Long-Distance Grouting, Materials and Methods
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Abstract

An abandoned 1600-meter (mile-long) rock tunnel had to be completely filled with grout. The total tunnel volume was approximately 4500 cubic meters (6000 cubic yards). The tunnel was water-filled with access only at each end through narrow, 25-meter deep (80 ft), vertical shafts. Access for pumping was feasible only from one end of the tunnel, thereby requiring unusually long distances for pumping.

Through an extensive laboratory testing and modeling program, different grouts were tested for suitability for this project. The ideal grout would have low viscosity, good stability and, after setting, low bleed, moderate strength and low permeability. Materials tested included cement-bentonite, cement-flyash and combinations including blast furnace slag cement. Data is presented on the various grout materials leading up to the choice of a cement-bentonite-slag cement blend as the optimal mix for the project.

The unusual conditions at this project required the use of divers and remote-operated vehicles to inspect the tunnel and to place the initial cable that would allow grout pipes to be drawn into the tunnel. Each component of the grout system was engineered to provide adequate capacity to fill the tunnel in three to four days, working around the clock. A backup system using a sleeve pipe to provide secondary grout was devised and installed.

The work in the field progressed more or less as planned, with a few unknowns cropping up to make for some difficult moments. As it turned out, the secondary grout line was necessary to complete the work. Grout samples were taken during the project for confirmation testing and borings were drilled into the tunnel after the work to verify that the tunnel was full. Data from this phase of the project are also presented.

This project presented an unusual opportunity to plan and test components pre-construction. While there is no way to verify, the distances that the grout was pumped may represent some kind of record.

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Project Outline

A former water intake tunnel extending under the Niagara River was contaminated with organic wastes from a nearby landfill and was to be filled and closed at the request of regulatory authorities. The two-meter (six-foot) tunnel is nearly 1600 m (one mile) long and accessible from just two 25-meter (80 ft) deep vertical shafts, one of which is in the river. Closure of the tunnel presented a unique remediation challenge because of the limited access, considerable volume of the tunnel, and because the tunnel was full of potentially contaminated water. A plan was developed and implemented that closed the tunnel by filling it with cementitious grout while simultaneously removing and treating the displaced water. The grout used to fill the tunnel had to meet demanding requirements for both regulatory acceptance and workability.

The project work plan had to take into account a number of unique complicating factors, including:

- The tunnel was level, making it difficult to displace water upwards with a heavier grout.
- Access for material placement was really only practical from the land end of the tunnel
- Access by divers into the flooded tunnel was limited to about 200 meters (600 ft) from each end.
- The tunnel could not be dewatered due to the nearly unlimited volume of water from both the tunnel and infiltration from the river that would need to be treated.
- Once work would begin to fill the tunnel, no further personnel access would be permitted, requiring a remote operation.
- Redundant systems would be required to account for multiple variations and breakdowns that might occur. It would be difficult to ever restart the work in the event of a disruption.
- The work plan had to account for the fact that the first stage of grouting might not be totally effective in sealing the tunnel up to the roof, so a secondary grouting system would need to be devised.
- Because of the dimensions of the project and the problems of grout setting, the system would be designed to operate continuously once work started until completion.

The key to success on the project was the selection of a grout with parameters that would fit the situation as well as the design of a placement system that could reliably place a large amount of grout over a period of a few days. Grout for an application like this had never been designed and it was necessary to go back to the laboratory to search out the ideal combination. Since the grout had to be mixed and pumped from shore and, based on the placement work plan, the initial grout would have to pass through almost 1600 m (5000 ft) of pipe to the point of placement and would have to flow back through the tunnel, displacing water, for a distance of at least 300 m (1000 ft) over a period of 30 hours or more before it would set too much to pump. The volumes were considerable. It would take approximately 4500 cubic meters (6000 cubic yards) of grout to fill the tunnel, so more than 1000 cubic meters (1300 cubic yards) would have to be placed before it would start to set. Based on these requirements, as well as regulatory requirements for the completed grout fill, parameters for the grout design were set as follows:

- Unconfined strength at 28 days in the range of 100 to 200 kPa (15-30 psi).
- Heavier and more viscous than water so that water would be displaced out of the tunnel as the grout was placed.
- The grout should be immiscible in water, so that it would form a face displacing the water, rather than a semi-mixed zone of water and grout.
- The grout should have an extended set time, 24 hours or more, to allow significant volumes of grout to be placed from a single point.
- The mixed grout had to have low viscosity, preferably less than 60 seconds Marsh Funnel to allow it to be placed through small diameter pipes over long distances without significant head losses.
- The permeability of the hardened grout had to be no higher than 1 x 10^{-6} cm/sec.

Laboratory Testing Program

Based on a review of the literature and previous experience, three basic types of grouts were selected for consideration in the laboratory testing program. The grout mixtures tested were divided into three groups labeled as Portland Cement-Bentonite with admixtures (CB); cement-bentonite with Blast Furnace Slag Cement and admixtures (BFSB); and Portland Cement-Fly ash with and without foam and other admixtures (CF). A variety of additives designed to improve grout workability were tested, including: super plasticizer, anti-wash, pre-formed foam, and lignosulfonate.

A total of 19 grout mixtures were formulated and tested. Seven grouts were CB, eight were BFSB, and four CF mixes. The proportions (all expressed as a percent by weight of water) and ingredients of six representative mixtures are provided in Table 1.

Table 1: Example Grout Proportions and Ingredients

	Grout Type & Mix Number					
Ingredients (% Wt of Water)	CF-4A	CF-4G	CB-5A	CB-5B	BFSB-(	BFSB-6D
Portland Cement	15	52	19	19	5.5	5.5
BFS	0	0	0	0	16.5	16.5
Fly Ash	35	115	0	0	0	0
Bentonite	5.5	0	5.5	4.5	4.0	4.5
Foam	0	2.5	0	0	0	0
Anti-Wash	0.14	0.26	0	0.13	0.13	0
Super plasticizer	0.06	0.11	0	0	0	0
Lignosulfonate	0	0	0.10	0.13	0	0.06

The grout mixtures were first subjected to a series of tests including: viscosity, density, set time, bleed, shrinkage, unconfined compressive strength, and permeability. The results of the tests on the six representative grout mixtures are provided in Table 2.

Table 2: Grout Properties

	Grout Type & Mix Number					
Property	CF-4A	CF-4G	CB-5A	CB-5B	BFSB-6A	BFSB-6D
Viscosity (MF sec.)	33	>90	49	60	55	43
Density (gm/cc)	1.27	1.22	1.14	1.14	1.15	1.15
Set Time (days)	5	1	3	3	5	6
Bleed (ml/1000 ml)	77	0	<5	0	<5	0
Shrinkage (%)	19.5	7	4.4	1.3	1.2	1.3
UCS – 7 day (kPa)	59	959	69	83	276	48
UCS – 28 day (kPa)	290	1884	159	179	1049	662
Permeability (cm/sec)	NR	4 E-7	5 E-7	5 E-7	8 E-8	6 E-8

With respect to viscosity, all of the grout mixtures were workable or could be made workable using additives. The set times of the CB and BFSB mixtures were acceptable, but some of the CF grouts set too quickly for the placement conditions (e.g. CF-4G) and BFSB grouts that did not include some Portland Cement did not set at all. The most significant finding was the variability in the bleed and shrinkage of some of the grouts. While the CB and BFSB had minimal shrinkage, the CF grouts performed poorly. No additive provided significant improvement in the bleed, so the CF mixtures were deleted from the program. While the strength and permeability of the CB and BFSB grouts were both acceptable, the BFSB grout had better properties. (See Figure 1 below)

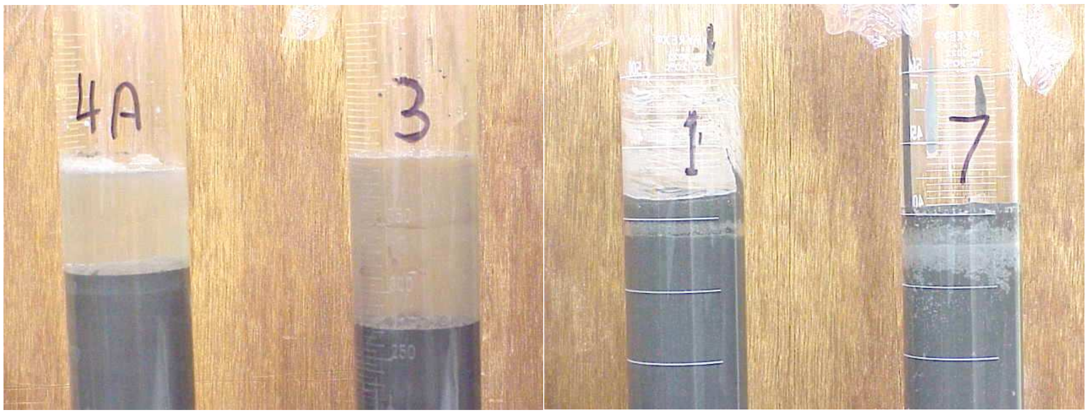


Figure 1. CF samples on left show significant bleed. CF Samples on right with foam show significant shrinkage.

Three kinds of tests were performed to check the compatibility of the grout mixes still under consideration with site leachate, specifically DNAPL (dense non-aqueous phase liquid) and APL (aqueous phase liquid). In the first test, the fluid grout is poured into pans full of leachate and of water (for comparison). The grout is tested with a modified set test apparatus (ASTM C-403) as it hardens and a comparison is made between the times for the grout to set in leachate compared to times to set in water. The results showed no effect due to the leachate.

The hardened grout was subjected to an immersion test (ASTM C-267) designed to predict the long-term performance of cement products exposed to chemicals. The test is performed by soaking cured grout specimens in sealed jars filled with leachate and tap water (for comparison) for up to 45 days. No effect due to the leachate was observed

A limited number of mixtures that had been permeated with water were retained for continued permeation with DNAPL and APL. With the DNAPL, the material apparently creates a coating that stops all flow within a few days. These tests were started after the permeability tests with water were completed. The results of the tests are shown in Table 3.

Table 3: Permeability of Grout Mixtures to Leachate

	Grout Type & Number			
Mix Number	CB-5A	CB-5B	BFSB-6A	BFSB-6D
Water Permeability (cm/sec)	5.8 E-7	1.9 E-6	8.1 E-8	6.2 E-8
APL Permeability (cm/sec)	3.9 E-7	1.3 E-6	1.69 E-8	3.8 E-8
Pore Volumes APL	1.6	1.3	0.18	0.12
Time of APL permeation (days)	13	14	19	6
DNAPL Permeability (cm/sec)	Stop	3.0 E-8	1.75 E-8	Stop
Pore Volumes DNAPL		0.025	0.015	
Time of DNAPL perm (days)		26	2	

The final grout mix was then selected based on the testing to date. It actually was a slight variation on mix BFSB-6D shown in this paper. It had minimal bleed and shrinkage, so it would maintain good contact with the top of the tunnel and all of the other properties met the requirements of the project. The final mix design was 4% bentonite and 22% cement by weight of water. The cement was a pre-blended combination of 75% Blast Furnace Slag Cement and 25% Portland Cement.

Model Testing Program

The final step in the testing program was model testing. The model tests were devised to investigate the potential behavior of the grout as it was placed underwater, in a long tunnel.

The first test was a simple tremie test with the grout placed through a tube into a container full of water. The grout should not mix with the water and the bleed of the grout should still be acceptable as it set underwater. The selected grout passed this test with no problem. Even when it was placed in a manner so that it dropped through the water, the grout bulb remained intact until it rejoined the grout at the bottom of the container with essentially no mixing with the water. Subsequent bleed during the setting process was no more than it had been in the earlier testing.

Figure 2. Model test of grout placement in a tunnel full of water

The second bench-scale test was devised to model the horizontal displacement of the water in the tunnel as the grout is placed. The setup was a half-pipe full of water with a grout tube inserted at one end. A long slope of grout pushing the water forward was expected. As the photo in Figure 2 shows, there was actually a surprisingly steep face of grout (1:5 vertical : horizontal) that formed. Again, there was essentially no mixing of the leading edge of the grout with the water.

Field Implementation

An unusual feature of this project was the available time to plan and think through each step in the operation. This planning was critical to the success of the project because a failure at a critical stage in the preparations or operation could leave the tunnel blocked with no way to restart the work.

The first step was to prepare the tunnels by inserting the grout pipes. The difficulty here was, as stated earlier, that the tunnel had to remain flooded and was only accessible to divers for a short distance. The shore shaft was a 2-meter diameter riser pipe 25 meters deep. At the bottom there was an immediate transition into the horizontal tunnel that generally was about 1.5 meters wide and 2 meters high, lined with concrete. The only other access was on a small concrete platform out in the river, 1600 meters (one mile) away, where there was a 2.5-meter diameter riser shaft.

Fabricated rollers were installed at the base of the access shafts to allow pipes and cables to be pulled through without damage. This was accomplished using divers. Next a small remote-operated vehicle went through the tunnel carrying a small diameter cable. This cable was used to pull through a larger cable that was about 3200 meters (10,000 ft) long. This cable was wound onto cable drive pipe pullers at both end of the tunnel so that it could travel back and forth through the tunnel, dragging in the many components of the grouting system. Considerable attention was paid to the details of cable connections to avoid the possibility of snagging on a previously placed component.

Figure 3. Pipe puller and shaft at the shore end of the project

The first part of the grout placement system to be installed was the secondary grout line. Since the most likely place for voids to form would be above the grout as it settled, this line had to be at the top of the tunnel. It consisted of a 75mm (3 inch) diameter HDPE pipe with rubber sleeve valves placed over holes drilled in the pipe on approximate 15-meter (50 foot) centers. The pipe was dragged through then evacuated by blowing the water out of the line with compressed air to a sump pump at the opposite end, forcing the line to float to the top of the tunnel.

The cable was then rewound on the pipe puller at the shore and attached to the first and longest primary grout pipe that was then dragged through using the river-end pipe puller. This pipe reached all the way to the base of the river shaft and succeeding pipes were each about 300 m (1000 ft) shorter than the last. A total of five primary grout pipes would be placed, ranging in diameter from 150mm (6-inch) to 100mm (4-inch). To speed placement of the pipes, they were prefabricated into sections of approximately 150 meters (500 feet). Each pipe had a conical tip designed to keep out sediment as the pipe was dragged into the tunnel yet that would open when grout pressure was applied. An emergency sleeve valve was mounted a short distance back from the tip designed to provide an outlet in the event the tip was blocked.

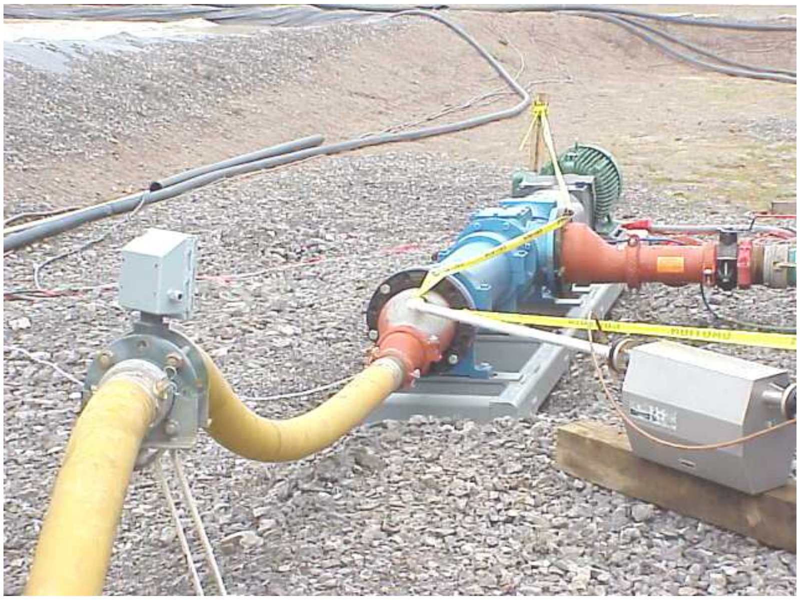
Once the pipes were all placed, it was time to block the river shaft so that grout would be forced back towards the shore once pumping started. This was accomplished by placing a steel “stool” in the shaft, sealing around the edges and pouring tremie concrete on top of the structure to seal the shaft. After this was done, the only grout pipe left accessible from both ends was the secondary grout pipe.

Figure 4. Placing the steel “stool” in the river shaft in preparation for the tremie seal

The tunnel was now ready for the grouting operation to begin. To simplify the mixing process, all the bentonite slurry needed was premixed and stored in large ponds on the site. Cement and blast furnace slag cement were delivered to the site pre-blended, so only one dry component would have to be mixed, allowing for easier quality control and a faster placement rate.

The one-component mixing system was crucial to the project design since it would allow for a continuous as opposed to a batch mixing system. The mix plant consisted of a 4.5 cubic meter (6 cubic yard) capacity colloidal enclosed mixer fed by a variable flow liquid system and a variable speed dry material feed system. The level in the mixer was controlled by a sonar device; feed rates of the materials were adjusted based on real time continuous density measurements provided by a highly accurate coriolis density meter. Slurry was pumped in a rate sufficient to keep the level in the mixer constant as the material was pumped out and the rate of feed for the cement blend was controlled based on density.

Figure 5. Grout mixing plant



Figures 6. Pumping unit with density meter to the right and flow meter to the left.

This highly productive mix plant was designed to produce grout at a rate of more than 750 cubic meters (1000 cubic yards) in a 24-hour period. After some test runs where grout was mixed and pumped into a pit on site, the work was finally ready to begin.

There were a few moments that pushed the system to its limits. The grout could barely be pumped the long distance out to the end of the first pipe. Once it began to consistently flow, water started to rise in the shore shaft. Work continued on a 24 hour a day basis until completion. Problems arose during the first run when a violent nighttime thunderstorm forced a cessation of operations and the pipe was lost before the grout reached the next pipe end. Work continued from the second pipe but it was known that there might be a gap at this location. Grouting through the succeeding pipes went according to plan. At one location, there was a breakout of grout into the riverbed through an old shaft that was supposed to have been sealed. The grout came up the shore shaft on schedule.

Once the primary grout had been allowed to set, the secondary grout program began. The secondary grout pipe was pressurized, allowing the seals to pop open in any locations where there might be a weakness and theoretically no grout. After a period of time, the secondary line was flushed out by pumping water through it and the secondary grout allowed to set before starting another phase of secondary grouting. By the end of this process, grout was coming out of the ground at various locations, so it appeared that the tunnel was tightly sealed.

Field Verification

Throughout the grouting operation, samples of the grout mixture were collected for strength and permeability testing. The results, Shown in Figures 7 and 8, show that the quality of the grout consistently met the project objectives of greater than 100 kPa unconfined strength and less than 1 x 10^{-6} cm/sec permeability after 28 days of cure.

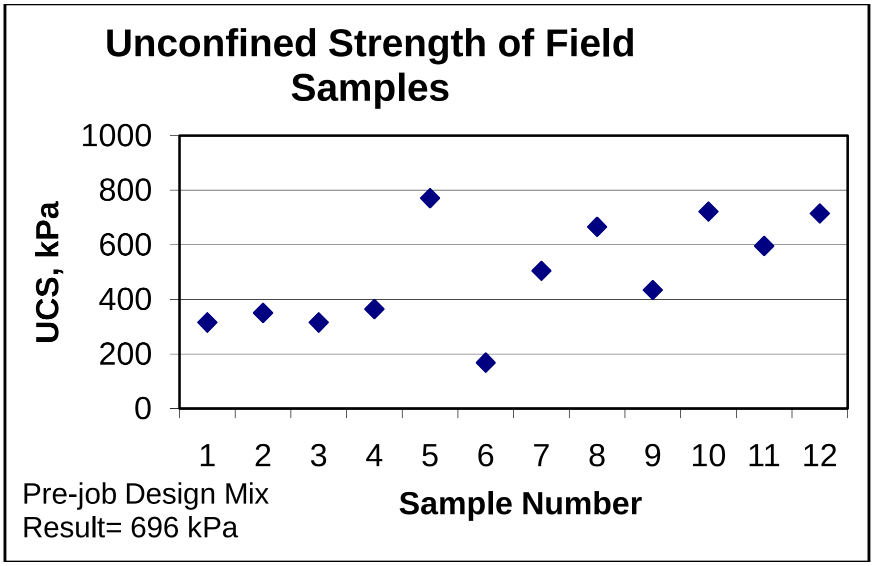


Figure 7. Unconfined strength of samples taken during the work

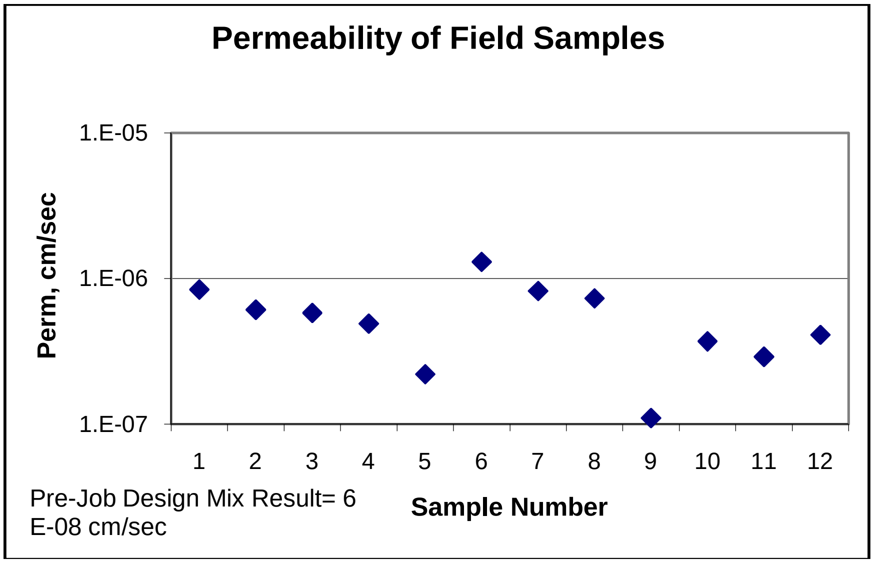


Figure 8. Permeability of samples taken during the work

An additional quality control requirement of this project was confirmatory drilling after placement and curing of the grout to visually confirm the effectiveness of the fill and to check for the presence of any voids above the grout. Because of problems that arose during the grouting, there were two locations in which grout was introduced into the tunnel from a tremie pipe that was in front of the grout face. This created the potential for a gap caused by hydraulically confined water. Three borings were advanced into the tunnel – one from land where the tunnel passed under an island and two from a barge in the river.

Locating the tunnel required great care, as none of the original construction plans were available. The drilling coordinates were calculated from known locations of the tunnel shafts. At each location, a well casing was carefully set vertically to the top of bedrock and a “Full-Hole” outer tube core barrel system was used to ensure a vertical hole through the bedrock down to the 25-meter depth of the tunnel. To check for the presence of a void in the grout at the top of the tunnel, caution was used at the appropriate depth and the drilling operation was videotaped to capture the drop of the drill stem if it were to occur.

The boring on land intercepted the tunnel on the second attempt and confirmed the presence of one of the suspected gaps (caused by the stoppage of grouting during the lightning storm). When the tunnel was penetrated, air erupted from the borehole and the drill bit dropped 2 meters to the tunnel bottom. A relief hole was bored into the gap some distance away so that additional grouting could fill the gap.

For the work in the 10-kph (6 mph) current of the river, the drilling rig was placed on a barge equipped with a 0.6-meter (2-ft) diameter hole for the drill bits. The hole was positioned directly over the calculated drilling coordinates using global positioning.

When the barge was close, one spud of the barge was sunk into the riverbed while a tug was used to rotate the barge to achieve the final location. Both of the borings in the river confirmed a complete fill with competent grout. The core in the upper part of Figure 9 (encased in a Lexan® sleeve) shows the integrity of the grout; in color, the grout is the green-black color that is typical of BFSB-based grouts. The cores in the lower part of the figure are samples of the concrete tunnel wall and the bedrock.

Figure 9. Confirmatory drilling core showing, from the top, grout from the tunnel, the concrete tunnel floor and bedrock.

Conclusions

The key to this project was finding a grout mixture that would meet the requirements of viscosity and set time to allow placement over the distances and time periods required as well as meeting the physical strength and permeability requirements set forth by regulatory agencies. The additional requirements of immiscibility with water and low decantation soon focused our search on combinations of blast furnace slag cements and Portland cement.

Blast Furnace slag cements need a percentage of Portland cement to perform at all in this application. Without it, they do not set. With a proper mix ratio, the grout will have a low viscosity, low bleed, low shrinkage and will form a grout of low strength (100-600 kPa) and low permeability (less than 1×10^{-6} cm/sec).

This project clearly tested the limits of the current knowledge of grout mix design as well as the technology of grout mixing and pumping. The project parameters and the design requirements made the job one of the most challenging imaginable. The combination of a far-sighted owner and a competent contractor to do the design, testing, and construction supervision made the project a success.