

Restoring the Century-Old Wachusett Aqueduct

by Ray Town

Every day, residents of Eastern Massachusetts quench their thirsts, bathe, flush toilets, do the dishes, and water their lawns with water drawn from the Massachusetts Water Resources Authority (MWRA) water system. Thanks to the Quabbin and Wachusett Watersheds and Reservoirs, 2.2 million people and 5500 industrial users have one of the most abundant and high-quality water supplies in the world.

The Wachusett system was constructed in 1897 to originally service the 29 municipalities within the 10 mile radius of the State House. At the time, the Wachusett Reservoir was the largest public water supply reservoir in the world. The Wachusett Aqueduct extends from the Wachusett Reservoir in Clinton, through Berlin to Northborough, MA. This 9 mile-long water system consists of 2 miles of hard rock tunnel and 7 miles of 11 ft-high horseshoe-shaped underground aqueduct constructed of nonreinforced concrete with a brick-lined invert.

From its completion in 1903 until the early 1960s, the Wachusett Aqueduct was the primary water transmission system from the Wachusett Reservoir to the City of Boston and surrounding communities. As Boston's water demand steadily increased, a new system called the Cosgrove Tunnel was developed in the 1960s to provide increased capacity. The Cosgrove Tunnel is a deep rock tunnel running roughly parallel to and deeper than the Wachusett Aqueduct. Since its completion, the Cosgrove Tunnel has essentially replaced the Wachusett Aqueduct as the main delivery system of Boston's water supply.

Today, a 10-year improvement program, initiated by MWRA with a series of projects to protect watersheds and build new water treatment and transmission facilities, is nearly complete. The Wachusett Watershed is just one

important component of MWRA's Integrated Water Supply System.

Construction on another, major component—the \$360 million Walnut Hill Water Treatment Plant Project—was started in 1999. This state-of-the-art plant, located at the terminal/initial end of both the Wachusett Aqueduct and the Cosgrove Tunnel, was developed to ensure that drinking water complies with the Federal Safe Drinking Water Act. In addition, the 18.6 mi MetroWest deep rock tunnel was constructed to transport water from Walnut Hill to the Boston water distribution system at Weston.

In preparation for construction of the Walnut Hill facility in the Spring of 2001, United Gunitex Construction Company, Inc., was awarded the contract to perform a \$21.4 million project to rehabilitate the Wachusett Aqueduct. This project was one of seven contract components of the MWRA Integrated Water Supply System Improvement Program.

Renovation of the aqueduct was necessary because the Cosgrove Tunnel was scheduled to be taken off-line while a connection was made between the newly completed MetroWest Tunnel and the Cosgrove Tunnel. During this time, the newly renovated Wachusett Aqueduct would again become the main transmission system for Boston's water supply. At the completion of this Metro West-Cosgrove connection, the Wachusett Aqueduct would also become the backup system for the new water supply.

The Restoration Challenge

The century-old Wachusett Aqueduct was originally designed and constructed as a gravity-fed conduit that emptied into an open system of surface aqueducts flowing to Boston. For the MWRA to take the Cosgrove Tunnel off-line and divert the flow through the Wachusett Aqueduct, the aqueduct required restoration to accommodate the increased flow requirement and resulting pressurization, a factor that was not considered in the original design.

The Restoration Process

The restoration project primarily consisted of applying a 3 in.-thick wire-reinforced wet-mix shotcrete lining to the entire surface of the 7 mi underground horseshoe-shaped concrete and brick portion of the aqueduct, incorporating over 15,000 yd³



Fig. 1: MWRA integrated water system

of shotcrete. The shotcrete lining was designed to strengthen the aqueduct and provide a smooth tunnel surface to accommodate the increased flows and the resulting pressurization, as well as to eliminate external water infiltration.

In addition to the shotcrete lining, rehabilitation included pressure-grouting for infiltration control, cleaning of the 2 mi rock tunnel portion, pressure-washing of the entire aqueduct, restoration of several granite block lined culverts running under the aqueduct, and removing sediment from a siphon crossing under the Assabet River.

Precise Specifications

Shotcrete tolerances specified for this project were extremely precise. The shotcrete finish was specified as: “the shotcrete surface shall meet or exceed the smoothness of a formed cast-in-place concrete surface obtained by using forms made from new and unused Plyform....” In addition, the variation in surface height required was “-0.0 to +0.25 in. at 2 ft in any direction.” The thickness tolerances were specified as “not less than 3 inches nor more than 3.5 in., with not less than 1.5 in. clear cover over the reinforcing mesh and not less than 1.5 in. of shotcrete between the mesh and the existing aqueduct surface.” In addition, the average bond strength of the shotcrete to the substrate and the minimum required 28-day compressive strength were required to be 150 and 4500 psi, respectively. As described later, a quality control program including extensive testing was developed and implemented to ensure specifications were met.

Two shotcrete mixture proportions were used for this project. The base mixture proportion incorporated 3/8 in. top-size aggregate, used for bringing the shotcrete beyond the mesh. The final or finish pass mixture proportion was similar to the base mixture but it did not include coarse aggregate. The lack of coarse aggregate helped achieve the precise finishing requirements needed to facilitate laminar flow of the water through the aqueduct. Maximum water-cement ratios (w/c) were 0.40 for the base mixture and 0.42 for the finish mixture. The cement used was Type I-II at 846 lb/yd³. A plasticizer, Master Builders Polyheed SG, was used to achieve the required w/c as well as act as a pumping aid. Air entrainment was specified to be between 3.5 to 5.0%. Specified slump measured at delivery to the pump was 1 to 4 in.

Galvanized welded wire fabric, 2 x 2-W0.9 x W0.9, was used throughout the entire project. The wire fabric was galvanized after welding for even greater corrosion protection. Specially fabricated 0.25 in. round anchor bolts with a 90-degree bend, 4 in.-long shank, and 2 in.-long horizontal leg, were used to support the mesh. While the specifications allowed for anchor bolts to be 3 ft on center, a spacing of 2 ft on center was used to create enough

Table 1: Wachusett System summary

Source	Elevation/Yield	Transmission Means	Storage Destination	Water Mains
Wachusett Reservoir	395 ft/118 mgd	Wachusett Aqueduct	Weston Reservoir	Weston Aqueduct Supply Mains
	65 billion gallons			



Fig. 2: Lighting installation



Fig. 3: Exterior view of aqueduct crossing stream culvert

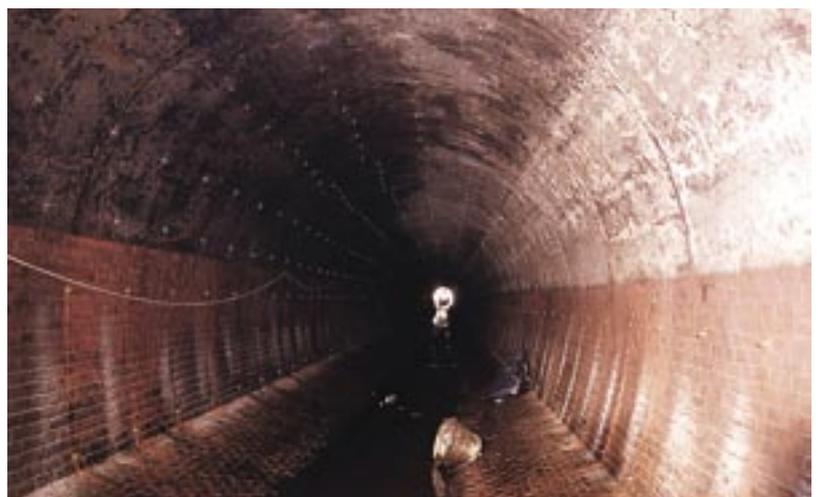


Fig. 4: Tunnel with wall and crown anchor bolts installed



Fig. 5: Finished tunnel

stiffness to ensure the mesh did not deflect from the impact of shotcrete placement. To ensure thickness and finish tolerances, guide wires and thickness pins were used throughout the entire 7 mi of tunnel, invert, walls, and crown.

Quality Control

The general contractor was primarily responsible for overseeing quality control (QC) of the Wachusett Project. This responsibility included development of a quality plan that provided oversight, inspection, and audit rights for the construction manager as well as the owner. The plan also required the contractor to appoint a full-time QC manager as well as a QC staff to implement the program. In addition, a full-time inspector from Corrosion Probe, Inc., the structural shotcrete lining designer, was on-site to review the inspection process.

The QC plan was divided into three phases: preparation, shotcrete placement, and inspection and testing of the in-place shotcrete. QC of the preparation included visual examination and surface pH testing of the hydroblasted surface. Anchor bolt placement was inspected for proper spacing and depth. As the wire mesh was installed, it was checked for proper overlap and distance from the surface as well as tautness. Guide wires and thickness pins were also checked for correct installation.

Quality assurance of the shotcrete placement phase began with preconstruction testing of the proposed mixture proportion. Nozzleman qualification was achieved as each nozzleman shot panels with the specified reinforcement installed in vertical and overhead positioned panels. Cores from each panel were graded as outlined in ACI 506.2. Throughout the project, shotcrete placements were monitored for proper shooting technique.

Testing of the in-place shotcrete began with checking surface tolerances. A 2 ft straightedge was used to check surface variation using a 0.25 in. shim slid under the straightedge. Any areas showing greater than 0.25 in. were marked, and the high spots were later ground to proper tolerance.

One set of three cores was taken from the in-place shotcrete within every 500 linear ft of tunnel. Coring was done through the shotcrete and into the substrate and extracted as specified in Canadian Standards Association A23.26B (“Direct Tensile Bond Pull-Off Test”). In addition to bond strength, the cores were evaluated for core grading as per ACI 506.2, shotcrete thickness, and mesh placement.

The final testing of the in-place shotcrete involved sounding of the entire tunnel, invert walls, and crown. The walls and crown were sounded by hammer. The hammer sounding of the crown and wall was a simple but very tedious endeavor. One crew, working on ladders, sounded the crown while another crew, while walking, sounded the wall from the invert to where the crown crew finished. The invert was sounded using a chain drag.

Testing Reveals Positive Results

A flow test of the aqueduct was done at the completion of the project. The test was used to determine if the capacity would meet the increased water demand, which was primary goal of the project. Testing revealed the restored aqueduct successfully handled increased flow capacity. A final walk-through inspection was conducted to determine if the increased flow had caused any structural damage, and only one very small leak was discovered, repaired, and approved in less than 1 hour. The century-old tunnel was rehabilitated and brought back to life, operating in a better capacity than originally designed.

Historical information about the Wachusett Watershed was provided by the Massachusetts Water Resources Authority.



Ray Town is a project manager at Pressure Concrete Inc., a leading provider of gunite, shotcrete, and pressure grout services. His career experience includes over 10 years in shotcrete

construction and contracting and 12 years with Master Builders, Inc., where he was a sales representative in the Underground and Shotcrete Division for 6 years. Town served as the Contractor Quality Control Manager for the Wachusett Aqueduct Project and has been involved with several major shotcrete tunnel rehabilitation projects, including the 4-mi North Metro Interceptor Project. Town is presently serving as project manager on a cobblestone and brick lined 15 ft-diameter tunnel being relined with shotcrete.