland and Russia. PBE has successfully sealed discrete inflows of 160 L/sec at pressures up to 20,000 kPa (2,900 psi), rendering it one of the few viable grout options for high-flow rate and high-pressure water leaks. In recent years, PBE has found application beyond its roots in mining. Leaking subsurface infrastructure such as subway tunnels, stations and building basements have benefited from the water-sealing properties of PBE.

1 INTRODUCTION

Uncontrolled water inflow and leak remediation into underground structures or inadequate control of the groundwater flow system impacting an open pit or underground mine, or tunnelling project, are some of the biggest challenges for engineers, owners of infrastructure, and operators of mines. Such inflows can lead to unsafe/hazardous conditions and endanger those who use and operate in them as well as impact the performance of equipment and machinery. In many cases, there is also a problem in dealing with the volume of water that needs to be managed in the dewatering process. A proactive approach to groundwater control can provide significant cost savings through reduced downtime and interruptions due to unexpected water inflows.

The success of PBE as a water-sealing grout is attributed to its unique physical properties. This paper provides an overview of the physical properties of the grout and applications. But firstly, many grouting programs designed to manage water ingress involve high pressure injection into water-bearing fractures to reduce/eliminate inflows. The optimal grout attributes for durable underground water control are considered to be:

- Exhibits low viscosity with very small particle size (suspension grouts) or no particles (solution grout) to permit deep penetration into water-bearing fractures; and
- Sets up as an insoluble, chemically inert, flexible or self-healing solid that maintains adhesion to wet rock surfaces and concrete despite recovering formation pressure and continued blasting or tunnelling, development induced subsidence and stress redistribution.

Therefore, it is considered that PBE is one of the few viable, proven grout options for successfully sealing water leaks in underground mines and tunnels, and it continues to be used to seal off high pressure/high flow rate water inflows when OPC and other specialty grouts have failed.

2 PBE PHYSICAL PROPERTIES AND BEHAVIOUR

2.1 *Introduction*

PBE is a suspension of colloidal polymer emulsoids dispersed in a solution of additives promoting flow and adhesion. PBE is injected in a fluid state and remains fluid until activated. PBE is a non-Newtonian, dilatant fluid; it sets by internal shear as the grout passes through fractures or other voids in water-bearing media. Set time may also be controlled chemically with the use of activator or inhibitor to regulate spread. Still, PBE is differentiated from solution grouts, because it is a single-part grout which does not require a chemical reaction to set.

Some PBE properties and behaviours are:

- Initial injection viscosity = 1.5 centipoise (cP)
- Specific Gravity ≈ 0.97
- Miscible in water
- Resistant to washout in high flow situations
- Will still set after dilution in formation water down to <15-25% of original concentration.
- Controlled cure rates from 2 seconds to several days
- Cures to a flexible solid with greater than 350% elasticity (elongation)
- Ultimate Tensile Strength ≈ 5 MPa
- Effective in both fresh water and water containing high Total Dissolved Solids (TDS).
- Strong adhesion to rock and concrete
- Curing is non-exothermic and non-expanding
- Non-hazardous in both liquid and solid states
- Demonstrated durability of +50 years with design life of +125 years
- Demonstrated radiation tolerance to 100 megarad (MRad)
- No adverse effects from freezing after curing
- No adverse effects from high temperature geothermal water
- NOH2O has a significantly lower carbon footprint than cementitious grouts

Because of its small particle size, low viscosity and miscibility in water, PBE can penetrate and seal water in small aperture fractures. These properties allow PBE to compete with resinous chemical or solution grouts as well as ultrafine or microfine cements for sealing water leaks in low permeability formations (Goodman et al. 2018). An advantage that PBE offers is that it can be diluted by groundwater to 15% of its original strength while passing through the formation and still set effectively. The tendency for PBE to set when agitated renders it highly useful in turbulent, high velocity flow situations where other types of grout will suffer dilution and washout.

2.2 *Differences between PBE and solution grouts*

PBE, as an emulsion, is a mixture of liquids as opposed to a cementitious, chemical or solution grout. A major difference between PBE and resinous solution grouts is in how the material sets from a fluid to a solid grout mass. Most resinous grouts require a chemical reaction between an agent and a reagent to set. Required reactions may be between a chemical solution and water, or between two to four components pre-mixed or injected simultaneously. In contrast, PBE can set solely by mechanical means; no chemical reaction is necessary. Because PBE activation can be achieved without a chemical reaction, grout set is non- exothermic.

The grouter actually has four ways to induce or influence PBE set (De Bruin et al. 1991; Gancarz et al. 2017). These are:

1. Mechanical Activation – When PBE flows through an orifice or fissure, the high shear action causes the dispersed polymer colloids to flocculate. These polymer flocs then start to adhere to the side walls of the orifice or fissure. Continued agitation causes additional flocs to form,

which, in turn, adhere to the now-rapidly-coagulating, jelly-like mass of polymers that builds up to block the orifice or fissure until flow ceases.

2. Chemical Acceleration – The grouter can use a chemical demulsifier (activator) with PBE to accelerate set when desired. The proprietary activator, Actical 500, will break the emulsion and induce the polymer colloids to coagulate into a jelly-like mass in as quickly as 2 seconds.
3. Chemical Retardation -- Conversely, if the rate of coagulation is too high (normally when injecting under high pressure in small aperture fractures or when formation water is saline) then a proprietary inhibitor, Inhibitor WP, can be used to promote greater spread of grout away from the injection point by keeping the emulsion stable in the geologic formation or behind a liner system for as long several days.
4. Exposure to Atmosphere – If PBE is exposed to atmosphere long enough for it to dehydrate, it will form a thin skin of very fine interlocking polymer laths.

A key difference in application of PBE and resinous chemical grouts is how desired set time is achieved (Gancarz et al. 2017). Set time for chemical grouts must be pre-determined and achieved by mixing a set proportion of catalyst in the resin prior to injection. Because PBE can be used as a single-component, self-activating grout, the need for a pre-determined set time is not necessary. Instead, set time is controlled based upon real-time field observations indicative of flow patterns/behaviour in a geologic formation or behind a liner system at any desired injection rate.

2.3 *Grouting equipment*

Because PBE sets when agitated, conventional high-pressure pumps cannot be used for injection. Air- powered, double-acting plunger pumps are used to inject PBE. The pumps are capable of delivery rates from about 40 to 120 liters per minute and discharge pressures up to 30MPa. Three pumps are typically mobilized to the job site: one for PBE grout, one for activator and one for inhibitor (Figure 1). High-capacity 35 MPa-rated hydraulic hoses (typically 1.27- or 0.64-cm) are used, with three separate delivery lines running from each pump to the grouting header. A valved injection manifold fitted with a pressure gauge is used, which allows for in-line mixing of PBE, Inhibitor WP and/or Actical 500, as illustrated in Figure 2.

Injection pressures can be controlled to meet site-specific criteria. For applications where injection pressure limits are critical, safety relief valves are set to the required relief pressure, together with a rupture disc which is set to relieve pressure if predetermined maximum injection pressures are exceeded.

2.4 *Other considerations*

PBE set-up is influenced by formation water chemistry (pH, total dissolved solids, major ion/geochemical facies, temperature, etc.). The PBE formulation and injection strategies can be adjusted to accommodate the specific geochemical formation conditions for each site to ensure optimal grout spread and setting. Consequently, basic water quality data or physical water samples are desirable to determine PBE behaviour in the formation water and to determine the optimal grout formulation for the project site.

Due to its tensile strength, strong bonding to rock and concrete, and its elasticity, PBE is uniquely suited for areas of high ground movement, such as nearby blasting in an active mine pit, or, in particular, where any ground movement at all may lead to migration of environmental contaminants (e.g. radionuclides, hazardous waste constituents, landfill leachate, tailings storage facility). Unlike brittle grouts (such as cements and some urethanes), PBE will not be easily ruptured during ground movements – leaving the grout seal intact. PBE-treated areas in mines and underground structures have maintained their dryness for over five decades without recurrence of leakage.

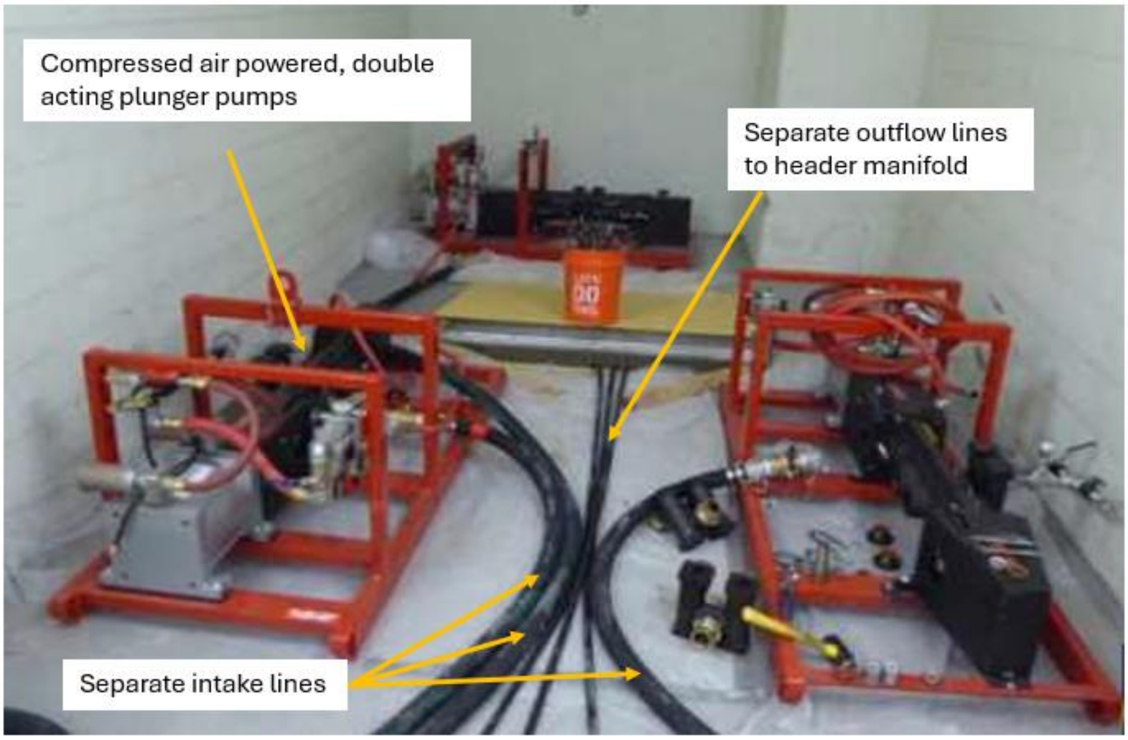

Figure 1. Separate positive displacement pumps used for PBE, activator and inhibitor.

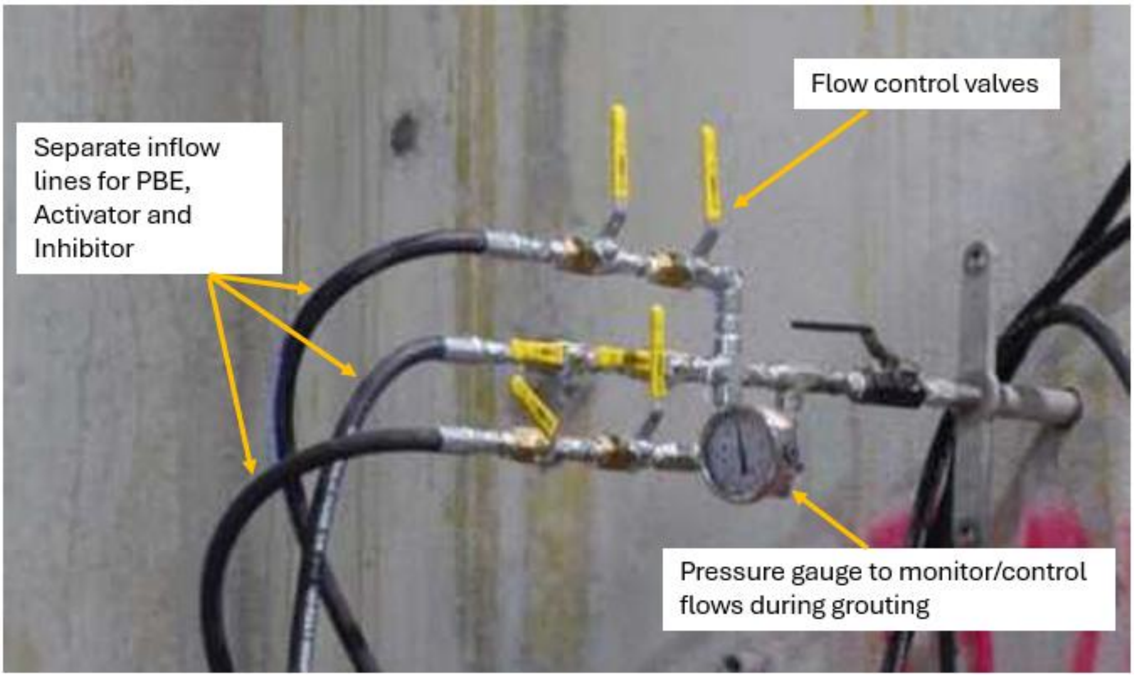

Figure 2. Grouting header manifold on injection hole to regulate mixture of PBE, activator/or inhibitor

3 MINING APPLICATIONS

3.1 *Injection strategies*

After its invention, PBE was first applied to seal leaks in deep subsurface mines. Hence, the grout had to perform well against both high pressure and high inflow rates, as well as in both fresh and saline groundwater. Sealing mine leaks is a complicated endeavor involving hydrogeological characterisation, selection of grout-hole locations and grouts to be used, and careful monitoring of mine conditions and surrounding formation pressures during and following grout injection.

Critical to success with any grout is establishing a connection between the grout injection hole and the water bearing structure contributing to the mine leak. Hence hydrogeological characterisation is a critical initial step, because even the best grouts cannot be effective if the injection holes are not drilled in positions to allow the grout to reach the leak site. The site hydrogeological characterisation is developed from project specific geology and structural information, ideally along with a geology resource model. The characterisation may also benefit from additional information gained from geophysical surveys to identify preferential groundwater flow paths.

Drilling grout holes in a radial fan around the planned opening is a standard part of shaft and initial decline excavation (Figure 3). For leaks in existing shafts, the injection holes are typically drilled beyond the liner system to avoid excessive pressure build-up on the concrete structure during grout injection. For linear structures or specific formation layers providing a conduit for flow to an open pit (Figure 4) or into an underground mine decline (Figure 5), the approach is to drill grout holes along the structure or perpendicular to the flow in the formation depending on the width of the flow line. The grout holes are typically cased (in weathered, broken rock) above the zone to be grouted and/or the grout injection interval is typically isolated using a pneumatic or mechanical packer.

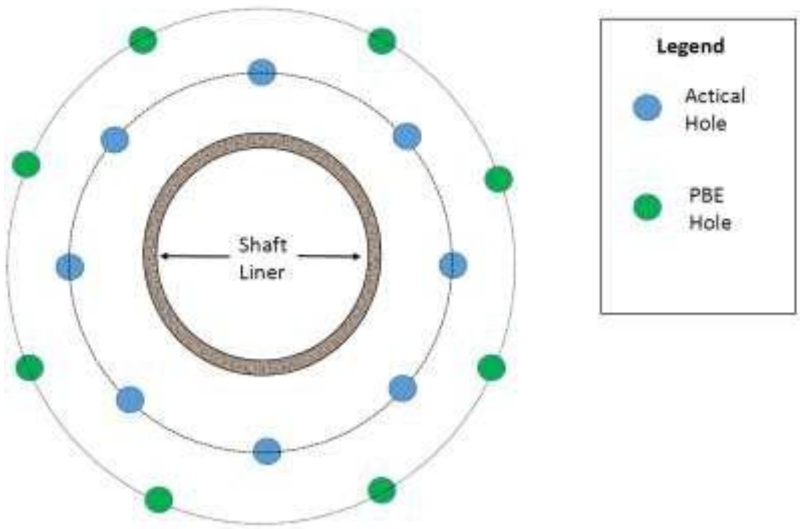

Figure 3. One of several typical ring patterns of grout holes using PBE with other products, including activator, inhibitor and/or Ordinary Portland Cement (OPC).

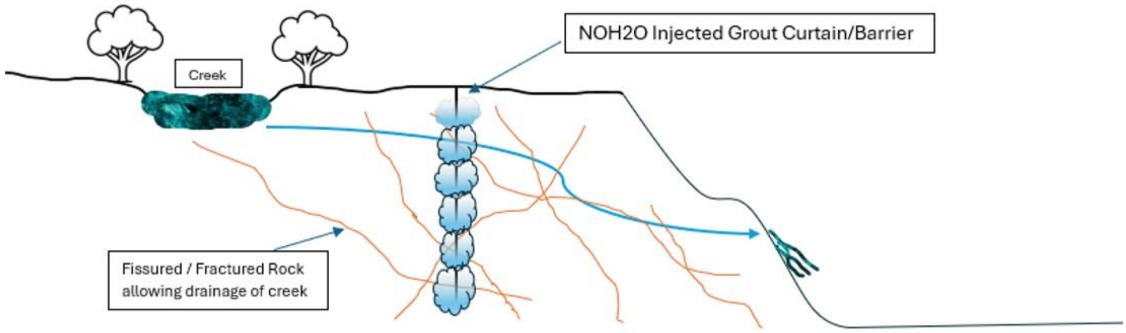

Figure 4. Installation of a PBE barrier to stop inflows to an open pit mine.

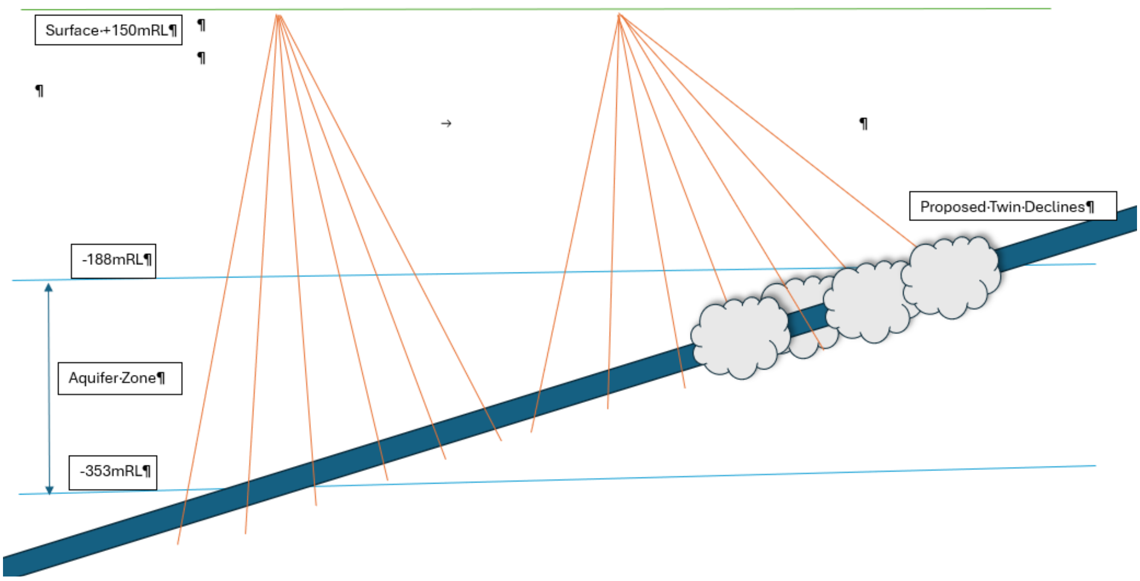

Figure 5. Pregrouting for decline development

4 TUNNELLING AND UNDERGROUND INFRASTRUCTURE APPLICATIONS

4.1 *Injection strategies: Negative side vs positive side*

The majority of PBE applications in underground infrastructure involve subway station and tunnel systems that are already constructed (Gancarz et al. 2017). If excessive leakage is discovered in a completed tunnel lining, there are two post-construction grouting methods that can be used to remedy the problem: crack-injection and curtain grouting. Crack-injection, or "negative-side grouting" is used to address individual leaks. By performing targeted drilling (usually at an angle, stopping before reaching the exterior of the lining) the individual crack is intercepted. A mechanical packer is fixed to the hole, and grout is injected directly into the plane of the crack, sealing the specific leak.

In contrast to crack-injection, which is a localised solution, curtain grouting aims to prevent all leaks in a given area. Curtain grouting aims to treat an entire area which is leaking (usually an earth-bearing wall or a roof slab in contact with the ground) by drilling a grid-like pattern of holes through the exterior of the concrete. Grout is then injected into the annular space between the tunnel's structural liner and the surrounding ground medium, creating an impermeable membrane "curtain" for that area.

4.2 *Negative side (crack) injection*

PBE is injected into the water flowing in a crack or fissure via a hole drilled to intersect the crack or fissure for this purpose. A multiport packer is inserted into the hole through which the PBE is injected. As the emulsion flows with the water along the crack or fissure it will be activated by the turbulent agitation it encounters, and a steady build-up of the coagulated rubber-like laths will occur which then form a seal. If the flow conditions dictate, then a chemical activator can be injected, either downstream from the PBE injection point, or at the same injection point through a different port in the valved manifold (see Figure 2)

4.3 *Positive side (curtain) grouting: the preferred cost-effective method*

Within a tunnel section, curtain grouting operations are sequential, one following after another in a deliberate fashion in order to push the water in one specific direction. Mini drill rigs used to create grout holes typically consist of an electric drill with a diamond core bit (usually 1.9 cm or 2.5 cm diameter) on a guided drill stand mounted to the wall. Mini drill rigs with diamond core bits have yielded the best results; they are portable, electrically powered (eliminating the need for compressed air) and can be securely mounted on a drill stand for guidance. The advantage of core drilling as compared to rotary percussive drilling is the significant reduction of lost holes due to drill cuttings obstructing the annulus.

Grout holes (typically 1.9 cm to 2.5 cm diameter) should be spaced to ensure sufficient coverage. Grid spacings of 3- to 10 m have proven adequate when using PBE for curtain grouting.

4.3.1 *Dye injection testing*

When all holes in a particular treatment area are drilled and fitted with packers, it is worthwhile to perform some preliminary injections using dye water. Since PBE has similar fluid properties to water, performing trial injections using dye water can provide insight into what to expect during grout injection. Injection parameters such as the pumping pressure required to achieve coverage, the volume of dye water injected and time it takes for dye water to communicate to cracks or nearby packers can be measured to give an estimate of what to expect while pumping PBE. It is neither necessary nor recommended to perform these measurements for every grout hole; three to four holes is more than sufficient. Most important is observing where dye water reports in the vicinity. Grout will likely report wherever dye water does, so if dye water comes out near sensitive equipment or into areas open to the public it gives advance notice of where to set up protective sheeting and what areas to section off. While usually straightforward, this task may require entry into locked rooms and gaining access to mechanical pits and overhead crawlspaces.

4.3.2 *PBE injection methods*

Treatment of a target zone means grouting each hole in that zone sequentially. In general, holes are treated in order of lower to higher elevation. Injection pressure is controlled by structural capacity of the wall or slab being treated and generally ranges from 0 to 5 MPa. Use of an activator or inhibitor may be justified if no pressure builds over time or if pressure spikes too quickly, respectively. Given the high mobility of PBE, it is prudent to periodically monitor the area for signs of discharging grout to estimate the extent of spread from a specific injection point.

5 PBE COSTS

Like any specialty grout, the unit cost of PBE is higher than the unit costs for commonly used cementitious grouts such as OPC. However, total grouting program costs compare favorably with cementitious grouting programs. The primary reasons are that PBE requires fewer labour hours, less shut-down time and less drilling than traditional grouting, and PBE exhibits long-term durability.

The penetrability of PBE contributes significantly to its cost-effectiveness for water-sealing. Because PBE is capable of spreading out over greater areas, the number of grout holes required (and therefore the labour required to drill and repair them) is greatly reduced. Greater value is provided in the mining sector where grout-hole lengths can be significant and/or where fewer grout holes are desired because of inadvertent contamination migration concerns, and unit rates for drilling may be quite high because of stringent environmental protocols. The grout itself is only one part of the total program costs.

6 CONCLUSIONS

PBE grout is designed specifically for groundwater control in mining applications and underground structures such as tunnels. Key attributes that set it apart from cementitious and solution grouts include:

- High penetration capability due to low viscosity and ultra small particle size
- Activation without chemical additives, resistance to washout, and flexibility.
- Durability (>50 years) and environmental friendliness.
- Estimated product life of +125 years.

With a proven success record of +50 years of use, across 400 projects in more than 40 countries on 5 continents, PBE has been referred to as the water brigade of the mining and tunnelling industry, particularly when used after other grouting efforts have failed. Those projects have included sealing leaks with flow rates up to 160 L/sec, pressures of 20 MPa and to depths of 1300m bgl.

In today's cost sensitive project world, it is considered prudent to investigate pre-excavation grouting with PBE to reduce permeability ahead of any underground development, as this will result in cost savings in construction through reduced down time and expensive interruptions due to unexpected water.

7 REFERENCES

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