

Hot Bitumen Grouting: The antidote for catastrophic inflows

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Abstract

Hot bitumen grouting technology has continually evolved since its early applications almost a century ago in France, Germany and the USA to seal persistent leaks in tunnels, below dams and for erosion protection along canals.

Advancements in the industry especially in the field of monitoring and grouting equipment has made the injection of hot bitumen in conjunction with cement based suspension grout, the most economical, practical and sure solution to stop major inflows through, below or around structures. These applications proved the effectiveness of the hot bitumen grouting technique to stop major water inflows and stabilize water bearing, cohesionless soils, in a fast, predictable and economical way. This paper elaborates on a few remarkable field applications, one of which was likely the largest grouting effort ever undertaken.

History of hot bitumen use in grouting

One of the oldest references to bitumen for use in bitumen grouting was for the construction of the Tower of Babel recounted in *The Antiquities of the Jews* (IV:3), by Flavius Josephus in the first century A.D. Bitumen has a long history in antiquity and through the Middle Ages for use in waterproofing applications and warfare.

By the end of the 19th century grouting with hot bitumen for remedial repair work on dams and seepage control in rock tunnels was introduced. Bitumen was first used at European dams in Switzerland and France and later at dam sites in North America. There is documented evidence in the records of Puget Sound Power and Light that hot bitumen was used during the 1920.s at Lower Baker Dam near Seattle, and on some projects for the Tennessee Valley Authority.

There is documented evidence that virtually all deep shafts in the Dutch, Belgian, French and German coal mines sunk near the end of the 19th century and the beginning of the 20th century were enveloped in bitumen poured or injected as a hot melt in the annular space between the liner and the formation.

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From the first two decades after the Second World War, there are a few more documented cases of the use of bitumen for stopping major water inflows. The use of emulsions, and their associated failures, had given bitumen a very bad reputation. Both from a technical and environmental perspective the emulsions were sensitive and often did not provide the desired results.

The selection of the type of bitumen to use during the first applications was often controversial. Residual seepage was often caused by extrusion of the bitumen from wide seams or cracks because of a lack of strength at ambient temperature. The selection of inappropriate grades of bitumen, such as road bitumen with low solidification point, as well as, the problems discussed above, made the use of hot bitumen for grouting applications almost extinct.

The development of different types of environmentally friendly bitumen expanded its use in the grouting industry. Oxidized blown bitumen replaced the softer bitumen typically used in road paving applications and emulsions in grouting, and played an important role in marine, civil and mining applications, mainly for seepage control.

During the late 1970.s and early 1980.s bitumen was used as a permanent grout for lining and sealing purposes on nuclear waste disposal sites in Germany and France, including the Manche nuclear waste deposit. It was also used in tunnel grouting and for contact grouting around concrete plugs in abandoned salt and potash mines in Europe.

The use of hot bitumen was "rediscovered" during the early 1980's with the success of the Lower Baker Dam and the Stewartville Dam grouting projects. Unfortunately the selection of the wrong type of bitumen by an inexperienced contractor at hydroelectric power projects near Waterton (New York) and Sault Ste. Marie during the mid-1980.s temporarily dampened the revival of bitumen grouting.

Hot bitumen grouting made a remarkable comeback during the late 1990.s. Projects in Asia, New Brunswick, West Virginia, and Wisconsin demonstrated that the application of bitumen technology is an efficient, economical and powerful tool to prevent or stop seepage and major leaks.

The nature of most bitumen grouting projects involved emergency situations in which very serious water inflow problems needed to be solved. This has actually hampered the exposure of bitumen grouting in the mining and civil engineering world, since clients often do not wish that detailed information be disseminated on their misfortune or problem situation.

How hot bitumen grouting works

Dr. Erich Schönian, one of the first scientists to study the penetrability and behavior of hot bitumen, documented remarkable findings regarding bitumen penetration in cracks (Schönian, 1999). As the bitumen grout comes in contact with water, the viscosity of the

grout increases rapidly resulting in a lava-like flow. A hard insulating crust is formed at the interface between water and bitumen and shelters the low viscosity, hot bitumen behind it. The "crust" or "skin" is remelted from within when hot bitumen continues to be injected.

When hot bitumen is injected into a medium saturated with water, it cools quickly at the interface with water. Steam is created at that point, decreasing the viscosity of the bitumen. The steam acts as an "air lift" drawing the bitumen into its pathway through small and large fissures or pore channels. The center of the bitumen mass remains hot, and continuously breaks through (remelting) the skin formed at the interface of the bitumen and water. There is absolutely no wash-out. The faster the water flows, the faster the bitumen cools off. The skin prevents washout while the "sheltered" hot bitumen behind the skin behaves as a Newtonian fluid, penetrating in a similar fashion as solution grouts

Because bitumen has good insulating characteristics, it can be injected for a very long time (days - even weeks) into the same grout hole without the risk of either premature blockage or wash-out. The width of the fissures accessible to hot bitumen depends on the duration of the grouting operation. The longer the grouting operation, the finer the apertures the bitumen will penetrate. Hot bitumen will penetrate fractures as small as 0.1mm as demonstrated during the Kraghammer Project in 1963, described below.

When hot bitumen cools it is subject to significant thermal shrinkage. This phenomenon is partially overcome in smaller fractures if pressure continues to be applied and warmer bitumen pushes the cooling bitumen into the shrinkage gaps.

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.

Holes that are being grouted with hot bitumen rarely come to refusal (zero flow at highest allowable pressure) when the initial pump rate is kept high (to establish a heat sink and prevent rapid cooling of the bitumen causing premature refusal).

The advantage of bitumen over other grouting systems to stop or control water flow, especially under high pressure and at high flow rates, is that blown bitumen will never wash-out. Modifying the mix design of cement-based grouts (used as balanced stable grout with thixotropic viscosity modifiers) or solution grouts (especially water reactive hydrophobic polyurethane) to prevent the grout from washing out while obtaining a large grout spread can be very difficult and often impossible. The project may require numerous boreholes, large volumes of grout, and several attempts, if it is at all successful. In order for the grout not to wash out, it needs to possess adequate cohesion to form a conglomerate larger than the particle size that corresponds with the "critical particle size" under the given flow conditions. The critical particle size refers to the size of the particle that will just be moved by a flow of a given velocity. As the velocity increases, the critical particle size increases. With bitumen, the skin has a very high cohesion, while the "interior" has a low cohesion and viscosity. With classic suspension grouts, on the other

hand, the grout has virtually the same rheological characteristics (including cohesion) throughout the grout cylinder. If a high cohesion is required to prevent wash-out, it will limit grout spread and penetrability. Bitumen combines the best of both worlds: a skin prevents wash-out while the low viscosity bitumen penetrates fine pathways. Hence the need for many grout holes if cement-based suspension grout or solution grout are used; and the need for fewer grout holes if hot bitumen grout is used. If the cohesion of the grout is too low, the grout will wash-out. It should be noted that, as more apertures and pathways are plugged, water travels faster, increasing the critical particle size and hence the required cohesion of the grout to prevent wash-out. This makes the requisite rheological characteristics of 'closure' grouts even more onerous.

Special considerations for using hot bitumen grouting

Based on the analysis of the various bitumen projects conducted during the last twenty years it is safe to conclude that hot bitumen always meets its objectives in the short-term. For long-term success, experience, knowledge and a sound engineering design must be applied.

The equipment and set-up are generally more complex for bitumen grouting than for the applications involving regular cement based grouts or solution grouts.

The operating temperature of the surface pipe system needs to be in the range of 180 - 225 °Celsius (356 - 437 °Fahrenheit). Moreover, a supply of hot bitumen needs to be obtained and maintained at the requisite temperature. The bitumen should, ideally, be delivered to the site in heated and insulated bulk tankers with the potential to boost or adjust the temperature on site in a custom built grout plant.

The piping system used during grouting to deliver the hot bitumen from the bitumen pumps to the sleeve pipe "stinger" located at the end of the bitumen grout hole, must either be pre-heated with hot oil, heat trace, or steam, potentially through a re-circulation system. Additionally, the grout pipes must be insulated and equipped with temperature sensors and pressure gauges. The flow rate, total volume of grout injected, and grouting pressure must be monitored and recorded in real-time. This allows informed decisions to be made while the operation is in progress. Additional safety measures for dealing with hot materials need to be respected, following general and specific site procedures. With proper safety procedures in place, the use of appropriate equipment and execution by well-trained and attentive crews under the supervision of an experienced engineer, hot bitumen grouting can be conducted safely and effectively.

It is required to continuously monitor the subsurface conditions for signs of cement grout wash-out by measuring the pH of the water, evaluate temperature changes as recorded via down hole sensors to assess the spread of the bitumen, and to interpret changes in apparent Lugeon value (i.e. changes in flow rates and injection pressures). The apparent Lugeon value is the permeability coefficient of the formation using grout as a test fluid (Landry, et al., 2000). It is noteworthy that during the execution of a hot bitumen grouting program the apparent Lugeon value typically decreases with time (contrary to

cement grouting operations) due to the excellent penetration properties of the bitumen into the formation.

Environmental issues

The injection of hydrocarbons into soil, rock or structures immediately raises environmental concerns. There are, however, many types of bitumen available with a wide range of characteristics. The desirable type for use in grouting is a "hard" oxidized environmentally friendly type of bitumen with a high solidification point.

Oxidized blown bitumen has a long history of successful use for lining (potable) water reservoirs in California (over 40 years) and in 1987 Washington and Oregon State wildlife authorities have used it for lining fish hatcheries ponds.

Oxidized bitumen has proven to be in compliance with American Water Works Association (AWWA) standards for leachate resistance of materials for use in potable water applications. Indeed, it is now routinely used for water pipeline lining applications. It could be considered the most environmentally friendly grout presently available on the market

Examples of field applications

Lower Baker Dam, Washington, U.S.A., 1920.s, 1950.s, 1964 and 1982

One of the oldest documented bitumen grouting operations took place more than 75 years ago to stop major leaks through the limestone foundation below the abutments of the Lower Baker Dam, operated by Puget Sound Power and Light.

Slotted steel pipes, pre-heated via a central steel cable were used. The operation was reported to be very successful in the short-term. Creep of the bitumen, however, opened secondary flow channels and resulted in further erosion of clay filled seams in the limestone foundation.

Another bitumen grouting operation was performed some thirty years later at the same dam, using virtually the same techniques with similar results. This was repeated again during the 1960's. It was concluded that bitumen grouting was not efficient since leaks reoccurred within a year.

In 1982, the owner attempted to use water reactive polyurethane prepolymers. It was injected via a "residence pipe system" which enabled the set time to be adjusted within a second. After weeks of attempts, all parties came to the conclusion that the polyurethane grouts either set in the immediate vicinity of the grout pipe or that it washed out rendering it impossible to make polyurethane grouts work under the prevailing flow conditions (many fine fissures with a flow through time less than 20 seconds).

Hot bitumen grouting was again successfully used to curtail the 2,200 litres per second inflow. At the end of two weeks of grouting, the leak was reduced to 2% of its original flow. The owner could not be convinced to use bitumen in conjunction with cement-

based grout. The leak gradually again increased over time and has stabilized at a rate of approximately 1,000 litres per second.

Stewartville Dam, Ontario, Canada. 1980's (Deans, et al. 1985)

The Stewartville Dam, located on the Madawaska River, measuring 63 metres high, and 248 metres long, was constructed in 1948. Hot bitumen in conjunction with cement-based grout was successfully used to seal a 22,000 litres per minute inflow beneath the dam foundation under a full reservoir head of 46 metres. The foundation is composed of predominantly massive competent limestone. Zones of weathered micaceous limestone susceptible to erosion occur on some bedding planes and joints. Leakage and wash-out gradually enlarged these zones and eventually water began to enter the foundation drainage gallery. This application illustrates the high degree of control to perform a surgical strike using hot bitumen in conjunction with cement based suspension grout since the leaks had to be stopped while not plugging the adjacent foundation drains.

Cement-based suspension grouting programs carried out between in the 1970's and early 1980's were ineffective. Grout clogged one drain with no measurable reduction in seepage. The grout typically washed out in spite of the use of rheology enhancing additives such as straw, sawdust, and other "innovative" additives.

Continuing on the same course of action was clearly not productive.

Following additional geotechnical investigations, extensive water and dye testing, and a review of available grouting technologies, it was decided in 1983 to proceed with the injection of hot bitumen in conjunction with regular cement-based grout to compensate for the thermal shrinkage of the grout and produce a durable end product.

The main challenge in the grouting operation was to grout under conditions of high flow, in fractures up to 0.2 metres wide, and within 7.5 metre of the foundation drain, which had to be kept open. Dye tests indicated less than 5 seconds "flowthrough" time below the dam.

Once the bitumen grouting began, reduction in seepage flow was immediately noted in the inspection tunnel connected to the foundation drain. After a few minutes of grouting the leakage from the treated portion of the dam was reduced to 10 % of the original inflow and was completely stopped after six hours of grouting. Cement based grout was injected in the same seams upstream of the bitumen grout holes.

A similar grouting program conducted in 1984 beneath the northern portion of the dam reduced seepage to almost nothing from over 9,000 litres per minute.

The visco-plastic properties of the hot, blown bitumen combined with controlled injection rates prevented excessive travel of bitumen from interfering with the foundation drains. Combined with the injection of cement based suspension grout, a durable end product was created. Post-grouting drilling revealed a good bond between the bitumen, cement-based grout and limestone.

Kraghammer Sattel, Germany, 1963(Schönian, 1999)

The Bigge Reservoir in Germany, located in the Kraghammer Saddle is situated on highly fractured permeable alternating strata of greywacke slate and sandy partly calcareous clay slate. Bitumen grouting was used to reduce the permeability of the formation beneath the reservoir dam.

The unique feature of this project was that the success of the bitumen grouting was checked by the excavation of two inspection tunnels through the grouted formation. Of significance is that a portion of the formation was grouted with regular cement based grout, and the volumes injected and final permeabilities were compared to the areas of the formation grouted with hot bitumen.

The results of the testing yielded three interesting findings:

- Grout takes per metre of borehole were considerably less over zones injected with hot bitumen than in zones injected with cement based-grout.
- Bitumen was found to have filled seams in the rock up to 3.5 metres from the boreholes and penetrated seams as narrow as 0.1 mm
- Zones with initial permeability in the 1-10 Lugeon range were successfully grouted with hot bitumen proving that hot bitumen is very suitable to treat formations with low initial permeability values.

Drainage Plug in Abandoned Open Pit Mine Tunnel, Asia

In the mid 1990.s the plug inside an old access tunnel, connecting a very large open pit mine used for tailing impoundment with the river failed. The reservoir was filled with millions of cubic meters of liquid waste and tailings. The slurry flowed out of the impoundment reservoir into a river causing major environmental problems. The flow reached a peak of 7 m³/second. The hydrostatic pressure in the tunnel (2.5 m wide, 2.5 m high and 3 km long), was in excess of 1 MPa.

In order to provide mechanical support to withstand the considerable forces resulting from the hydrostatic pressures behind the future plug, a number of large geotextile barrier bags were inflated with cement-based suspension grout in the tunnel. The geotextile bags were strapped onto steel sleeve pipes and lowered into the 175 metre deep drill holes intersecting the tunnel. The bags were inflated in stages with cement-based suspension grout to a diameter of two meters. After inflation, additional reinforcing steel was lowered into each sleeve pipe that straddled the tunnel. As a result, the slurry was forced to flow through a fence of reinforced "concrete piles".

A sophisticated grouting operation involving the local mine forces was undertaken. The grout hole was pre-heated with hot oil. Bitumen grouting started when down-hole thermocouples indicated that the temperature was adequate.

Cement-based suspension grout was injected upstream of the bitumen injection point. Some of the cement grout holes were used to inject a mortar with cohesion in excess of 500 Pascal (injected with a concrete pump using mortar supplied by transit mixers). Further upstream a low viscosity, polymer enhanced, stable suspension grout was "jet

grouted" into the tailings flow. Within the hour, the flow of water and slurry through the tunnel was stopped. At that point, water started to flow only through the fissures and joints in highly sheared bedrock (highly pervious $k > 500 \text{ Lu}$) surrounding the tunnel. Bitumen was originally traveling upstream and downstream of the injection point. Once the flow was stopped, bitumen was traveling "against the flow", drawn into that direction by steam. Soon, the first cement grout hole reached refusal (no flow at 70 bar). Within four hours, bitumen had traveled more than 40 metres upstream of the injection point and sealed, one at a time, all six cement grout holes, as far as 100 metres upstream of the bitumen grout holes.

Large pockets of tailings remained encapsulated in the cement/bitumen plug after the flow was stopped. The tailings were systematically removed via cross-hole flushing between newly drilled grout holes. The voids were filled with stable, balanced cement based suspension grout, while the formation surrounding the tunnel was grouted with microfine cement based suspension grout. The piezometers in the area slowly recovered, eventually reaching the reservoir level, some 100 metres above the crest of the tunnel.

Potash Mine, Canada - 1997

In 1997 inflow of fresh water into a potash mine in Canada had increased to a point threatening the mine's continued operation. A slow leak of fresh water had gradually dissolved the salt layer between overlying shale formation and lower basalt rock forming a large cavern. Eventually the overhanging mudstone and limestone collapsed. The dewatering system was overwhelmed and an emergency grouting program was designed and implemented to attempt to save the mine. Inflows of fresh water ranged from 10 - 15,000 cubic metres per day.

The proposed method was the injection of hot bitumen in conjunction with regular cement-based suspension grout to fill the cavern and stop the inflow. The initial "gas testing" indicated that the volume of the underground cavern above the rubble pile was 19,000 cubic meters.

The cavern was located approximately 700 metres below a large brine pond. Two 1,600 metre long drill holes, one for injection of hot bitumen and one for injection of cement-based suspension grout, were installed from surface using directional drilling.

Conceptually the grouting would encompass two phases: initial filling of the cavern with bitumen and water repellant cement grout to cut-off the leak to the mine; and, grouting of the aquifer feeding the cavern.

There was the danger that once the leak was stopped, there was the possibility that the hydrostatic pressures would rise in the cavern and the deteriorated formation could collapse sending a tidal wave of water through the mine.

Once the bitumen grouting operation was successfully launched, cement grouting was initiated. Crews of 50 people per shift performed the grouting operation around the clock. Tanker trucks filled with, hot oxidized blown bitumen were brought in from as far as 800

km away. There were as many as twenty-six insulated tanker trucks involved in what might have been the largest production grouting operation ever undertaken. The site facilities were capable of boosting the temperature of the bitumen to the required temperature. Flow, accumulated flow, pressures, hole temperature, temperature of the bitumen, and temperatures in various exploration holes near or above the cavern were all displayed in real time and monitored at several locations during the project.

Bitumen was injected at an average flow rate of approximately 25 m³/hour for more than two weeks of continuous operation. Cement-based suspension grout formulations were injected at a rate of approximately 45 m³/hour.

After 24 hours of bitumen grouting and cement-based grout injection into the cavern, inflow rates began to decrease and hydrostatic pressures in the formation started to rise. After three days of around the clock grouting the inflow completely stopped and formation pressures continued to rise. After five days a major collapse of the "cavern floor" occurred. Immediately the hydrostatic pressure in the formation dropped. A tidal wave rolled through the mine as millions of litres of water rushed in over a few hours. The grouting operation continued without interruption. The inflows were again substantially reduced and formation pressures rose once again after an additional five days of around the clock grouting at the aforementioned injection rates.

The inflow was completely stopped again. The spirits of the team were high. Victory appeared to have been accomplished. On the thirteenth day of grouting, before the cavity was filled with grout, the formation collapsed again. The second tidal wave again flushed millions of litres of water into the mine.

A sophisticated "gas test" was again conducted, concluding that the "void" above the rubble had increased to more than 100,000 cubic meters. A final effort of injecting bitumen at a rate of 40 m³/hour and cement-based suspension grout in conjunction with sodium silicate (via concentric pipes) at approximately 60 m³/hour was launched. The grout did not wash out (as was verified via pH tests) but the hydrostatic pressure in the formation did not recover. The collapsed zone covered the size of several football fields. The rock formation had lost its structural integrity. After 15 days of continuous, around the clock grouting, the operation was terminated. More than 23 million litres of grout had been placed. It was concluded that the salt horizon had been too severely undermined to be recovered.

The fact that injection of hot bitumen and cement-based grout temporarily completely sealed an inflow of such magnitude at such a great depth is a testament to the robust nature of the technique. The failure of the plug was not a failure of the bitumen grouting technique but was a consequence of the undermining of the salt horizon surrounding the newly formed plug that had occurred over the two months prior to grouting.

Quarry in Eastern United States, 1998.

During routine mining operations in an old limestone quarry, the floor of which was located some 70 metres below the level of an adjacent river, a major water in rush

occurred. Piping through clay filled karsts caused a hydraulic connection to the river that led to inflows into the quarry of over 3,000 liters/ second.

It was determined that karsts filled with erodible clay and gouge, some as high as 40 metres were acting as flow conduits. A grout curtain was installed using the following techniques:

- 1) In zones where small fissures and interconnected vugs governed the hydraulic conductivity cement based suspension grouts were injected.
- 2) In other areas where large vugs and karsts were encountered in the absence of significant water flow, a classic, low mobility grout was used.
- 3) Cement grouting was used to channel the flow to windows. where these classic grouts were no longer suitable to stay in the formation under the governing water flow. Grouting was typically conducted with the two aforementioned systems until wash-out of the grout became too severe. These "windows" were successfully grouted using hot bitumen in conjunction with regular cement-based grout.

Milwaukee Tunnel, Wisconsin, U.S.A. - March, 2001

Jay-Dee Contractors, Inc., an established American tunneling contractor, excavated a 1.2 meter diameter tunnel in soft saturated alluvium containing coarse sand and gravel in Oak Creek, near Milwaukee, Wisconsin.

During the installation of a vertical feeder pipe into the unlined tunnel, a collapse associated with heavy inflows of ground and water occurred. Several hundred cubic meters of sand and gravel washed into the tunnel. The tunnel was approximately 35 metres below surface. The water table was 5 metres above the crown of the tunnel. No significant dewatering of the soil was permitted.

Extensive grouting from surface via open-ended pipes and sleeve pipes had been conducted for several weeks and resulted in temporary sealing of the leak. This allowed the contractor to substantially excavate the tunnel leaving a 13 m long zone straddling the breach in place. At this point the leak reoccurred at a rate of 100 litres per second.

Finally, hot bitumen was injected via sleeve pipes into the area where the collapse occurred from within the tunnel. Two temporary bulkheads were used to contain the sand and gravel inside the tunnel. Hot bitumen and regular cement-based grout were injected behind the bulkhead. The hot bitumen saturated the loose sand and gravel inside the tunnel and traveled to the collapsed area and into the surrounding soils stabilizing the entire area around the tunnel. The grouting operation only lasted a few hours. The tunneling contractor was able to excavate the collapsed tunnel and install the concrete liner without any further difficulties.

New Yung Chung Tunnel, Ilan, Taiwan, 2002

In 1998 the New Yung Chung railway tunnel was excavated into a water bearing marble formation that was bounded on both sides by weak greenschist rock with abundant gouge material present. The high ambient water pressures of approximately 50 bar (750 psi) and inflows of up to 4 cubic meters/second caused a major collapse in the tunnel.

The initial tunnel trajectory was abandoned and two new tunnels (7 meter and 5 meter diameters) trajectories were planned through the water-bearing zone. An extensive hot bitumen grouting program was implemented from within the new tunnels to enhance the stability of the rock mass surrounding the planned tunnel excavation and decrease the permeability of water bearing marble zone.

Over the course of four grouting phases, 3084 cubic meters of hot bitumen was injected into the formation via 16 bitumen delivery pipes at pressures as high as 125 bar (1800 psi). During the grouting operation hot bitumen was injected into individual bitumen grout holes. The longest operation lasted for nine days with approximately 1450 cubic meters of bitumen injected into a single hole. Grouting regimes noted during the grouting included permeation grouting, permeation grouting in conjunction with hydrofracturing, and at extreme pressures, hydrofracture grouting alone.

The hot bitumen grouting program conducted in the New Yung Chung Tunnel resulted in a reduction in the hydraulic conductivity of the formation surrounding the main tunnel of approximately 95 %. This is likely the first bitumen grouting program ever conducted entirely from within a tunnel. At the time of writing this paper, one tunnel has been excavated through the marble zone and the second tunnel is approximately 10 meters from completion. There is reported to be almost no water entering the face of the excavation, extensive bitumen has been encountered, and there have been no problems with ground stability.

Conclusions

When installed in accordance with a sound engineered design by a competent contractor with suitable equipment using the appropriate type of bitumen the hot bitumen in conjunction with cement grouting technique has never failed to stop inflows.

Bitumen grouting techniques can be applied safely, economically, and extremely effectively, even under adverse conditions. Last but not least: blown oxidized bitumen is probably the most environmentally friendly grout available at present.

Acknowledgements

Special thanks to Mr. Stephen Hooey, P.Eng, for his assistance in writing this paper.

The author acknowledges the trust, cooperation and assistance of numerous individuals who played a role in some of the bitumen projects described. With the risk of having left some out they are: C. Brawner, Don Bruce, J. Bruce, M. Fallet, G. Grimmig, D. Haas, L. Jaillard, Dr. K. Kading, D. Krizek, E. Landry, B. Lukajic, T. Moody, G. Moore, J. Pordon, G. Rorison, E. Schönian, W. Thrytall, M. Yates
Many thanks also to Whitman Benn, Jay Dee Contractors, and U.S.L.

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