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Bitumen

Hot Bitumen Grouting – Rediscovered

Heißbitumenverpressung – wiederentdeckt

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Hot Bitumen Grouting – Rediscovered – Part 1

Heißbitumenverpressen – wiederentdeckt – Teil 1

Erich Schönian and Alex Naudts[*]

Kurzfassung (German abstract)

Als in den zwanziger Jahren des zwanzigsten Jahrhunderts in den USA das erste Mal Heißbitumen zur Dichtung von Dammkörpern und ihrer Aufstandsfläche eingesetzt wurde, wurde der Einsatz in der Neuzeit als ein mutiger Schritt betrachtet. Die Erfolge, mit einem solchen in Jahrtausenden als beständig erkannten Dichtungsmaterial Hohlräume sehr unterschiedlicher Größe zu füllen, führten u. a. außer in den USA unterhalb der Hales Bar Betonmauer 1924 mit Verpressen von 4.300 t Oxidationsbitumen und nach einer Dammerhöhung 1925 in der Aufstandsfläche des Great Falls Dammes 1945 mit getrenntem Verpressen von mehr als 2.000 t Bitumen und von Zementsuspension auch in einigen anderen Ländern der Welt zu Ausführungen, wie z. B. in Frankreich 1950 für durchlässige Tunneldächer mit Bitumen 70/100 und in Deutschland im Kraghammer Sattel an der Biggetalsperre 1963 mit Bitumen 70/100. Das Verfahren stieß jedoch in der Verpress-Industrie auf kein besonderes Interesse – wohl auch, weil firmeneigenen Verfahren mit den dazu gehörigen Gerätesätzen sowie selbst entwickelten Füllstoffen schon aus Wettbewerbsgründen im allgemeinen der Vorzug gegeben wurde – und blieb deshalb nur auf besondere Ausnahmefälle beschränkt, in denen mit besonderen Bedingungen in Bezug auf Fließwassermenge und -geschwindigkeit im Substrat, sehr engen und gleichzeitig sehr viel weiteren Rissen, Klüften und großvolumigen Hohlräumen sowie mit vorhersehbaren späteren Setzungen und Dammverformungen zu rechnen ist

In den zwanziger Jahren am Lower Baker Damm in den USA und in den folgenden Jahrzehnten wurde das Verfahren wieder aufgenommen, am Stewartville Damm und in einer Kalimine in Kanada, in einem Steinbruch in West Virginia, einer großen Mine in Asien, einem Damm in Brasilien und einem Tunnel in Milwaukee, wo größere Mengen Bitumen verpresst wurden. Dabei kam, bis auf den Lower Baker Damm, erstmalig ein neues Verfahren zum Einsatz, bei dem Bitumen – im wesentlichen Oxidationsbitumen – und zementöse Verpressmittel kombiniert nebeneinander gleichzeitig in verschiedenen Bohrlochreihen, aber auch einmal im gleichen Verpressrohr zum Einsatz kamen.

Der Vorteil liegt u. a. in Fällen vor, in denen – wie schon erwähnt – mit besonderen Bedingungen in Bezug auf Fließwassergeschwindigkeit und -menge im Substrat, sehr unterschiedlich weiten Rissen, Klüften und großvolumigen Hohlräumen sowie mit vorhersehbaren späteren Setzungen und Dammverformungen zu rechnen ist. Die Verpressmenge von zementhaltigen Mitteln kann bei deutlich geringeren Bitumenmengen wesentlich reduziert werden, der Zeitaufwand ist deutlich verringert und die Umweltverträglichkeit des Bitumens ist optimal, da zementöse Mittel immer Zusatzmittel geringer Verträglichkeit enthalten müssen. Ein deutlicher preislicher Vorteil besteht gegenüber kunstoff-basischen Verpressmitteln.

Folgende Anwendungen werden im Einzelnen beschrieben:

***Lower Baker Damm, Washington, USA:** eine Schwergewichtsmauer, bei der unterhalb der Mauer aus den Felshängen seit Jahrzehnten immer wieder neue Risse und Klüfte durch den Wasserdruck im Gebirge freigepresst werden, so dass erneut Hangwasser austritt. In Abständen von Jahren wurden die zum Tal offenen Klüfte an den talseitigen Hängen mit Heißbitumen – zuerst mit Straßenbau- und später mit Oxidationsbitumen – erfolgreich gedichtet.*

***Stewartville Damm, Ontario, Kanada:** die 1948 gebaute Schwergewichtsmauer zeigte am Mauerfuß einen Wasserzufluss in den Dränagetunnel von 22.000 Litern/Minute. Jahrelange Versuche, mit anderen Verpressmitteln den Zufluss zu stoppen, ohne den Tunnel dabei zu verstopfen, führten 1983 schließlich dazu, mit dem kombinierten System zuerst mit der Injektion von Oxidationsbitumen und dahinter gleichzeitig mit Zementsuspension den Zufluss vor dem Tunnel zu stopfen, und das innerhalb einer Zeit von Stunden.*

***Kraghammer Sattel der Biggetalsperre im Sauerland:** Der Ruhrtalsperrenverein, später Ruhrverband, der über viele Talsperren in dem Gebiet verfügt, hat dort 1963 im Zuge von Verpressarbeiten des Satteldammes mit Zementsuspensionen trotz der damit verbundenen höheren Kosten dankenswerterweise auch 3 Bohrlöcher von einem oberen Kontrollstollen aus mit Heißbitumen verpressen lassen, um diese Verpressmethode, dafür hergestellte Geräte, Wirtschaftlichkeit und Erfolg zu prüfen. Später wurde im verpressten Bereich 25 m tiefer ein zweiter Kontrollstollen aufgefahren, in dem man den Erfolg augenscheinlich prüfen konnte – einmalig auf der Welt. Dabei stellte sich heraus, dass das Bitumen bis 3,5 m vom Bohrloch vorgedrungen war, feine Risse bis herunter zu 0,1 mm Breite füllte und an der Tunneldecke auch aus verfüllten Klüften von 2 cm Dicke kein Bitumen herauslief. Eine Abbildung des mit Bitumen verpressten Bereichs im Tunnelkopf wird gezeigt (Abb. 6).*

***Abwassertunnel einer Tagebaugrube in Asien:** die stillgelegte sehr große Grube diente zur Lagerung von Millionen m^3 Abfallerz und flüssigem Abfall und entwässerte während des Betriebs über einen Tunnel, der nach der Stilllegung durch einen Pfropfen geschlossen wurde, in einen nahe gelegenen Fluss. In den neunziger Jahren versagte der Pfropfen und der dann aus dem Sammelbecken ausfließende Schlamm verursachte größere Umweltschäden. Um dem hydrostatischen Druck widerstehen zu können, wurden im 175 m tiefen Tunnel geotextile Säcke deponiert, in Etappen mit Zementsuspension auf 2 m Durchmesser aufgeblasen und mit Bewehrungsstahl versehen. Der Schlamm wurde dadurch gezwungen, durch einen Zaun von bewehrten »Betonpfeilern« zu fließen.*

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Der zweite Teil dieses Beitrages: 5. Anwendungsbeispiele und 6. Zusammenfassung wird in der nächsten Ausgabe dieser Zeitschrift veröffentlicht.

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Für die dann folgende Verpressaktion wurden die Bohrlöcher mit aufgeheiztem umweltfreundlichen Öl vorgewärmt und anschließend mit Oxidationsbitumen verpresst. Gleichzeitig wurde oberhalb des verpressten Bitumens Zementmörtel von zwei verschiedenen Mannschaften verpresst und dabei in einige der Zementverpresslöcher ein Mörtel mit einer Kohäsion von über 500 Pascal injiziert, ferner oberhalb eine niedrigviskose Polymer-angereicherte stabile Suspension über Düsen verpresst. Innerhalb 1 Stunde konnten das Fließwasser und der Schlamm gestoppt werden und Wasser nur noch durch Risse und Fugen im gewachsenen Fels mit sehr geringer Scherfestigkeit austreten. Innerhalb 4 Stunden wanderte das Bitumen bis 40 m oberhalb des Verpresspunktes und dichtete, einen nach dem anderen, alle 6 Zement-Verpresslöcher bis 100 m oberhalb der Bitumen-Verpresslöcher. Große eingeschlossene Taschen von Abfallerz verblieben im Zement/Bitumen Pfropfen, die systematisch entleert und wieder stabil gefüllt wurden.

Kalibergwerk in Kanada 1997: *Der Zufluss von Frischwasser bedrohte den kontinuierlichen Betrieb. Ein Leck frischen Wassers hatte langsam und allmählich eine Salzschicht zwischen der darüber liegenden Schieferschicht und tieferem Basaltfels aufgelöst, was zur Bildung einer großen Kaverne führte. Der Zufluss von Frischwasser betrug zwischen 10 und 15.000 m^3/Tag. Eine einleitende »Gas-Messung« deutete auf eine Größe der unterirdischen Kaverne über dem Gesteinsschutt von 19.000 m^3 hin. Die Kaverne lag zudem etwa 700 m unter einem Salzlaugensee. Zwei 1.600 m lange Richtungs-Verpressbohrungen wurden von der Oberfläche heruntergeführt, je eine für das Heißbitumen und eine für die Zementsuspension. 2 Arbeitsphasen waren geplant: 1. die Verfüllung der Kaverne mit Heißbitumen und wasserabweisendem Zementverpressmittel und 2. das Verpressen des Grundwasserleiters. Der Bauherr war jedoch vor Beginn der Arbeiten darauf hingewiesen worden dass, für den Fall des Ansteigens des hydrostatischen Druckes in der Kaverne, die sich verschlechternde Formation zusammenbrechen könne, was zu einer Flutwelle durch das Bergwerk führen würde. Die Herausforderung bestand erstmalig darin, das Bitumen im 1.600 m langen Verpressrohr richtig zu beheizen.*

Die Injektion von Heißbitumen wurde mit etwa 25 m^3/h und die mit Zementsuspension mit etwa 45 m^3/h rund um die Uhr durchgeführt. 24 Stunden nach Beginn der kombinierten Verpressung begann die Zuflussrate abzusinken und der hydrostatische Druck in der Formation anzusteigen und nach 3 Tagen insgesamt hörte der Zufluss völlig auf. Nach 5 Tagen kollabierte dann der Kavernenboden und eine Flutwelle rollte mit Millionen von Litern durch das Bergwerk. Das Verpressen wurde ohne Unterbrechung weitergeführt und der Zufluss reduzierte sich wieder und der Druck erhöhte sich nach weiteren 5 Tagen wesentlich, was erneut zu einer völligen Beendigung des Zuflusses führte. Am 13. Tag – noch bevor die Kaverne völlig verfüllt worden war – kollabierte die Kaverne wieder und die zweite Flutwelle rollte mit gleicher Menge wie die erste durch das Bergwerk. Ein erneuter Gastest ließ darauf schließen, dass sich die Kaverne jetzt auf ein Volumen von 100.000 m^3 vergrößert hatte.

Als letzte Anstrengung wurde die Bitumenmenge auf 40 m^3/h und die Menge der Zementsuspension zusammen mit der Zugabe von Natriumsilikat über ein konzentrisches Rohr auf 60 m^3/h erhöht. Das zementöse Verpressmittel wurde nicht ausgewaschen (PH-Wert im Abflusswasser kontrolliert), aber der hydrostatische Druck in der Formation ließ sich nicht wiederherstellen. Der kollabierte Bereich hatte die Größe mehrerer Fußballfelder erreicht und die Formation ihre strukturelle Einheitlichkeit verloren. Nach 15 Tagen ununterbrochenen Verpressens wurden die Arbeiten endgültig eingestellt, nachdem mehr als 23 Millionen Liter Verpressmittel eingebracht worden waren – möglicherweise die größte Verpressarbeit in der Geschichte. Die Tatsache, dass das kombinierte System zweimal in einer solchen Tiefe einen Zufluss dieser Größenordnung zeitweise völlig abgeschnürt hatte, ist ein Beweis der robusten Eigenschaften desselben. Es kann in keinem Fall als das Versagen einer Heißbitumeninjektion interpretiert werden.

Steinbruch im Osten der USA, 1998: *während der üblichen Arbeiten in einem alten Kalksteinbruch 70 m unterhalb des Wasserspiegels eines nahen Flusses stellte sich ein hydraulischer Grundbuch von über 3.000 Liter/Sekunde durch innere Erosion mit auskolkbarem Lehm gefüllter Karste und damit eine hydraulische Verbindung zwischen Fluss und Steinbruch ein. Der Zufluss konnte durch einen 300 m langen Verpressschleier parallel zum Fluss mit dem kombinierten System Heißbitumen und Zementsuspension gedichtet werden.*

Jaburu Damm, Brasilien in 1980ern: *der Damm liegt in der Sierra Grande Region, ist 47 m hoch und 770 m lang. In 1988 trat eine Leckage von 20 Litern/Sekunde auf, die sich bald auf 47 Liter/Sekunde erhöhte. Mit einfachsten Mitteln – ohne Injektionsdruck durch einfaches Eingießen in Verfüllrohre im Zusammenhang mit Verpressen von Zementsuspensionen konnten die Wasserverluste auf einen gleichmäßigen Fluss von 3 Litern/Sekunde reduziert werden. Da in der Gegend kein Oxidationsbitumen verfügbar war, wurden direkt aus Bitumentankwagen insgesamt 60 m^3 Straßenbaubitumen ohne zusätzliche Heizung in die Rohre gepumpt.*

Milwaukee Tunnel, Wisconsin, USA im März 2001: *Beim Bau eines Tunnels mit 1,2 m Durchmesser in weichem, wassergesättigtem Alluvium ereignete sich beim Einbau eines Beschickungsrohres in den noch nicht mit Beton ausgekleideten Tunnelquerschnitt ein Kollaps mit starkem Zufluss von Boden und Wasser. Einige Hundert m^3 Sand und Kies wurden in den Tunnel eingeschwemmt. Ausgedehnte Verpressarbeiten von der Oberfläche mit unten offenen Rohren und mit Überschiebmuffe während mehrerer Wochen führten zu einer zeitlichen Dichtung des Lecks und erlaubte dem Tunnelbauer, den Tunnelquerschnitt wieder zu räumen. Zurück blieb eine 13 m lange Bruchzone, in der das Leck mit 100 Litern je Sekunde wieder auftrat. Sand und Kies wurden hinter zwei provisorischen Schotts zurückgehalten. Zum Schluss wurde Heißbitumen über Muffenrohre vom Tunnel aus in den Raum, in dem der Kollaps auftrat, injiziert, wieder kombiniert mit normalem Zementverpressmittel. Das Bitumen stabilisierte das Erdreich und verhinderte weiteren Wasserzufluss, sättigte den losen Sand und Kies im Tunnel und wanderte in den Bruchbereich und das umgebende Erdreich ein. Die Verpressarbeiten dauerten nur wenige Stunden. Der Tunnelbauer konnte dann den Querschnitt leer räumen und die Betonauskleidung ohne weitere Schwierigkeiten herstellen.*

Schlussfolgerungen:

Der Vorteil des gemeinsamen Verpressens von Heißbitumen und Zement zum Schließen von größerem Wasserzufluss unter extremen Bedingungen wird hervorgehoben. Es ist jetzt möglich, wirkungsvoll katastrophenhafte Undichtigkeiten schnell, dauerhaft und wirtschaftlich zu schließen. Die letzte Entwicklung zeigt, dass das Verfahren ebenfalls für kleinere Objekte zu verwenden ist. Es stellt zudem ein ökologisch hervorragend geeignetes System dar. Sehr kleine Risse und Poren werden gefüllt, so dass es möglich ist, sowohl Felsgesteine als auch grobkörnige Böden zu verpressen und wasserrückhaltende Bauwerke zu dichten.

Abstract

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

Advancement in the industry especially in the field of monitoring and grouting equipment has made the injection of hot bitumen, often applied in conjunction with cement based suspension grout, the most economical, practical and sure solution to stop major inflows through, below or around structures. Hot bitumen remedial grouting was successfully applied in projects such as the Stewartville Dam and the Lower Baker Dam in the USA, a potash mine in Canada, a quarry in West Virginia, a large mine in Asia, a dam in Brazil, and a tunnel in Milwaukee. 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.

Hot bitumen is the ideal grout to stop major inflows due to its temperature dependent viscosity. At high temperatures, the dynamic viscosity of bitumen is typically in the range of 15 to 100 cP (1 cP = 10^{-3} Pa s), which allows the bitumen grout to flow and permeate very small fissures and sore channels. The steam created during contact of the hot bitumen with the water enhances the penetrability of the bitumen grout.

The first report on the penetrability and behaviour of soft-graded hot bitumen as a single grout by van Asbeck/Schönian [4] documented remarkable findings regarding bitumen penetration in cracks. As the bitumen grout comes in contact with water (colder temperatures), the viscosity of the grout drastically increases 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" is remelted from within and facilitates the bitumen to penetrate the medium to be grouted.

The cement based suspension grout injected in conjunction with the hot bitumen sets up on contact with the hot bitumen creating a more competent "creep-free" end product able to resist the hydrostatic pressures. The purpose of the cement based suspension grout is also to compensate for the shrinkage of the bitumen as it cools. The hot bitumen and cement based suspension grout combination form a stable, chemical-resistant, environmentally friendly solution. This paper elaborates on a few remarkable field applications, one of which probably was one of the largest grouting efforts ever undertaken.

1 Background

One of the oldest references to bitumen for use in bitumen grouting was for the construction of the Tower of Babel (recalling the ziggurats of the ancient Babylonian Kingdom) recounted in *The Antiquities of the Jews (IV:3)*, by Flavius Josephus in the first century A.D. This is also one of the first, maybe the first reference to the application of grouting in history. Bitumen also has a long history of use in warfare. There are also historical accounts of the Saracen Turks defending cities in Palestine by pouring hot bitumen on the attacking knights during the crusades of the 10th and 11th century A.D. The literature does not mention whether the crusaders were wearing the proper PPE or if this type of the low pressure grouting operation was brought to absolute refusal.

By the end of the 20th century grouting with hot bitumen for remedial repair work on dams and rock tunnels for seepage control 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 that hot bitumen was used during the 1920's in the records of Puget Sound Power and Light at Lower Baker Dam near Seattle and on some projects for the Tennessee Valley Authority (TVA) in the USA. There is also documented evidence that virtually all deep shafts in the Dutch, Belgian and German coal mines (sum about 30), further in French and Canadian mines and 3 in Louisiana/USA as well as sunk near the end of the 20th century and the beginning of the 21st century were enveloped in a bitumen compound filled with limestone dust and poured or injected as a hot melt into the annular space between the liner and the formation, where it was the intention, that the melt would be able to penetrate fissures in the rock under the head of the filled-bitumen column to seal them in the course of settlement or lateral shifting of the shafts due to a hanging effect.

Hot bitumen forms a visco-plastic end-product that is efficient and readily available to stop or prevent seepage. The selection of the types of bitumen for 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 (road bitumen with low solidification point as well as environmental problems associated with some tar-enriched bitumen) made the use of hot bitumen for grouting applications almost extinct.

From the first two decades after the Second World War, however, there are a few more documented cases of the use of bitumen for stopping major water inflows. They were typically an extension of the bitumen applications in marine environments. The development of different types of environmentally friendly bitumen expanded its use in the grouting industry. Oxidized (blown) bitumen typically replaced the softer bitumen used in road paving applications and emulsions for grouting applications. Bitumen played an important role in marine, civil and mining applications predominantly for seepage control. 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 very often did not provide the desired results. The use of "caseine" to break the emulsion shortly after injection caused environmental and technical problems (either caused premature solidification or the polymerisation never took place). Bitumen as a grout seemed to be destined for the history books.

The use of hot bitumen was 'rediscovered' during the early eighties with the successes of the Lower Baker Dam grouting 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 to take a prominent place in grouting.

During the late 1970's and early 1980's bitumen was proposed as a permanent grout for the later lining and sealing purposes on

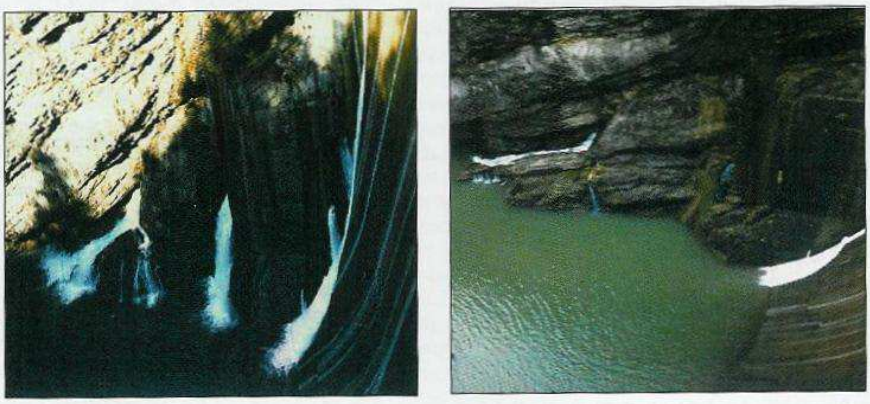

Figure 1 **Lower Baker Dam – Before and After Bitumen Grouting (1982)**

nuclear waste disposal sites in Germany and France, including the Manche nuclear waste deposit. It actually was used in tunnel grouting and for contact grouting around concrete plugs in abandoned salt and potash mines in the eastern part of Germany.

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.

Figure 2 **Bitumen and cement based grout flowing out of seepage intake pathways in the river (Quarry grouting, West Virginia, 1998)**

2 How hot bitumen grouting works

Bitumen is a natural hydrocarbon based product. While there are numerous 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. 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 quicker the bitumen cools off. The skin prevents the wash-out while the "sheltered" hot bitumen behind the skin behaves as a Newtonian fluid, penetrating in a similar fashion as solution grouts.

Hot bitumen must be injected into a watery environment. The steam created by the bitumen (injected at temperatures between 190–240 °C) propels the grout through the pervious medium to be treated. The steam enhances penetration into and clears debris from the fractured medium (rock or structures) or facilitates the permeation of bitumen into pore channels (soils).

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 behaviour of bitumen during grouting has often been compared to the flow of lava. 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 is often injected in conjunction with cement based suspension grout for any of the following reasons:
- to reduce grout spread;
- to make bitumen less creep susceptible;
- to cool off the bitumen faster and compensate for thermal shrinkage of the bitumen during cooling;
- to increase the mechanical strength of the end product; and,
- to eliminate water flows and facilitate the grouting of regular cement based grout which otherwise could not be injected.

Hot bitumen will penetrate fractures as small as 0.1 mm as demonstrated during the Kraghammer Project in 1963, described below. The visco-elastic nature of the bitumen makes it possible for it to be forced into the fractures while it is still warm and under pressure from the hotter less viscous bitumen. Adhesion (bond) between the bitumen, cement, and rock is excellent as shown in Figure 3. In larger flow channels or fractures the cement based suspension grout and hot bitumen form a "swirl" as shown in Figure 2. The cement based suspension grout sets up very quickly in contact with hot bitumen and strengthens the end product.

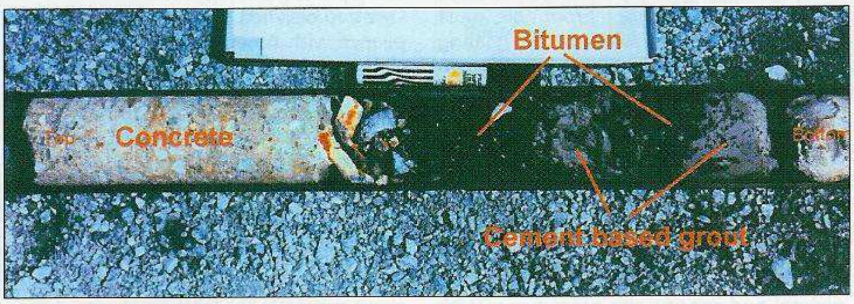

Figure 3 **Close-up of core showing contact of bitumen with concrete and cement-based suspension grout**

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 by the warmer bitumen pushing the cooling bitumen into the fissures, filling the shrinkage gaps. Thermal shrinkage is, however, typically overcome by injection of cement based suspension grout.

The viscosity, rheology and set characteristics of bitumen must be selected for each specific application. For instance, sealing large fractures under conditions of high pressure and high flow may require the injection of a more viscous bitumen (lower temperature) with the addition of polymers; or it must be injected in conjunction with large volumes of regular cement based grout or even low mobility "compaction" grout, to fill shrinkage gaps and to be less subject to creep. For this reason, cement based suspension grout is often injected via the same sleeve pipe in conjunction with bitumen or after bitumen grouting is suspended in order to form a competent "plug."

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 pre-mature refusal). The combination the suction created by the steam and the penetration characteristics of the low viscosity hot bitumen enables the bitumen to travel extensively into the formation and penetrate finer fissures than regular cement based grout.

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. It may require a significant number of boreholes, large volumes of grout, and several attempts, if it is at all successful. The occasionally cited premise that - if enough cement based grout is injected - something will eventually stick and plug up the flow channels, is neither realistic, practical nor cost effective (nor is adding oats, wheat, cereals, horse manure or fiberglass, etc.). 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. A high cohesion of the grout – in contact with the flow – is therefore required (to seal the "windows"). 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 where cement based suspension grout or solution grout is used, and the need for fewer grout holes where bitumen grout is used. If the cohesion 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.

Even if 2-component grout systems are used (a solution grout or cement based grout in conjunction with a solution grout) that produces a rapid increase in cohesion and fast setting of the grout, with the mixing taking place near the exit point, limited wash-out can be accomplished but only at the expense of limited penetration into finer fissures and greatly reduced grout spread. For this reason, neither "compaction grouting" nor "auxiliary grouting" are not nearly as effective (or don't even work) compared to hot bitumen grout under adverse flow conditions.

The overall supply and installation cost of hot bitumen is relatively low. Installed costs for hot bitumen range from \$ 300 US to \$ 1,000 US/m^3 in North America compared to \$ 9,000 to \$ 20,000 for polyurethane solution grout, or even \$ 4,000 to \$ 7,500 for the hydroblock system (using a specially addivated cement-based grout in conjunction with polyurethane). Considering that using hot bitumen in conjunction with regular cement based grout may need considerably fewer boreholes and requires only a fraction of the volume of material (and much less time) of more conventional grouting systems, the potential cost savings that are realized using hot bitumen in conjunction with regular cement based grout are typically substantial. If the contractor would only be compensated for the volumes of grout that stay in the formation, the cost benefit of hot bitumen are even more pronounced. Note that it is rather easy to figure out the amount of grout that stays in the formation via pH-tests in the water flow downstream of the injection point.

3 Special considerations for using Hot Bitumen Grouting

Based on the analysis of the various bitumen projects conducted during the last 20 years it is safe to conclude that hot bitumen always meets the objectives in the short-term. To make it last, it requires experience, knowledge and a sound engineering design.

The equipment and set-up typically are more complex for bitumen grouting than for the application of regular cement based grouts or solution grouts. The operating temperature of the surface pipe system needs to be in the range of 180–225 °C. 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. On the other hand, no mixing of ingredients is needed at the site.

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, heating cable, steam or via a hot oil or hot bitumen circulation system. Additionally, the grout pipes must be insulated and equipped with temperature sensors and pressure gauges. The flow rates and total volume of grout injected as well as the pressures must be monitored and recorded in real-time making it possible to make informed decisions. 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 with the execution by well trained and attentive crews under the supervision of a competent grouting engineer, hot bitumen grouting can be applied very safely.

With the injection of hot bitumen grout in conjunction with cement based suspension grout, 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 latter ideally is done using custom developed software monitoring and assessing all parameters in real-time. CAGES™ is perfectly suited to gage the response of the formation to the grout. This allows the grouting engineer to direct the operation with confidence. The apparent lugeon value is the permeability coefficient of the formation using grout as a test fluid, with reference to the paper by Landry, et al. [6]. It is noteworthy that typically the apparent lugeon value, during the execution of a grouting program, decreases with time (contrary to cement grouting operations), which explains the excellent penetration of the bitumen.

Designing and building custom made bitumen grout plants and delivery systems on a series of projects resulted in the construction of a containerized highly sophisticated grout plant capable of performing multiple hole bitumen grouting at high injection rates (30 m^3/h), whereby each hole is individually monitored and assessed in real-time. A concentric sleeve pipe system has also been developed to inject hot bitumen and cement based suspension grout simultaneously.

4 Environmental issues

The injection of hydrocarbons into soil, rock or structures immediately raises environmental concerns. However, oxidized 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 hatchery 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, bitumen is now routinely used for water pipeline lining applications in many countries.

The oxidized bitumen can be used in potable water environments and since it does not wash out, it has absolutely no negative impact on the environment and could be considered the most environmentally friendly grout presently available on the market.

(to be continued in next issue)

Hot Bitumen Grouting – Rediscovered – Part 2*

Heißbitumenverpressen – wiederentdeckt – Teil 2*

*Erich Schönian and Alex Naudts***

5 Examples of field applications

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

Lower Baker Dam, operated by Puget Sound Power and Light, was constructed shortly after the turn of the century.

One of the oldest documented bitumen grouting operations took place more than 80 years ago to stop major leaks through the limestone foundation below the abutments. The old-timers used slotted steel pipes, pre-heated via a central steel cable. The operation was reported to be very successful in the short term. Creep of the bitumen and opening up secondary flow channels lead to further erosion of clay filled seams in the limestone foundation.

Another bitumen grouting operation was performed some 30 years later at the same dam, using virtually the same techniques and with the same outcome. This was repeated again during the sixties. It was concluded that bitumen grouting was not efficient since the leaks reoccurred within a year.

In 1982, the owner attempted to use water reactive polyurethane prepolymers, installed under the direction of ECO. It was injected via a "residence pipe system" which enabled to adjust the set time to 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 fissure, 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.

5.2 Stewartville Dam, Ontario, Canada – 1980's

Hot bitumen in conjunction with cement-based grout was successfully used to seal a 22,000 litres per minute inflow under a dam foundation under full reservoir head of 46 metres. 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.

The Stewartville Dam, located on the Madawaska River, measuring 63 metres high, and 248 metres long, was constructed in 1948. The foundation is composed of predominantly massive competent limestone. Zones of weathered micaceous limestone occur on some bedding planes and joints. These zones are susceptible to erosion by moving water. Initial dam foundation preparation was insufficient to treat all these zones. Leakage and washout gradually enlarged these zones and eventually water began to enter the foundation drainage gallery.

Cement based suspension grouting programs carried out between in the 1970's and early 1980's were ineffective. It caused the clogging of a drain, the death of a lot of fish (wash out of cement grout causes increase in pH) but no measurable reduction in seepage. The grout typically washed out and leakage was not curtailed, 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. ECO produced the design for the grouting operation and directed the fieldwork. Figure 4 shows schematically how the grouting program was conducted.

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 "flow-through" time below the dam. A durable product was also required.

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 por-

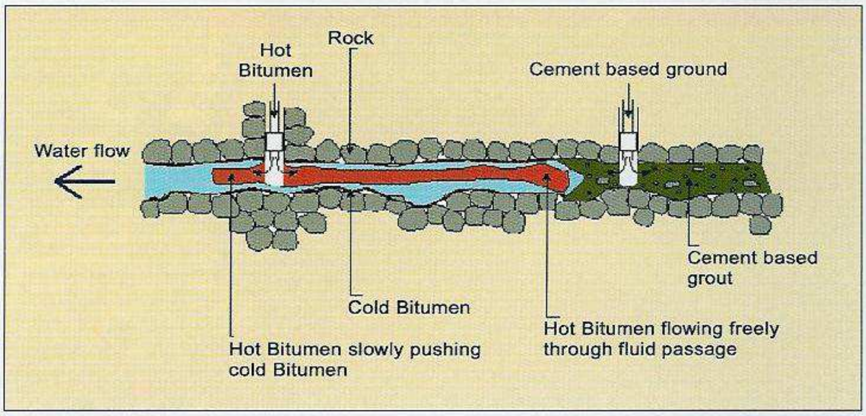

Figure 4 **Schematic of Bitumen and Cement Based grout injection at Stewartville Dam. (Lukajic et al [1+1a] and Schönian [5])**

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*Der erste Teil dieses Beitrages einschließlich einer erweiterten deutschen Kurzfassung mit einer Kurzbeschreibung aller Anwendungsbeispiele (5.) wurde in der letzten Ausgabe dieser Zeitschrift veröffentlicht.

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tion 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.

Thermocouples installed in a number of observation holes made it possible to trace the travel of the hot bitumen with time. A mathematical model of the travel pattern based on the data obtained is described in the papers by Lukajic, et al. [1–1c]. Bitumen traveled against the flow and in the direction of the flow.

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 grout and limestone.

For comparison purposes it is noteworthy that during 1982 a typical "summer grouting exercise" using regular sand-cement based suspension grout, 224 cubic metres of cement based grout and 73 cubic meters of sand were injected over two months with negligible results. In 1983, 11 cubic metres of sand-cement based grout, and 7.2 cubic metres of hot oxidized bitumen were injected in one day to shut off the leak. The following year, 24 cubic metres of sand-cement based grout, 4 cubic metres of bitumen were used in one day with excellent results (reducing the flow to almost nothing). It should also be noted that sand is not an appropriate additive for most permeation grouting programs. It was accepted as a compromise, as is often the case, to allow some contribution by the Owners' staff.

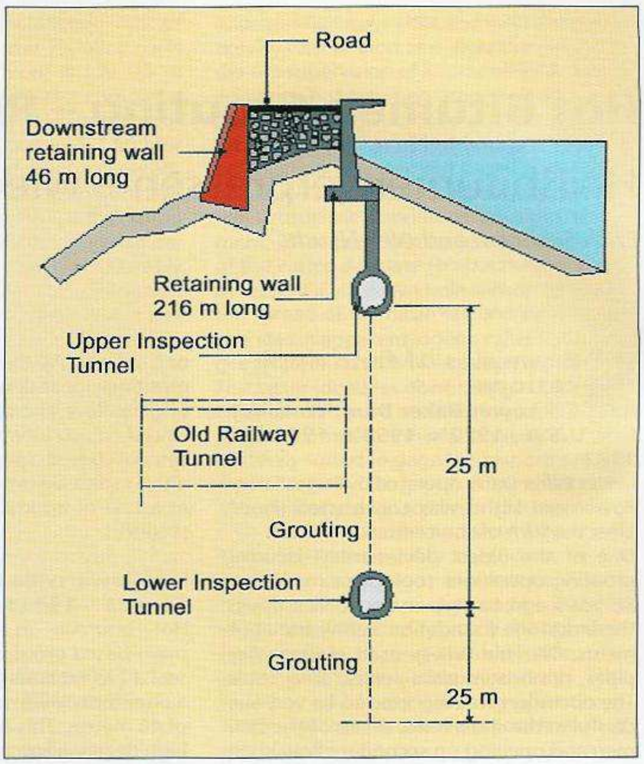

Figure 5 **Plan view of dam and inspection tunnels (Schönian [5])**

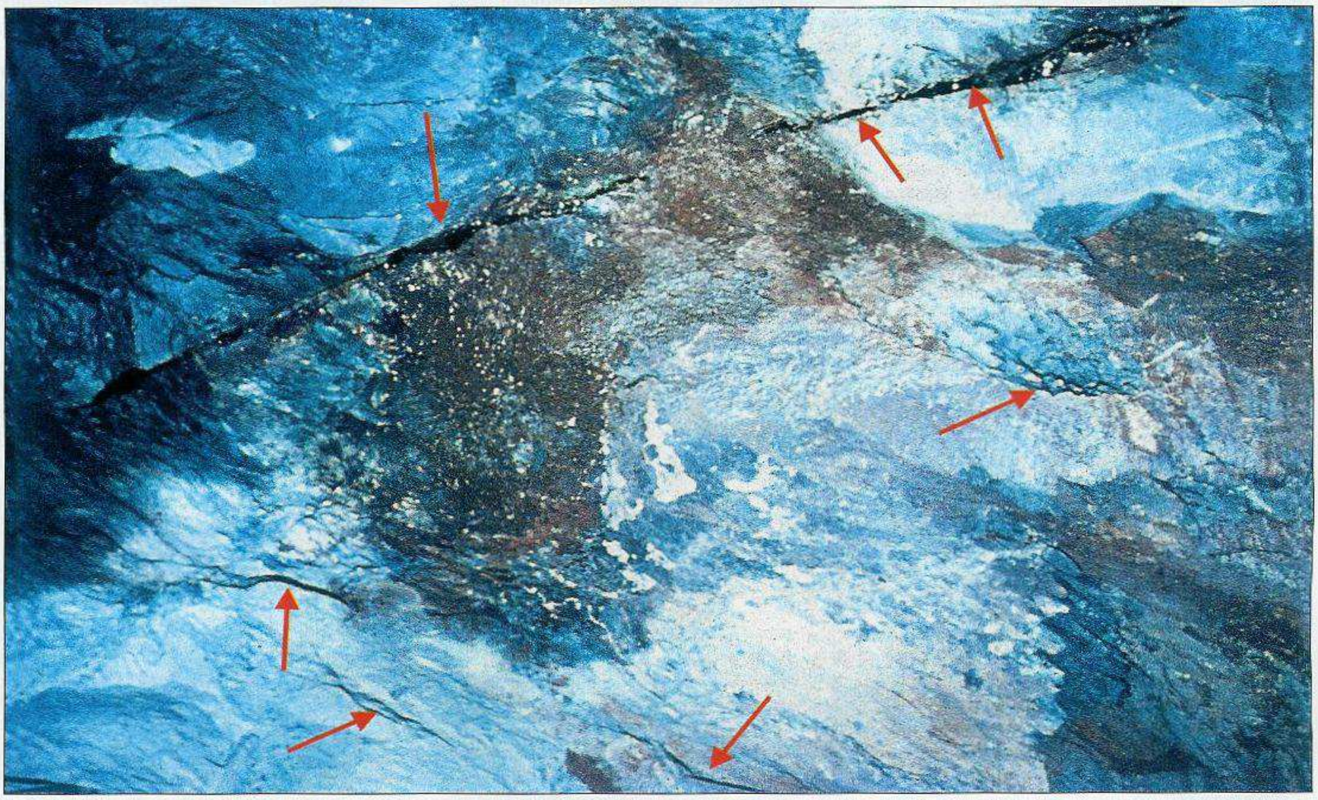

Figure 6 **Kraghammer Sattel: rock fissures in tunnel roof filled with bitumen. Arrows lead to fissures filled with bitumen in widths of 2 cm to 0.1 mm (Schönian [5])**

5.3 Kraghammer Sattel, Germany, 1963

In the course of constructing the Bigge reservoir in Germany, the Kraghammer Saddle in the vicinity of the main dam was to be heightened by a cement concrete structure, to facilitate the planned maximum water level of the reservoir. The saddle is situated on highly fractured permeable alternating strata of greywacke slate and sandy partly calcareous clay slate. The Owner, the Ruhr-Valley Dam Association, was prepared – in addition to the cost of using cement based grout – to pay the surplus costs for the hot bitumen grouting system to study the effectiveness of the system and the new equipment to reduce the permeability of the formation of the saddle dam – to gain experience and to compare costs in view of the great number of other dams and structures of the Association.

The unique feature of this project was that the success of the bitumen grouting could be checked by the excavation of two inspection tunnels through the formation filled with regular cement based and bitumen grout (Figure 5). Of significance is that the main portion of the formation was grouted with regular cement based grout, and the volumes injected and final permeabilities could be compared to the areas of the formation grouted with hot bitumen (Schönian [5]).

The results of the testing yielded seven 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 (see Figure 6).
- In the roof of the lower inspection tunnel the soft Pen-grade bitumen 80/100 did not leak from filled seams around 2 cm wide and even did not bulge.
- Zones with initial permeability in the 1–10 Lugeon range (Lugeon (Lu) is a unit defining the permeability e.g. of a rock or soil formation) were successfully grouted with hot bitumen proving that hot bitumen is very suitable to treat formations with low initial permeability values.
- All cracks were filled to their full length, without any sections of them not being filled.
- The bitumen had not shrunk from the sides of the cracks, in spite of the influence of thermal contraction when cooling down. There was no loss of adhesion to the rock.
- The rock formation visually was not loosened by the injection pressure or the influence of heating up the borehole to injection temperature and hot bitumen being pressed into the cracks.

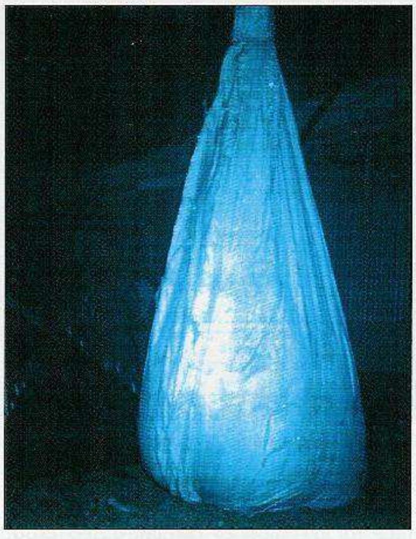

Figure 7 **Geotextile bag**

5.4 Damaged Environment at German Federal Testing Station for Air and Space Travel

In a case where the environment already was polluted and where the cement concrete foundation of the building of the Deutsche Forschungsanstalt für Luft- und Raumfahrt (German Federal Testing Station for Air- and Space-Travel) at Lampoldshausen, Germany was attacked over time by the groundwater contaminated with fluorine resins of missile fuels, the foundation was rehabilitated successfully in 1967/68 via 21 boreholes and the surrounding sandstone via 27 boreholes by grouting with hot bitumen, which is insensitive against most resins [4]. Only concentrations of the fluorine resin above 20 % attack bitumen – a figure not reached here.

5.5 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 with a river failed after an earthquake. The abandoned open pit mine acting as a reservoir then was filled with millions of cubic meters of liquid waste and tailings slurry. The slurry flowed out of the impoundment reservoir into the river causing major environmental problems in 1996. The flow reached a peak of 7 m^3/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 pressure) for the future plug, a number of large geotextile barrier bags were inflated with cement based suspension grout in the tunnel (Figure 7).

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 downhole thermocouples indicated that the temperature was adequate. The custom built bitumen plant is shown in Figure 8.

The operation began with injection of an environmentally friendly hot oil followed by blown bitumen. Cement based suspension grout was injected by two different crews, upstream of the bitumen injection point.

Some of the cement grout holes were used to inject a mortar with a 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 Lu) surrounding the tunnel. Bitumen was originally travelling 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 1000 psi). 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

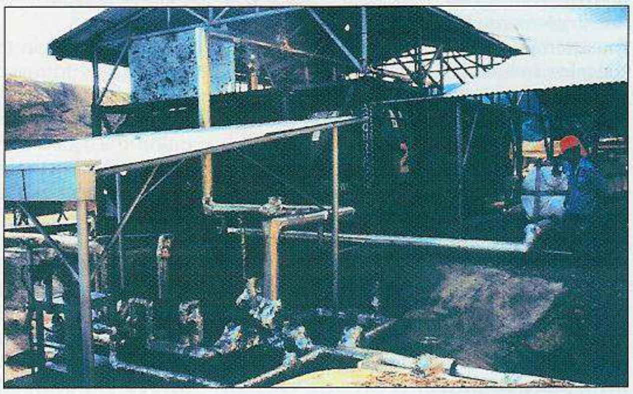

Figure 8 **Custom built hot bitumen plant**

far as 100 metres upstream of the bitumen grout holes.

There were four high shear mixers used. Six standardized mix designs were used, with 5–8 different ingredients. The local "miners turned grouters" respected the mixing time after introducing each one of the ingredients (large clocks were placed above each mixer) producing consistent mixes all the time. This level of discipline and perfectionism was unsurpassed in the second author's experience. Each mix was subject to rigorous quality control tests including bleed, specific gravity, initial cohesion, evolution of cohesion, initial gel time, initial and final set, and pressure filtration.

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.

5.6 Potash Mine, Canada – 1997

In 1997 inflow of fresh water into a potash mine located 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 mine's dewatering system was overwhelmed and an emergency program was designed and implemented in the 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 as shown in Figure 9. While drilling proceeded large grout plants were assembled on surface for injection of cement-based grout and hot bitumen.

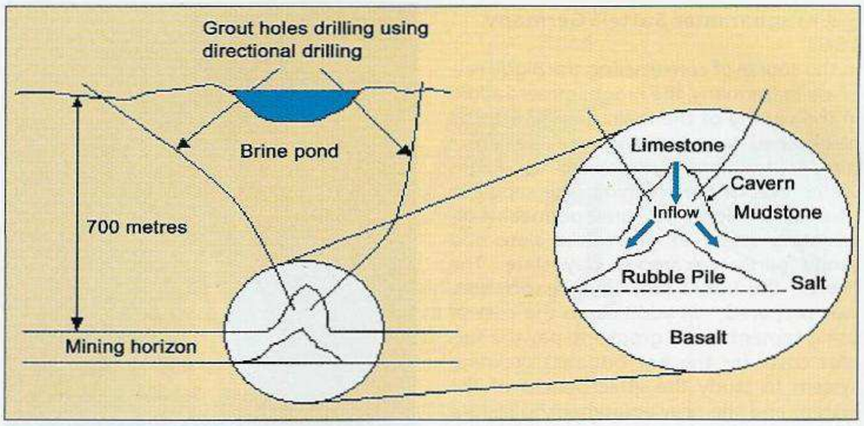

Figure 9 **Schematic diagram of the grout hole layout at the potash mine**

Conceptually the grouting would encompass two phases: 1) initial filling of the cavern with bitumen and water repellant cement grout to cut-off the leak to the mine; 2) grouting of the aquifer feeding the cavern.

ECO designed the grouting program and directed the field operation. The client was informed before the start of the grouting program that once the leak was stopped there was the possibility that once hydrostatic pressures would begin to rise in the cavern, the deteriorated formation could collapse sending a tidal wave of water through the mine.

Figure 10 **Custom built hot bitumen plant**

The challenge was to properly heat and condition the 1,600 metres long bitumen pipe delivery system in the grout hole. It involved several specialized engineers to make this work.

Once the bitumen grouting operation was successfully launched the cement grouting kicked in. A crew of 50 people per shift performed the grouting operation around the clock. Tanker trucks filled with hot oxidized 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 on this planet. The site facilities were capable of boosting the temperature of the bitumen to the required temperature. The custom designed bitumen plant is shown in Figure 10. The real-time monitoring and assessment of the grouting program was impressive. 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 m^3/hour for more than two weeks of continuous operation. Cement based suspension grout formulations with varying rheological properties (viscosity and cohesion) were injected at a rate of approximately 45 m^3/hour.

After 24 hours of bitumen grouting and cement 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 and 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 stopped again completely. 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.

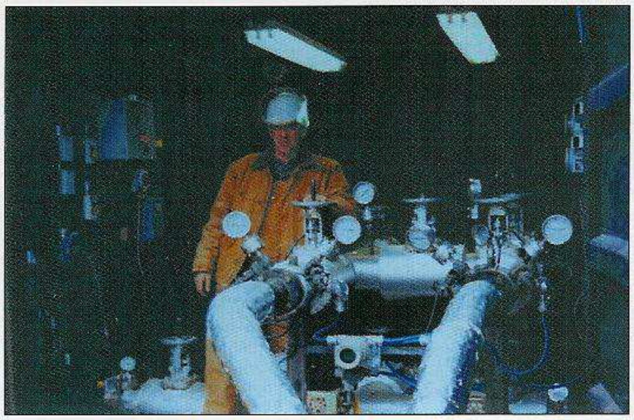

Figure 11 **Containerized hot bitumen plant**

Figure 12 **Insulated bitumen pipe**

A final effort of injecting bitumen at a rate of 40 m^3/hour and cement based suspension grout in conjunction with sodium silicate (via concentric pipes) at approximately 60 m^3/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 and further efforts would be futile. 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 during the two months prior to grouting.

5.7 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 inrush 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. Several techniques were evaluated to install a 300 metre long grout curtain parallel to the river (to be installed under flow conditions - because the quarry needed to continue operating).

A grout curtain was installed using the following techniques:

1) In zones where the hydraulic conductivity was governed by fissures and small interconnected vugs and karsts – in the absence of a substantial waterflow - regular, balanced water repellant cement based suspension grouts were injected via sleeve pipes.
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 to fill these voids.
3) In the first two scenarios 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 in turn grouted using hot bitumen in conjunction with regular cement based grout. The insulated piping system and mobile bitumen plant are shown in Figures 11 and 12 respectively.

Special techniques that were designed and used at the quarry included:

- Hydro-thermal mapping to differentiate between river-inflow and static groundwater
- Hot bitumen grouting in conjunction with cement grouting;
- Compaction grouting to stabilize the overburden and "no flow" or "low flow" karsts
- Downstream well pH monitoring to determine the amount of cement washout during grouting operations
- Permeation grouting with custom tailored water repellant cement based grouts in permeable areas with low flow or no flow; and
- Custom designed dual zone bitumen stingers were used to provide simultaneous injection of bitumen and cement based suspension grouts to targeted zones, via the same sleeve pipe.

5.8 Jaburu Dam, Brazil, 1980's

Bitumen grouting applications are not only limited to large scale 'crisis' projects. In many cases only a small volume of bitumen is required to solve a problem.

The Jaburu Dam, located in Brazil's Serra Grande Region, 47 m high and 770 metre long was built in the early 1980's on jointed siltstones and shales. The foundation was initially grouted with a cement based grout using grout holes 9 to 12 metres deep spaced at approximately 3 metres. The grout takes in these holes was reportedly low.

In 1988 seepage of 20 litres/second was noted under one of the dam abutments. The seepage soon increased to 47 litres/second. An initial grouting attempt using sanded

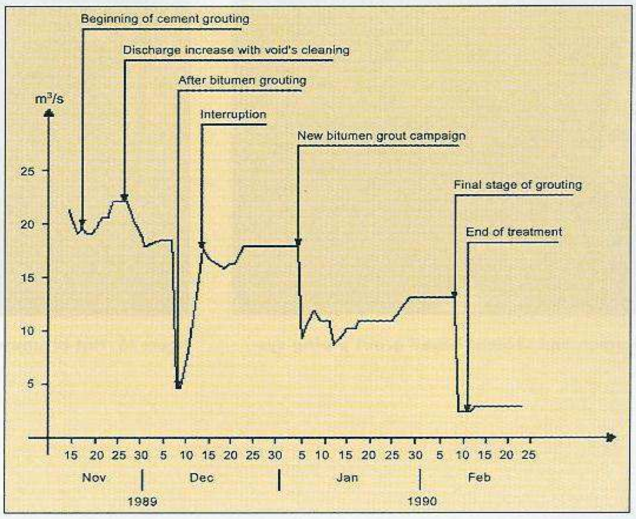

Figure 13 **Flow reduction in response to bitumen grouting. Jaburu Dam (Schönian, [5])**

cement grout to stem the seepage proved unsuccessful. A bitumen grouting program in conjunction with cement based suspension grout was conducted. After several attempts, using drill holes at varying depths the seepage was reduced to a steady flow of 3 litres/second (Figure 13).

In this instance, the most suitable bitumen was not readily available and a much less viscous bitumen with lower solidification point was used without the benefit of pre-heated bitumen lines. A non-oxidized bitumen was pumped directly from the heated bitumen transport truck into the grout holes at a pressure of 0.4 bar. A total of 60 m^3 of bitumen was used.

5.9 Milwaukee Tunnel, Wisconsin, U.S.A. – March, 2001

Jay-Dee Contractors, Inc., an established US 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.

ECO designed and directed the installation of a grouting program (under flow conditions) to recover the tunnel and facilitate the installation of the concrete lining.

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.

The sand and gravel inside the tunnel was contained by two temporary bulkheads. Hot bitumen and regular cement based grout were injected behind the bulkhead into the soil in the area of the collapse. The surface extension of the piping system is shown in Figure 14. The bitumen grout stabilized the soil and prevented further infiltration. The 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.

6 Conclusions

The advantage of applying hot bitumen grouting in conjunction with cement based grout over conventional grouts in the quest to halt major inflows under extremely foul flow conditions is formidable. It is now possible to effectively seal these catastrophic leaks quickly and permanently.

The latest evolution in hot bitumen grouting in conjunction with cement-based grout is comprised in the fact that the technique is not only limited to major projects, but can also be successfully applied to smaller projects. It has become the most appropriate, environmentally sound solution for all projects associated with adverse flow conditions. It penetrates very fine fissures and pore channels which makes it a suitable grout for rock grouting, and coarse soil grouting as well as the sealing of water retaining structures.

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References

[1] Lukajic, B., G.F. Smith and H. Deans. Use of asphalt in treatment of dam foundation leakage: Stewartville Dam. ASCE Spring Convention, Denver, Co., April 1985, pp. 16

[1a] Lukajic, B., Smith, G.F. and Deans, H. Application of asphalt grout in treatment of dam leakage. ICOLD 15th Congress, Lausanne 1985, Vol. V, C. 18, pp 13-19

[1b] Lukajic, B., Smith, G.F. and Deans, H. Performance evaluation of asphalt grouting to stop high velocity flow. . ICOLD 16th Congress, San Francisco 1988, Vol. III, C. 17, pp 1217-1221

[1c] Lo, K.Y., T. Ogawa, B. Lukajic, G.F. Smith and J.H.K. Tang. The evaluation of stability of existing concrete dams on rock foundation and remedial measurements. 17th ICOLD Congress, Vienna 1991, Vol. II, Q. 65-R53, pp 963-990

[2] Bruce, D., A. Naudts and G. Smoak. High Flow Reduction in Major Structures: Materials, Principals, and Case Histories. In Grouts and Grouting. Proceedings: Geo-Congress 98, Boston, Ma. Oct 18-21, 1998, pp. 156-175.

[3] Naudts, A. Grouting to Improve Foundation Soil. In Practical Foundation Engineering Handbook. Chapter 5B. Ed. Robert Wade Brown. McGraw-Hill. 1995, pp. 5.277-5.400.

[4] Van Asbeck, W.F. and E. Schönian. Bitumen im Wasserbau, Band 2 (Bitumen in Hydraulic Engineering, Vol. 2). Hüthig und Dreyer, Heidelberg, and Deutsche Shell AG, Hamburg, 1968, pp. 323-326.

[5] Schönian, E. The Shell Bitumen Hydraulic Engineering Handbook and CD (more text and Figures/Photos). Shell International Petroleum Company Ltd., London 1999.

[6] Landry, E., D. Lees and A. Naudts. New Developments in Rock and Soil Grouting: Design and Evaluation. Geotechnical News. Richmond, British Columbia. September 200, pp. 38-44.

Figure 14 **Insulated hot bitumen and cement based grout piping system**

Figure 15 **Hot bitumen transfer station**