Closure of an Underground Tunnel with Long-Distance Grouting

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ABSTRACT: A former water intake tunnel extending under the Niagara River was contaminated with DNAPLs and was closed at the request of regulatory authorities. The six-foot tunnel is nearly a mile long and accessible from just two 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. An extensive laboratory testing program was implemented to design the grout for compatibility with DNAPLs, low permeability, strength, flow, and set properties. In the fall of 2000, the tunnel was filled with over 7500 cy of grout in five days, using multiple and redundant grouting pipes while pumping from a stationary grout plant on the shore of the river. The primary filling operation was followed by secondary pressure grouting. Closure of the tunnel required underwater divers, remote-operated robots, and barge operations, as well as a state-of-the-art grout mixing and pumping plant. Field observations, sample testing, and continued monitoring indicate that the closure was successful. This paper presents a brief overview of the laboratory testing and construction phases of the project. A future paper is planned to present a more complete discussion of the project including monitoring results.

THE TUNNEL: The tunnel begins at the site of a former municipal water treatment facility located adjacent to a chemical landfill in Niagara Falls, NY. The tunnel extends from the south shore of the Niagara River to a vertical intake shaft in the river near the Canadian border. The concrete-lined tunnel is generally in good structural condition but full of water with occasional/suspected pockets of DNAPLs. The original tunnel was constructed in 1937 and is 5 ft wide; a 1955 extension of the tunnel is 6 ft wide, both sections having a semi-circular roof. On the shore, the tunnel is accessed through an 8-ft diameter concrete shaft that is 60 ft deep. The intake shaft in the river is 10 ft in diameter and rises above the river, forming a 30 ft by 50 ft platform. Both of the shafts, as well as the entire mile-long tunnel, had to be filled and closed. The size and length of the tunnel make it a difficult and dangerous place for divers to work. In fact, no one had been all the way through the tunnel since construction. Leakage into the tunnel and the cost of wastewater treatment, made it impractical to consider dewatering to gain access into the tunnel.

GROUT DEVELOPMENT: The special demands of the remediation imposed extraordinary requirements on the grout materials for filling the tunnel. The grout design criteria included the following: a UCS (unconfined compressive strength) in the range of 15 to 300 psi; a density sufficient to ensure displacement of the water; minimal bleed and shrinkage; immiscibility in water; a set time of 1 to 10 days; and a viscosity less than 50 cP. In addition, regulatory agencies required that the grout demonstrate compatibility with concentrated DNAPLs in both fluid and hardened states; and a permeability of less than 1×10^{-6} cm/sec.

Data on grout mixtures for this type of application were not found in the literature. Therefore, the laboratory testing began with three types of mixtures: cement-bentonite (CB), cement-fly ash (CF) and combinations including blast furnace slag cement with cement and bentonite (BFSB). In addition, various admixtures were tested.

A total of 19 different mixtures was tested. The testing quickly focused on CB and BFSB. The CF mixtures had higher strengths (UCS about 100 psi in 7 days), but bleed, even with foam and other special admixtures, that was typically more than 10%. The other mixtures exhibited lower strengths (UCS about 10 psi in 7 days), but a more acceptable bleeding in the range of 1 to 5%. When grouting, mixtures with excessive bleed could be expected to trap excess water above the mass of the grout, thereby compromising the tunnel closure. The cause of the excess bleed in the CF mixtures was probably the high carbon content of the available fly ash. A number of sources of blast furnace slag were investigated. It was found that the slag hardened only when a portion of Portland cement was added to the mixture. A higher strength was available with the BFSB mixtures, typically about 100 versus 25 psi for the CB mixtures at 28 days. The BFSB mixtures have permeabilities of 0.6 to 2 x 10^{-7} cm/sec, whereas the CB mixtures have permeabilities in the range of 0.2 to 2 x 10^{-6} cm/sec.

Some innovative features of the laboratory testing included modeling of the grout placement and development of a method for testing the compatibility of the grouts with a concentrated leachate (APL and DNAPL). Model tests were devised to show the conditions of grout placement by tremie and pumping in a horizontal tunnel. The grouts formed a competent face underwater without mixing with tunnel water and an angle of repose of about 5:1 (horizontal to vertical). Compatibility of the grouts was evaluated by immersion of the hardened grout in leachate and by performing set-time tests with the fluid grout immersed in leachate. Either a lack of hardening or a longer-term degradation of the hardened grout could make the tunnel closure unsuccessful. The leachate did not delay the set of the grout compared to the same set time when the fluid grout was immersed in water. Hardened grout cubes immersed in leachate did not change in weight or dimensions nor were they otherwise physically attacked by the leachate. Flexible wall permeability tests on grout samples permeated with DNAPL for up to 30 days and 1.5 one pore volumes tended to slowly decrease in permeability with no indications of degradation. APL would not flow through the grout at gradients less than 30. A summary of typical laboratory grout properties is given below. All ratios shown are dry weight of materials divided by the weight of water.

	C/W	BFS/W	B/W	28 day UCS (psi)	Density (pcf)	Viscosity (cP)	SetTime (days)	Bleed (%)	Perm. (cm/sec)
CB grout	0.19	0.0	0.055	25	71.9	< 35	2-10	2	6 x10^{-7}
BSFB grout	0.05	0.165	0.04	100	72.2	< 30	6-10	5.5	1 x10^{-7}

Based on the laboratory testing, two mixtures were chosen for implementation. The primary grout was a mixture of blast furnace slag, Portland cement, and bentonite clay in water. The secondary grout mixture included Portland cement and bentonite clay in water. The solids content of the BFSB grout was slightly higher and the viscosity was slightly lower, even without an admixture. The material costs of the two mixtures were similar, but the added transportation costs of BSFS made it more expensive.

CONSTRUCTION: The work began with an inspection of the tunnel using a remote-operated, submarine robot. A torpedo-like device was later used to draw a cable through the tunnel to permit the grout pipes to be pulled through the tunnel by a large cable-pulling device stationed on the river shaft platform. Each component of the grout system was engineered to provide adequate capacity to fill the tunnel in three to four days of continuous pumping. In preparation for the grouting, five primary pipes (4 to 6 inch diameter) were pulled into the tunnel, each 1000 feet shorter than the last. A secondary grout pipe (3-inch diameter) with rubber sleeve-valves installed at 50-foot intervals was also pulled into the tunnel and floated to the top using air. If there were voids left after the primary grouting, the secondary line would be pressurized with grout and the sleeve-valves would open and allow the voids to be filled. The last item of the tunnel preparation was to seal the river shaft with a tremie concrete plug. The pumping of the grout would start at this farthest point, at the shaft in the river, forcing the water in the tunnel back toward the shore for removal and treatment.

The grout was mixed in a high-capacity mixing and pumping plant. First, the bentonite slurry was mixed and stored in several large ponds. Then the slurry was pumped back through the plant and the blended cement/blast furnace slag was added. The mix ratio was controlled by continuous, precise measurements of the output density of the resultant grout. The grout was placed in a round-the-clock operation at rates of up to 400 gpm.

There were two intermediate observation points available to view the progress of the grouting, and the grout arrived at these points on schedule. As it turned out, it was necessary to switch the pumping to the shorter pipes as the grout arrived at those points. Pushing the grout back 1000 feet in the tunnel required pressures up to 200 psi.

Once the primary grouting was complete, the secondary grout line was pressurized and grouted. About 10% of the total grout volume was placed through the secondary grout pipe. During this stage of the work there were a couple of instances of the grout becoming visible in the river bottom and emerging at other sealed locations, so there is a high degree of confidence that the tunnel is completely filled and sealed.

Twelve samples of the grout were obtained during primary grouting, cured 28 days and tested for strength and permeability. The average UCS and permeability were 70 psi and 5.6×10^{-7} cm/sec. Borings were drilled into the tunnel after the work to verify that the tunnel was full. Data from this phase of the project will be presented in a future paper.

CONCLUSION: This project was a landmark in a number of respects: the distance that the grout was pumped, the volume that was placed and a number of the methods that were used to prepare the job site in advance of the grout placement. Of critical importance however, was the pre-job laboratory testing program that determined a feasible combination of materials while at the same time giving the owner and the regulators confidence that the required design parameters could be met. The mixes developed for this project will have wide application on other sites where large volumes must be filled with inexpensive and stable grouts.