# Water Ingress Mitigation Programs for Underground Mines – Hydrogeological and Rock Mechanical Demands on Grout Properties

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**Abstract**

Many grouting programs designed to manage mine water ingress involve high pressure injection into water-bearing fractures to reduce/eliminate inflows. Optimal grouts for durable mine water control 1) exhibit low viscosity and very small particle size (suspension grouts) or no particles (solution grouts) to permit deep penetration into water-bearing fractures; and 2) set 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, mining-induced subsidence and stress redistribution.

**Keywords:** grout, water ingress, fractures, cementitious, solution, bitumen, precipitate, polymer-based emulsion

## Introduction

Underground mines commonly combat water ingress into shafts, declines and production areas. Depending on a region's hydrogeology, a mine may have to manage significant water inflows simply to maintain operation. Grouting is one means of managing mine and tunnel leaks. Grout types used for water ingress control vary widely but can be generally categorized as cementitious, solution, bituminous, precipitate and polymer-based emulsion.

Each type of grout has strengths and weaknesses for water sealing. Some grouts are used in combination to improve efficacy and to control costs. For example, low-cost Ordinary Portland Cement (OPC) is commonly used with more expensive specialty grouts. OPC is used to fill a significant percentage of void space, and the specialty grout with superior wash-out resistance and penetrability is the principal means of sealing off the water.

This paper is a review of grout types commonly used for water ingress control. Applicability of different grouts depends on pore space aperture, differing inflow rates, hydrostatic pressures, water geochemistry and rock movement.

## Hydrogeologic Considerations

High compressive strength of many rock types permits mining at considerable subsurface depths. Given a hydrostatic pressure gradient of 9.8 kPa/m in freshwater systems, pressures at practical mining depths (greater than 3500 m in South Africa, for example) can be very high.

Many mines use active dewatering in advance of mining to increase the cone of depression (reduce hydrostatic pressures) and thereby reduce the rate at which water enters the mine through exposed fractures in shafts and production areas. Still, inflow rates can be significant, and very large water volumes require management unless routine grouting programs are part of the mine's operation and maintenance plan.

Even small leaks in salt mines can lead to dissolution of halite and failure of shafts and engineered systems such as at the Belle Isle Salt Mine in Louisiana (Kupfer 1998). Even though some mines have pumping systems capable of handling large volumes of mine water, large inflows can be erosive to both cement and country rock (Momber and Kovacevic 1994; Banghua et al. 2018).

## Grouts for Water Ingress Control

Grout types used for water control vary widely but can be generally categorized as cementitious (suspension), chemical (solution), bituminous, precipitate and polymer-based emulsion. Each category of grout has strengths and weaknesses relative to its application to water ingress control as summarized below.

Cementitious Grouts: Cements are a type of suspension grout – they contain solid particles suspended in a liquid (typically water). Cementitious grouts are differentiated based on particle size as Ordinary Portland, Microfine and Ultrafine.

Ordinary Portland Cement (OPC) has historically been widely used grout for leak control, but exhibits performance limitations without additives. OPC will permeate fissures with apertures as small as 70 microns (Henn 2017), but intragranular pore space in many permeable sedimentary rocks is often smaller. Furthermore, OPC washes out when injected into high pressure, high rate inflows. Additives (e.g. Type F fly ash, slag, silica fume, pumice, bentonite, $CaCl_2$) are needed to combat washout, control bleed, and resist pressure filtration (Naudts et al. 2003). Dispersants, water reducers, and superplasticizers are used to improve mixing, and viscosity modifiers, retarders, and stabilizers are commercially available and can be incorporated into the mix. Grouters may use other additives to neutralize adverse effects of H2S (present in some limestones and evaporites) and improve set up in saline water environments.

Microfine and ultrafine grouts are milled finer (particle size about 30 microns and 10-15 microns, respectively) to penetrate smaller fissures. Some microfine grouts are slag-based. Plasticizers and viscosity modifiers are often added. Ultrafine grouts are composed of Portland cement, pumice and dispersant (Magill and Berry 2007). Although finer, microfine is still mostly applicable to fracture injection and much less so to permeation grouting of intragranular porosity in rock. Ultrafine can be used for permeation grouting although hole spacing on the order of 1-2 meters is required because of limited penetrability. Ultrafine has also been used to grout fractures in salt to reduce leaks into crude oil storage caverns at Weeks Island, Louisiana, USA (Magill and Berry 2007) and at the Waste Isolation Pilot Plant in Carlsbad, New Mexico, USA.

Cementitious grouts are brittle when set up. Consequently, in evaporites (salt and potash) that exhibit high creep rates, these types of grout can crack allowing inflows to restart. Hence, there has been considerable experimentation with, and commercialization of, alternative grouts that are either flexible or self-healing and that can also penetrate very fine aperture fractures and pores.

Solution (Chemical) Grouts: In contrast to cementitious (suspension) grouts, solution grouts do not contain particles. As such, they can penetrate very small fissures and pore space (Naudts 2003). Commonly used solution grouts include polyurethanes, acrylamides, and acrylates among others. Ideal solution grouts exhibit an initial, stable and very low viscosity followed by a sudden increase in viscosity immediately prior to gelation or curing. Gelation and set times can be controlled through the use of catalysts or inhibitors. Solution grouts are also generally chemically resistant.

Polyurethanes are commonly used to grout shafts and tunnels, and to further reduce seepage from residual wet zones after grouting with other products. Naudts (2003) categorizes polyurethane grouts as 1) water reactive; 2) two component foaming grouts (polyol-isocyanides combination); and 3) two component polyurethane elastomers. Water reactive grouts use available water to create a foam or gel. Naudts (2003) differentiates hydrophobic and hydrophilic sub-categories, and notes that hydrophilic grouts are not ideal for water ingress control. Hence they are not considered further here.

Hydrophobic polyurethane grouts repel water after the amount needed for curing is used. Hydrophobic polyurethanes penetrate, expand and fill cracks as fine as 8 microns. Different hydrophobic polyurethane grouts set up as a flexible solid (for crack injection – injectable tube applications), a semi-rigid solid (stopping large water inflows), and a rigid solid (for soil injection). In saline water environments, large mine inflows can be grouted by injecting both brine and polyurethane. The cured grout can accommodate movement along fractures (Magill and Berry 2007).

Hydrophobic polyurethanes are pH, pressure and temperature sensitive (Magill and Berry 2007). Neutral pH produces the most ideally cured grout; quality degrades in water above a pH of 8-9, and reactivity slows as the pH decreases below 7. Extremely acidic waters may preclude reactivity. These grouts react most efficiently at temperatures above 10° C. At 100 kPa pressure, reaction time, expansion and swelling begin to decrease and at 1000 kPa, no expansion or swelling occurs. Grouts may also fail to react in the presence of high concentrations of hydrocarbons. Groundwater TDS may affect gel time through chemical reaction or pH buffering. High water salinity may promote flocculation, which limits grout penetrability.

Acrylamide is a monomer used as an aqueous solution in geo-technical grouting applications for over 50 years (Magill and Berry 2007). Catalysts, activator and inhibitors are mixed together to obtain a gel grout that is impervious to water. Grout constituents include acrylamide, methylene-bis-acrylamide, acrylic acide, triethanolamine, and ethylene glycol (Spalding et al. 1987).

Acrylamide ranks high among solution grouts for water ingress control because of its extremely low viscosity (about 2 centipoise [cP]), high penetrability, controllable gel time (from 3 seconds to 10 hours), long half-life (>300 years) after injection, and resistance to shrinkage and microbiological degradation (Gentry and Magill 2012; Babcock 2016; Spalding et al. 1987). Acrylamide grout can also be used with cementitious grouts, and can withstand exposure to nuclear waste. Acrylamide grout can be mixed with brine for use in salt mines (Magill and Berry 2007).

One notable concern with use of acrylamides is health and safety during the mixing process. Mono-acrylamide is a neurotoxin that can enter the body by inhalation, ingestion or absorption through skin (Magill and Berry 2007). Grouters using acrylamide must receive special safety training. In gel form, it is non-toxic, however.

Magill and Berry (2007) also note that acrylamide is susceptible to shrinkage and premature polymerization if subjected to constant UV rays, and the grout will degrade if exposed to continual freeze-thaw and wet-dry cycles. Acrylamide does not adhere to concrete surfaces and will not stretch in a moving crack. Acrylamide also reacts more slowly in the presence of petroleum hydrocarbons.

Acrylate grouts were developed to be a less toxic alternative to acrylamide grouts. Similar to acrylamide, acrylates require a base resin to be mixed with a catalyst in order to set up a flexible gel-type grout; set times range from about one minute to one hour (Babcock 2016). United States Army Corps of Engineers (1995) describes the gelling reaction to be catalyzed by the addition of triethanolamine and ammonium or sodium persulfate to a metal acrylate (usually magnesium acrylate). Methylene-bis-acrylamide is used as a cross-linking agent. Potassium ferricyanide is used as an inhibitor if long times of setting are required. Adhesion to concrete is reportedly good, and lab testing indicates that acrylate grout can cure in the presence of extremely hot water (82°C), making it feasible for deep mining applications. (Sunder 2015). These grouts have been used in salt mine settings by balancing grout chemistry with brine.

Some acrylates physically absorb vast amounts of water and swell, thereby losing their strength (Magill and Berry 2007). The life span of acrylate grout is about 50 years, which is considerably lower than acrylamide (Babcock 2016).

Precipitation grouts: $CaCl_2$ injections have long been used to seal mine leaks at the K2 potash mine in Esterhazy, Saskatchewan (Ziegenbalg and Crosby 1997). Injected $CaCl_2$ reacts with the brine in an overlying aquifer to precipitate NaCl that clogs flow paths connecting the aquifer to the mine workings. Although somewhat successful, timing of NaCl precipitation cannot be controlled, and the finely crystalline halite precipitate does not always extend beyond the boundaries in a plug flow situation. Continued research led to development of a second precipitation grout using solutions supersaturated with gypsum (Ziegenbalg et al 2009). Supersaturation is achieved using $NaSO_4$ and $CaCL_2$ solutions as inhibitors.

Achieving an effective seal using precipitation grouts (or any grout for that matter) requires that enough solids block the flow conduit and exhibit enough strength to hold against rebounding formation pressure. Secondly, flow must be sufficiently turbulent to induce gypsum precipitation.

Hot Bitumen: When injected into a water-saturated medium, hot bitumen cools quickly at the interface with water; the viscosity increases rapidly (Naudts and Hooey 2003). Steam is created at that point, however, thus decreasing the viscosity of the bitumen and serving to draw the bitumen into pore space. The faster the water flows, the faster the bitumen cools off. The skin prevents washout while the "sheltered" hot bitumen behind the skin penetrates void space in similar fashion as solution grouts. Naudts and Hooey (2003) cite a case study involving a Saskatchewan potash mine where hot bitumen was able to temporarily seal a 7000 lpm mine inflow.

Bitumen's good insulating characteristics allow it to be injected for a very long time (days - even weeks) into the same grout hole without risk of either premature blockage or wash-out (Naudts and Hooey 2003). The width of the fissures accessible to hot bitumen varies with the duration of the grouting operation. The longer the grouting operation, the finer the apertures the bitumen will penetrate. Naudts and Hooey claim that hot bitumen will penetrate 100 micron fractures.

When hot bitumen cools it is subject to significant thermal shrinkage (Naudts and Hooey 2003). Cement-based suspension grout is often injected in conjunction with hot bitumen to compensate for the thermal shrinkage of the bitumen; to make the bitumen less susceptible to creep; and to increase the mechanical strength of the end product.

Besides safety considerations in the application of hot bitumen, injection of hydrocarbons into the ground raises environmental concerns. There are, however, many types of bitumen available with a wide range of characteristics. Naudts and Hooey (2003) recommend use of a "hard" oxidized environmentally friendly type of bitumen with a high solidification point.

Polymer-Based Emulsion (PBE): PBE is a suspension of polymer emulsoids colloidally dispersed in a solution of additives that promote flow and adhesion (Gancarz and Yilmaz 2017). PBE is injected in a fluid state and remains a fluid until activated. The grain size of the particles in the polymer is less than one micron, and the viscosity of the polymer is 2.5 cP. Hence, the dilatant polymer solution at the time of injection is extremely penetrable and will go where water travels.

PBE was developed in the 1970s and first applied to high pressure-high rate inflows into deep South African mines. The grout has sealed discrete inflows of up to 12,000 lpm at pressures up to 20,000 kPa (Gancarz and Yilmaz 2017).

Inhibitors and activators are used to change the characteristics of the polymer, enhancing the control over direction of flow and resulting in greater penetration. The polymer remains stable in its fluid state until activated. Activation may also be achieved through agitation when the polymer is subjected to shear action as it passes through an orifice of a fissure. Once activated, the dispersed colloidal compound coagulates to form a mass of linked and tethered rubberlike laths.

When first formed, the activated polymer transforms to a hydrated jelly–like plug of matted laths. As pressure is applied to the activated polymer, the water is expelled and the laths adhere to each other to form a denser and more competent plug that is both impermeable and flexible.

PBE is non-expanding, non-toxic and user friendly. PBE is not exothermic – no heat is generated during the curing process.

At present, PBE is available only through a single entity that holds the patent. The grout cannot be purchased for use other than by license holders. The grout is primarily used for sealing fissures (consolidation grouting). PBE has not yet been extensively used for sealing intragranular pore space (permeation grouting).

## Conclusion

Optimal grouts for durable mine water control 1) exhibit low viscosity and very small particle size (or no particles in the case of a solution grout) to permit deep penetration into water-bearing fractures; 2) set up as an insoluble, chemically inert, flexible or self-healing solid that maintains adhesion to wet rock surfaces and concrete despite continued blasting, mining-induced subsidence and stress redistribution; and 3) withstand high formation pressures. Precipitation grouts can be useful but only where mine waters are highly saline. Ultrafine cement satisfies the first and third criteria, but is brittle and may fracture in rocks that are prone to shifting or creep. Polyurethane grouts satisfy the first and second criteria, but may be pushed out of fissures under high fluid pressures. Acrylamide satisfies the first and second criteria, but does not adhere to rock/concrete. Hot bitumen and PBE grouts satisfy all three criteria. Hot bitumen and PBE have proven ability to stop large mine inflows. Hot bitumen poses environmental and safety issues whereas PBE is environmentally safe. Hot bitumen may not seal water-transmissive pore space smaller than 100 microns, whereas the particle size for PBE is less than one micron. Hot bitumen is commercially available and can be applied by appropriately trained grouting crews, whereas PBE is a patented product that can only be applied by users under license. Low-cost OPC can be used in combination with any of the above-referenced grouts to fill larger voids and to provide strength.

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