

Control of Fluid Properties of Particulate Grouts:
Part 2 - Case Histories

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Abstract

The companion paper by the same authors provides fundamental background to the new developments in control of hydration, rheology, washout resistance, penetrability and other factors relating to particulate (cement-based) grouts. This paper provides summary details of recent case histories to illustrate the field application and effectiveness of the various types of additives.

Keywords: Particulate grout mix designs; additives; hydration control; rheology control; antiwashout properties; case histories; lightweight grout.

1. Introduction

In the companion paper, Gause and Bruce (1997) describe recent advances in controlling the hydration and rheology characteristics of particulate (cement-based) grouts. In addition, they describe how grouts can be made more penetrative, less dense, or more resistant to washout or dilution. This paper provides details from five recent projects where experience in these new materials was effectively exploited:

- Channel Tunnel, UK - rheology and hydration control.

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- Logan Martin Dam, AL - the use of an antiwashout additive.
- Deer Island Outfall Tunnel, Boston, MA - hydration control and the use of a foam additive.
- Inter-Island Tunnel, Boston, MA - rheology control and use of an antiwashout additive.
- Barrick Gold, Elko, NV - rheology and hydration control.

2. Tunnel Backfill Grouting: Channel Tunnel, UK (Annett and Stewart, 1991)

The tunnels were driven through the Lower Chalk Marl which was badly jointed and had a zero standup time in certain places. Some areas were particularly wet, having saline water ingress rates of around 120 liters/minute at over 1 MPa pressure. Effective grouting behind the tunnel linings was therefore essential for the successful construction and operation of the tunnels. The two running tunnels have an internal diameter of 7.5m and the service tunnel is 4.5 m in diameter. In the U.K. sector, precast concrete segments were used as the final lining, and grouting was required to fill a 20 mm annulus between the lining and the Chalk. Tunneling rates of approximately 250 meters per week were foreseen, and the initial projected grout volume for the U.K. sector of the tunnel was about 55,000 m³, with each complete ring of precast concrete lining segment requiring about 0.85 m³ of grout to be injected into the annulus. Any delays caused by the grouting operation would have had a dramatic impact on the completion dates of the project.

The grouts were required to develop sufficient early setting characteristics to take the invert load of the segment trains within 1 hour of grouting, i.e., setting was needed within 15 minutes of the grout being pumped into place behind the tunnel linings. Reliable antiwashout performance was required to cope with water ingress, and the large overall volume of grout which was often placed in relatively small batches required a long pumping life prior to injection.

The salient points in the materials specification for the annulus grouting were:

- The minimum strength should be 1.0 MPa at 1 day, and 8 MPa at 28 days.
- The initial set should be achieved within 45 minutes of injection at a temperature of 20°C.

- The final set should be achieved in a maximum of 6.5 hours at a temperature of 20°C.
- The grout should not bleed "significantly" during hydration.

Grouts used previously for such wet conditions incorporated long-chain polymer-based admixtures with accelerators added at the packer. However, these grouts display rapid viscosity evolution and are therefore incompatible with long pumping times.

Extensive laboratory and full-scale site trials were carried out to develop and prove a suitable grout mix, and to refine the production and placing techniques. The solution that was finally chosen dealt specifically with the need to provide a correctly grouted invert in the marine running tunnels, where conditions would try to cause grout wash-out. The grouting systems and materials were designed to be flexible and capable of dealing with both fast and slow rates of tunneling progress.

The base grout was a p.f.a./Portland cement mixture, to which various admixtures were added (Table 1) to provide the desired fluid properties.

Ordinary Portland cement	200-250 kg
Pulverized fuel ash (p.f.a.)	200 - 250 kg
Fine sand	1,400 - 1,500 kg
Superplasticizer	4 - 6 kg
Hydration control stabilizer (by weight of cement)	0.6 - 1.5%
Water	300 - 320 kg
w/c	0.7 - 0.8
Slump	> 250 mm
Spread	> 650 mm
Added at the injection point: Hydration control activator (by weight of cement)	2.0 - 5.0%

Table 1. Composition of typical backfill mixes.

The plasticizer ensured ease of pumpability while the use of the stabilizer resulted in fluid grout always being available upon demand. The liquid activator was added to the stabilized grout via an in-line mixer at the grout injection nozzle in proportions designed to provide rapid gelling and set of the grout once in place.

The dry components were held in 4.5-m³ static bunkers, mounted on the TBM sledge, and which, in turn, were supplied by transit car from storage silos outside the tunnels. The plant, finally adapted for "wet" conditions, consisted of paddle mixers, moyno pumps, and metering pumps. More sophisticated weigh-batching equipment was mainly used in drier conditions.

This system was used throughout the construction of the tunnels with consistent success. The grout was proved by tests to have the antiwashout characteristics of a long-chain polymer grout, but the pumping properties of a fluid particulate grout. It provided the specified high early strengths, while at the same time was always available, ready mixed, to meet field demand.

3. Dam Foundation Grouting: Logan Martin Dam, AL (Jansen et al., 1995)

Logan Martin Dam is on the Coosa River about 45 km east of Birmingham, AL. The 1890m long dam consists of concrete structures flanked by the west embankment (265m long) and the east embankment (1417m long). During construction (1960 - 1964), the bedrock was extensively grouted to contemporary standards to create a 12m deep blanket under the concrete structures and a 54m deep single row grout curtain under about 1000m of the concrete structures and the homogeneous earth fill abutments. The bedrock comprises intensely deformed, faulted and fractured Cambro-Ordovician sediments, primarily siliceous dolomite with smaller amounts of chert, limestone and sandstone. Karstic solutioning has severely affected the carbonate rocks. A series of near vertical faults, striking northeast, appear to control major leakage paths. The highest permeabilities generally occur in a nearly horizontal zone, about 60m thick (Figure 1), offset vertically by faulting at several locations.

Review of the long history of embankment sinkholes, soils and high leakage volumes left little doubt that sizable passages existed in and through the foundation.

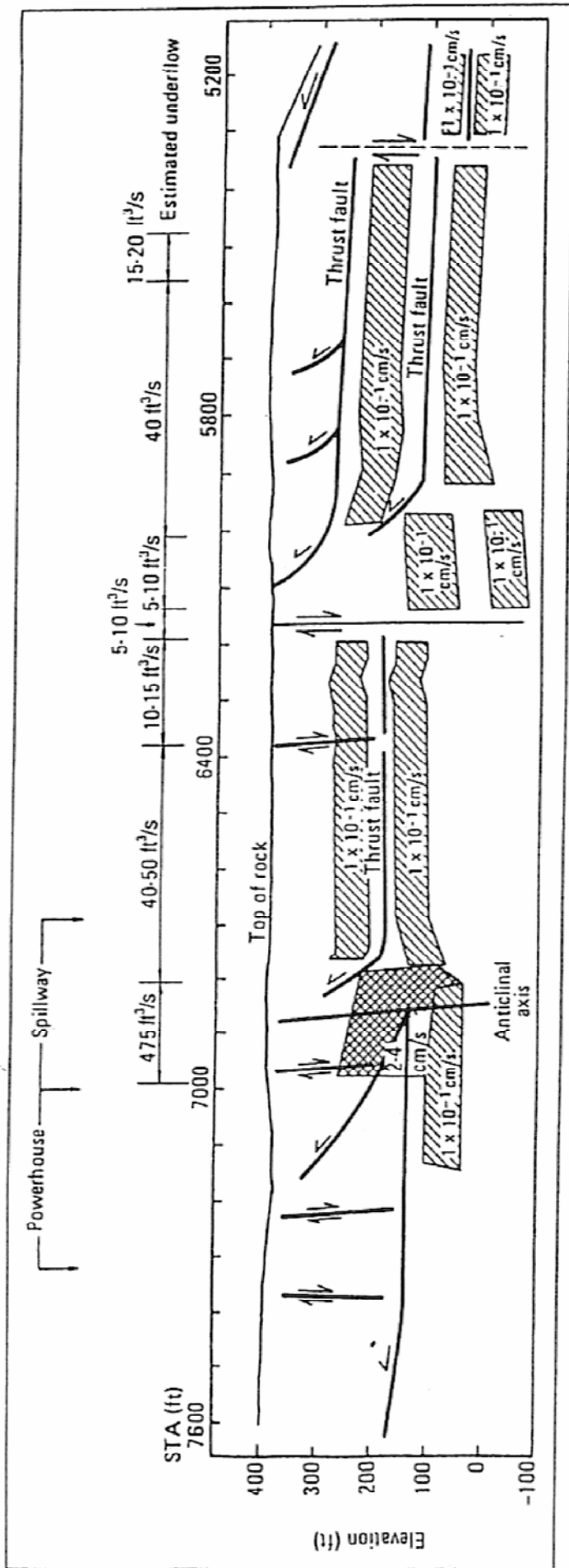


Figure 1. Longitudinal foundation section, showing estimated permeability and underflow ($1 \text{ ft}^3/\text{s} = 0.028 \text{ m}^3/\text{s}$) (Jansen et al., 1995).

These have been addressed by backfilling, further grouting, drains, rockfill bolsters and earth blanketing. As monitored about 500m downstream of the dam, foundation seepage had increased from 7m³/second soon after construction, to 21m³/second in 1989.

In 1991, an intensive investigation and remedial treatment program was initiated to reduce leakage and ensure the stability of the structures. The investigations consisted of drilling, sampling and dye testing to assess the foundation's permeability. The remedial test program consisted of installing a deep grout curtain along a 90m section of the east embankment between Sta. 62+00 and 59+00 (Figure 2). This test section extended the curtain to greater depths (152m into rock), and so into previously untreated rock. Because of the positive results of the test program in reducing seepage volumes, the deep curtain treatment was extended west, through the entire river section of the east embankment.

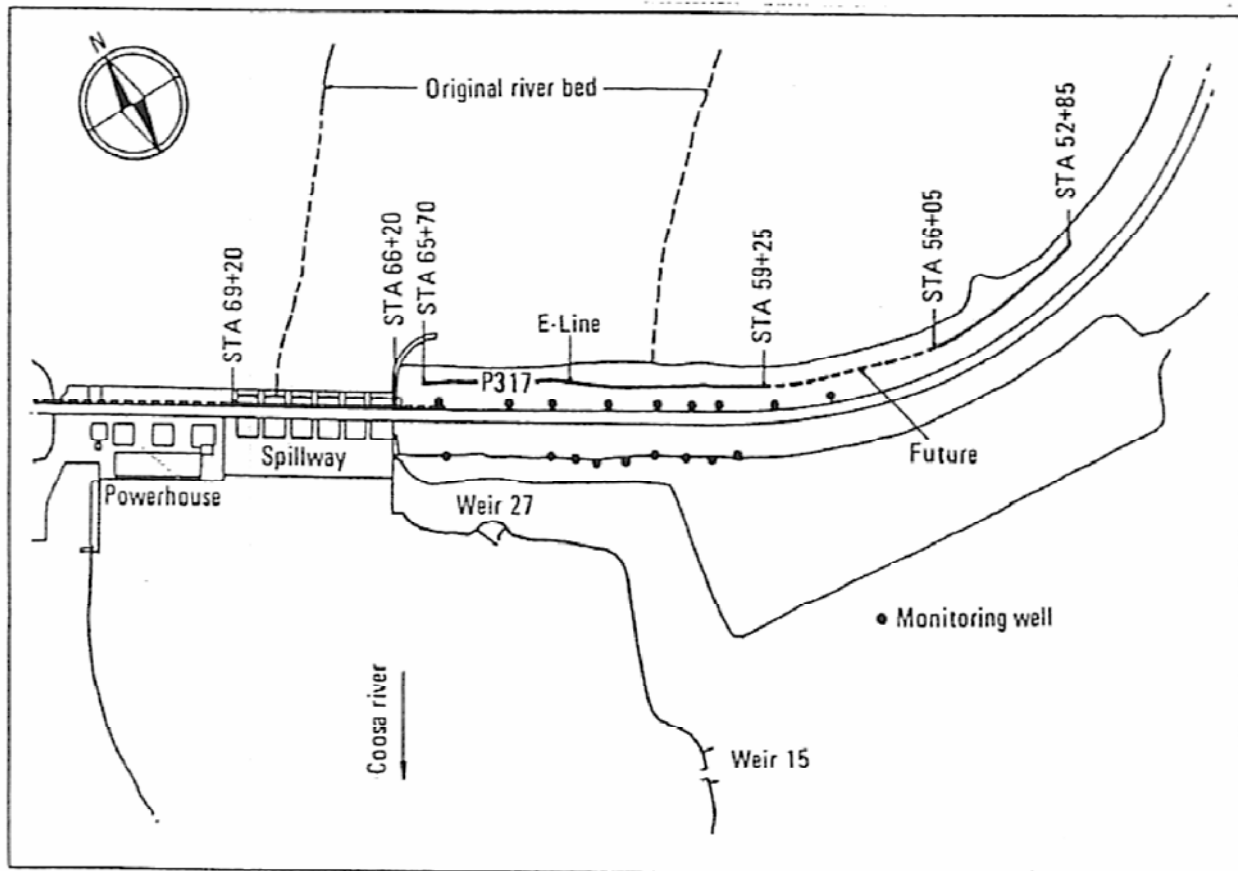


Figure 2. Plan view showing grout curtain, monitoring wells and weirs (Jansen et al., 1995).

An automated high-capacity grout plant was assembled, capable of quickly changing mix designs in response to the various conditions encountered in foundation cavities, some with flowing water. The downstage grouting procedure was aided by a borehole television camera and caliper tool which helped locate the optimum packer setting. Special flushing equipment and methods were developed to wash soil deposits from the weathered zones.

Since the intensified grouting began in August 1991, more than 400,000 bags of Portland cement and nearly 1,500 tons of sand and coarse aggregate have been injected into about 9000m of drilled holes. The project team experimented with bentonite, calcium chloride, plasticizer, fibers, urethane foam, sawdust, sodium silicate and a modified cellulose antiwashout additive. The use of antiwashout additive in conjunction with a high-range plasticizer enabled a water:cement ratio as low as 0.4:1 by volume to be used in particularly permeable zones. The antiwashout admixture minimized bleed water, virtually eliminated segregation, provided thixotropic action and resisted washout. To the authors' knowledge, this project involved the first large-scale use of this particular admixture for dam remedial grouting purposes.

The new grout batching plant was put into operation at the dam in November 1993, and was capable of combining as many as eight components, including sand and small gravel. The central batching facility supplied two high-speed colloidal grout mixers with dedicated delivery systems, enabling grouting in two holes simultaneously.

Since the 1991 grouting began in the river section of the east embankment, many positive results were recorded. Flows measured at Weir 27 (Figure 2) were reduced to 14 liters/second from 170 liters/second, and further reductions were expected as grouting proceeded. Piezometric levels in observation wells equipped with continuous recorder were monitored during the grouting program in the east embankment from Sta. 59+00 to Sta. 65+70. The records showed a definite pattern of lowering water levels downstream from the grout curtain in this reach, while wells upstream from the grout curtain showed a trend of rising water levels. Indicative of the effect of remedial grouting was the record of monitoring well P317 (Figure 2), in which the water level peaked at El.

131.9m in November 1992 and then declined sharply to about El. 125.8m later in that month, dropping further to El. 124.4m in 1994. This compares to a crest elevation of 148.5m. Lesser but still favorable changes have occurred in other wells. These trends continued as the program progressed and their pattern seemed more permanent than those from previous attempts.

Jansen et al. (1995) concluded that the new grouting program using the anti-washout additive "accomplished favorable changes in piezometric levels and an appreciable reduction in leakage". They further noted that the high seepage rates under the concrete structures "should be reducible by grouting procedures that have been pioneered in the east embankment."

4. Backfill Grouting: Deer Island Outfall Tunnel, Boston, MA

This 12km long, 7.2m diameter tunnel being constructed for Massachusetts Water Resource Authority in Boston, MA, completed mining in September, 1996. Because the tunneling extended fully out under Boston Harbor, a decision had to be made on how to remove the TBM from the tunnel. To sink a shaft in the harbor, or disassemble the TBM and return it to the tail tunnel would have been very costly. It was therefore decided to excavate an additional length of tunnel equal to the length of the TBM. The TBM would then be stripped in place of all worthy components, backfilled with grout and so its shell therefore left in place, beyond the end of the useful tunnel. A grout utilizing cement and sand achieving a strength of 10 MPa was specified for this backfill operation.

Road trucking of materials was not permitted through local communities to the jobsite, and so materials had to be delivered by barge. When the cement and sand reached the docks on the island, the material had to be then transported to the batch plant, so increasing further the cost of the grouting materials. Once this grout was batched, the transit time from batch plant to point of placement could be as much as 5 hours. Therefore, the usable life of this grout had also to be carefully addressed as the second major challenge to the cost-effective execution of this grouting project.

As his response, the contractor selected a chemical foaming agent and a hydration control system. The hydration control system ensured fresh, unhydrated grout could be placed even after an elapsed time of 5-6 hours from time of batching. The foaming agent increased the volume of grout by 20%, so reducing by the same amount the materials and the mixing required.

The hydration control admixture was added at the batch plant during the mixing. The grout was then discharged via a 200mm diameter slick line to the tail tunnel where it was received by three 10 m³ rail cars for transport to the point of placement, where it was then re-mixed prior to being discharged into an 450mm diameter screw conveyor. The grout was then conveyed to a re-mixer where a pre-formed foam was added to increase its volume. Once the grout and foam were thoroughly mixed, the grout was then discharged into a second screw conveyor which transferred the expanded grout into the hopper of a concrete pump with a 150-mm diameter cylinder. The grout was then pumped for distances up to 750m to its point of placement.

The contractor found that this combination of hydration control and pre-formed foam proved to be highly advantageous given the twin challenges of material handling, and the elapsed time from which grout was batched until it was actually placed. The pre-formed foam increased the pumpability of the grout and reduced material handling costs on the surface. The hydration control admixture ensured that fresh un-hydrated grout was placed throughout the successful backfill operation.

5. Annulus Grouting: Inter-Island Tunnel, Boston, MA

The Inter-Island tunnel is also a part of the Boston Harbor Project, and features 7500m of tunnel under Boston Harbor from Nut Island via Long Island to Deer Island. With access only being from shafts on each island, the high early strength annulus backfill grout had to be pumped long distances. To further increase the complexity of this operation, water flows of up to 50 liters/second were encountered in the annular space behind the concrete lining of the tunnel.

The contractor chose a grout plant comprising a colloidal mixer and special pumps to deliver the grout up to 3300m through a 25mm diameter steel line. The grouts

had therefore to be relatively fluid, had to achieve a specified strength of 10 MPa in 72 hours, and had to have a strong antiwashout characteristic. In order to achieve early strength, a water/cement ratio of 0.7 was selected, and so to ensure adequate fluidity, a melamine-based dispersant was added at a dosage of 1.25 percent. An antiwashout admixture (0.75%) was added last to prevent the loss of the cementitious component when the grout encountered the flowing water. Prior to the use of the antiwashout additive, site tests showed that conventional grouts could not be retained behind the lining. This situation was completely rectified by the modified grout subsequently used.

6. Backfill Grouting of a Stope, Barrick Gold Mine, Elko, NV

In underground practice, mined areas are backfilled with lightly cemented waste rock to provide a degree of ground support. Traditional methods feature the hoisting of mine waste rock to the surface where it is processed through a concrete batch plant. Cement is added proportionally and the cemented rock is then placed in the stope for backfilling. For reasons of economics and equipment availability, it was decided that the backfilling of a certain stope at this mine had to be performed using a different method: the use of particulate cementitious grouts to treat in situ the preplaced, blasted, waste rock would be attempted. This procedure was required to provide an interim means of stope backfill pending the construction of the permanent underground batch plant.

Considering the gradation of the waste rock - a poorly graded gravel (66%) with sand (25%) and silt (9%) - a non-sanded mix was chosen for the grouting. The grout was required to produce an ultimate compressive strength of 8 MPa, and to retain its originally batched fluid properties for a minimum of 2 hours.

Based on previous experience in the injection of preplaced aggregate, injection was conducted via a series of 50-mm diameter steel pipes, preplaced into the stope. Each set of grout pipes consisted of three separate tubes (#1, #2 and #3): #1 tube extending down the stope to 1m from the bottom; #2 tube extending to 6m from the bottom; and #3 tube extending to 6m from the bottom of tube #2. Each tube was color-coded for easy

identification during the grouting operation. It was determined that any rise in grouting pressure above the normal system pressure (head and line) would constitute refusal, at which time the next tube in the series would be injected.

The mix design utilized for the grouting comprised:

cement	860 kg
water	490 kg
dispersant	0.5% (by weight of cement)
hydration control additive	0.6% (by weight of cement)

The dispersant allowed for increased fluidity, but more importantly, aided in the prevention of cement lumps which usually occur when batching neat cement and water in a ready-mix truck. The hydration control admixture provided increased workable time for a grout that would otherwise be relatively fast to set. This was valuable on occasions when grout remained in the slick line between loads, especially near the stope itself, as the ambient and waste rock temperature was approximately 45°C.

The grout was batched into a ready-mix concrete truck in 5 m³ quantities, and was then discharged to the 370m level of the mine through a 200mm diameter slick line. The grout was received in an agitator tank of 6 m³ capacity. A 100mm diameter slick line stretched approximately 120m to reach the top of the stope where it was reduced to 50mm diameter for connecting to the grout pipes.

As a pilot program, the successful grouting of the preplaced waste rock proved the feasibility of the method. In situ strengths are still to be verified, while the economics have not yet been compared to that of the conventional method. This pilot program did, however, allow the stope to be backfilled in a timely manner, and this was critical to permit continued mining activity in this area, given that the conventional backfill plant was not yet complete. The owner is pleased with the results and, together with other local mining companies, is currently considering the use of this method in other locations.

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