Structural Modifications to Hydroelectric Turbine Draft Tube Ceiling

Using Accelerated Wet-Mix Steel Fiber-Reinforced Shotcrete Applied Up to 2 m Thick Overhead

By Shaun M. Radomski, Dudley R. (Rusty) Morgan, Lihe (John) Zhang, and David Graham

The U.S. Army Corps of Engineers (USACE) is engaged in structural modifications to the reinforced concrete draft tube exits from the turbines in the Ice Harbor Lock and Dam located on the Snake River near Burbank, WA. These structural modifications, along with new advanced technology hydroelectric-generating turbines, are intended to improve hydraulic conditions for fish passage, as well as provide improved electrical generating efficiency. As part of this reshaping of the draft tubes, there was a need to apply an accelerated wet-mix shotcrete, with 100 lb/yd^3 (59 kg/m^3) of steel fiber, up to 6.5 ft (2 m) thick overhead. Overhead application of shotcrete to such thickness is seldom done and posed a challenge for the designer and contractor. This article describes the measures taken to develop a suitable shotcrete mixture design, consistent concrete supply, and proper application procedures to successfully meet this challenge. The draft tube modification design and a rigorous set of project specifications were prepared by the USACE. The specification required the construction and testing of large mockups with dimensions of 7.9 x 5.9 ft (2.4 x 1.8 m) and varied in thickness from 3.9 to 6.2 ft (1.2 to 1.9 m). One mockup panel was required for each nozzleman proposed to shoot on the job to prequalify the mixture designs, nozzlemen skills, and construction procedures. This paper describes construction and testing of both the mockups and the actual work.

Fig. 1: Shaft for Turbine Unit No. 2

The structural modification to the draft tube was completed using wet-mix shotcrete, except for the final finish shotcrete layer, which used dry-mix shotcrete. Quality control testing, including compressive strength of cores and bond strength to the prepared concrete substrate and between layers of shotcrete, demonstrated that the completed work satisfied the project specification requirements.

PROJECT BACKGROUND

Ice Harbor Lock and Dam was constructed in 1956 and is located along the Snake River near the confluence with the Columbia River, approximately 12 miles (19 km) east of Pasco, WA. The dam is a concrete gravity run of the river dam operated by the USACE and provides electrical power through six turbines for electrical distribution through the Bonneville Power Administration in the state of Washington.

Accelerated silica-fume-modified wet-mix shotcrete with 100 lb/yd^3 (59 kg/m^3) of steel fibers was applied overhead up to 6.5 ft thick as part of a structural modification made to a draft tube ceiling downstream of Turbine Unit No. 2. This shotcrete application posed challenges for the contractor performing the work. Rigorous shotcrete specifications were developed by USACE for this work. This article details:

- Development of the shotcrete mixture designs;
- Optimizing accelerator dosage for this application;
- Shotcrete application procedures developed during the preconstruction mockups;
- Equipment setup;
- Construction sequencing and challenges to overcome while shooting the draft tube; and
- Quality control test data.

Applying shotcrete up to 6.5 ft thick overhead is challenging and seldom done. Because of proper attention to the materials, equipment, and shotcrete placement, the work

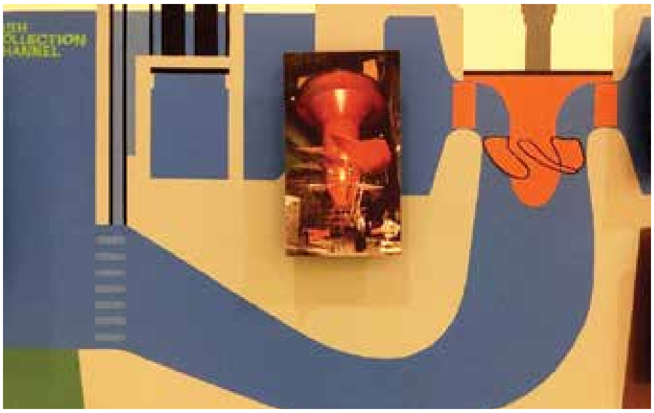


Fig. 2: Illustration of draft tube

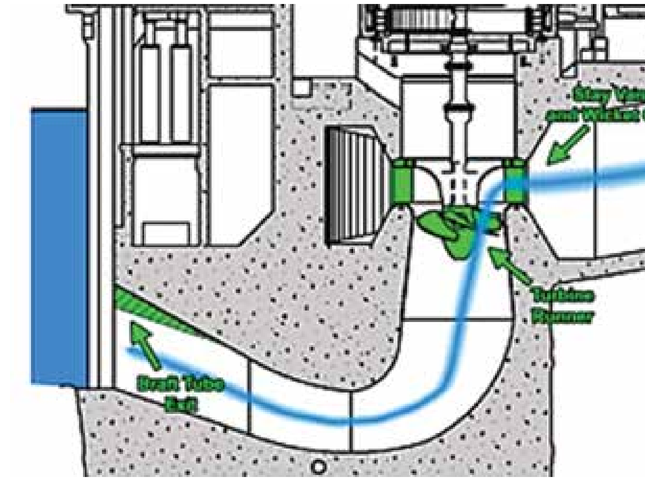


Fig. 3: Illustration of draft tube modification

was completed successfully and fully satisfied the project requirements. The USACE approved the work following the final inspection.

DRAFT TUBE

The draft tube is 100 ft (30.5 m) below the surface, based on measuring the distance between the draft tube floor at the downstream exit door and the tailrace deck located at the surface. The draft tube is 91.5 ft (27.9 m) long and is split into two sections (Barrels A and C) by a concrete pier nose. Barrel A and Barrel C are each 34.1 ft (10.4 m) wide at the stop logs (furthest downstream). The structural modification was completed to the ceiling from the location of the draft tube exit doors and upstream to approximately 36.7 ft (11.2 m) away from the exit doors. Figure 2 shows a cross-sectional model of the draft tube and Fig. 3 shows a cross-sectional illustration of the draft tube modification.

DESIGN

The USACE designed structural modifications to the turbine draft tube to improve hydraulic conditions for fish passage and electrical power-generating efficiency. This required the ceiling at the draft tube (furthest downstream) to drop by approximately 6.5 ft, while maintaining an overall slope of 22 degrees in Barrel A and 23 degrees in Barrel C until the shotcrete terminated at a 2.5 in. (65 mm) cut notch, which was to be built out flush with the existing ceiling. The design included the drilling of 1 in. (25 mm) diameter (Type 1) and 1/2 in. (13 mm) diameter (Type 2) anchors into the existing ceiling concrete and installing No. 5 reinforcing steel positioned 2.5 in. from the concrete substrate and No. 9 reinforcing steel positioned approximately 4 in. (100 mm) from the final finished shotcrete surface. Figure 4 shows a reflective ceiling plan for structural design details for the shotcrete modification. Figure 5 shows a sectional view of reinforced shotcrete modifications to the draft tube.

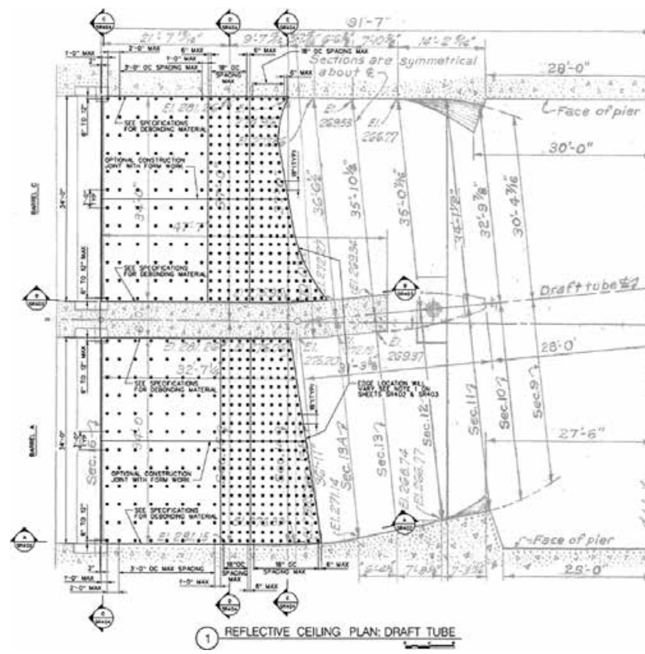


Fig. 4: Reflective ceiling plan for reinforced shotcrete modifications to draft tube

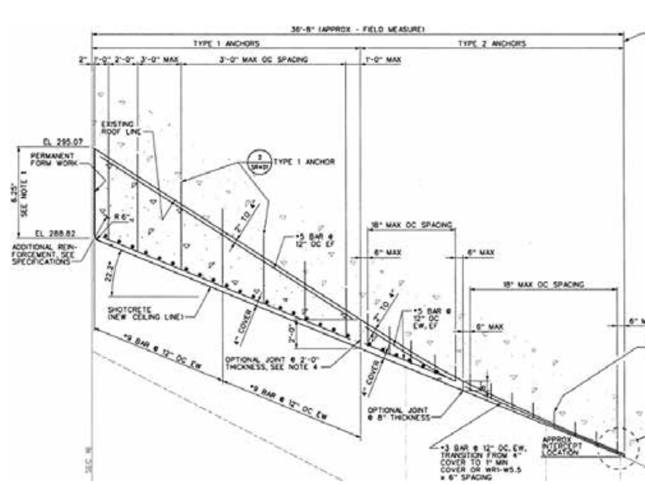


Fig. 5: Sectional view of reinforced shotcrete modifications to draft tube

SHOTCRETE SPECIFICATIONS

Performance-Based Specification

The USACE required the contractor to assume all responsibilities for the shotcrete mixture design and application and meet the following performance requirements:

- A minimum specified shotcrete compressive strength of 5000 psi (35 MPa) at 28 days and a minimum bond strength to the prepared concrete substrate of 100 psi (0.7 MPa);
- Demonstrate that the specification requirements could be achieved by constructing large full-scale mockups 7.9 x 5.9 ft and varying in thickness from 3.9 to 6.2 ft, one for each nozzleman proposed to shoot on the job; and
- Prequalify the mixture designs, accelerator dosage, nozzleman technique, and shooting procedures (Fig. 6 through 9) with mockups. Two different sets of three mockups were constructed using two different brands of accelerators to optimize accelerator type and addition rate for the job.

Fig. 6: Start of preconstruction mockup construction

Fig. 7: Nozzleman building out shotcrete to cover reinforcing bar and around anchor rods of preconstruction mockup

Fig. 8: View of preconstruction mockup after completion of installation of wood forms

Shotcrete Mixture Design

The Shotcrete Consultant, Wood Environment & Infrastructure Solutions, provided the Shotcrete Contractor, PCiRoads, LLC, with a steel fiber-reinforced wet-mix shotcrete mixture design using local aggregates. The mixture was proportioned with the following materials and designed to meet the following materials and plastic shotcrete properties:

- Local aggregates with 3/8 in. (10 mm) maximum size meeting the ACI 506 Grading No. 2 requirements;
- Steel fiber 100 lb/yd^3 or 0.75% by volume;
- ASTM Type I normal portland cement;
- 8.3% fly ash by mass of cementing material;
- 9% silica fume by mass of cementing material;
- 7 to 9 in. (180 to 230 mm) slump at discharge into the shotcrete pump;
- 7 to 10% plastic air content at discharge into the shotcrete pump; and
- 2 to 5% air content as-shot.

The shotcrete supplier hauled the shotcrete loads in transit mixers approximately 45 to 60 minutes from the batch plant to the jobsite. With additional staging and offload time, this required the use of a hydration control admixture to delay the onset of hydration and extend the working life of the shotcrete. A rapid-set accelerator was added at the nozzle to "wake up" the shotcrete from the effects of the hydration control admixture so that the shotcrete would nearly instantly set upon impacting the overhead receiving surface. After 180 minutes from addition of water to the transit mixers, the slump consistency in the shotcrete loads was found to be maintained at close to the initial slump tested upon arrival at the jobsite.

Preconstruction Mockups

Full-scale mockups were constructed for each nozzleman as part of the prequalification process using the reinforcing details specified for the work (Fig. 6 through 9). An initial set of three mockups was shot using one brand of an alkali-free shotcrete accelerator added at the nozzle. It was found necessary to build the shotcrete up in no more than 4 in. thick layers, with the shotcrete being allowed to achieve initial set before shooting the next layer to prevent shotcrete delamination and fallout. The initial alkali-free accelerator used had to be added at an additional rate of 8% by mass of cement to achieve an initial set time of 13 minutes and final set time of 46 minutes as measured by the ASTM C403/C403M penetration resistance test. There was, however, a concern that this rate of setting would slow down productivity excessively. Also, this high accelerator addition rate resulted in a considerable compressive strength reduction compared to shotcrete without accelerator, or a lower (6%) accelerator addition rate. Consequently, a second set of three mockups was constructed, using a different brand of alkali-free accelerator. This second accelerator, when added at 6% by mass of cement, achieved an initial set time of 8 minutes and final set time of 32 minutes, which was considered to be satisfactory for productivity purposes.

Fig. 9: Nozzleman shooting final lift of full-scale mockup

Fig. 10: Diamond wire-cut section of full-scale mockup showing excellent shotcrete consolidation around reinforcing bar and saw-cut prisms for bond testing

Also, the shotcrete readily satisfied the USACE specification requirements for a minimum compressive strength of 5000 psi at 28 days and minimum bond strength between shotcrete layers of 100 psi at 7 days. Following visual examination of reinforcement encasement across diamond wire saw-cut cross sections of the mockups (Fig. 10), the shotcrete used in the second set of mockups was approved for reprofiling of the draft tubes.

Accelerator Dosing Pump Calibration

One of the most critical aspects of the fiber-reinforced wet-mix shotcrete overhead application was obtaining an adequate dispersion of alkali-free accelerator in the shotcrete stream at the nozzle and introducing the correct amount of accelerator so that the shotcrete mixture would rapidly stiffen as it impacted the overhead receiving surface without any sloughing or fallouts, while maintaining adequate compressive strength and overall quality of the hardened shotcrete. This was achieved by pumping the mixture at a slump ranging between 8 and 9 in. (200 and 230 mm) (Fig. 11) and performing a calibration of the peristaltic accelerator dosing pump using the proposed construction setup prior to overhead application, so that an accurate accelerator addition rate would be provided during shooting of the draft tubes at specific dial settings on the dosing pump.

The calibration process included having a nozzleman shotcrete into a 4 ft^3 (0.11 m^3) box. Accelerator consumption was measured to verify the accelerator addition rate as a percent by mass of cement at different dial settings on the accelerator dosing pump. Initially, flow rates were measured at various dial settings on the accelerator dosing pump and accelerator consumption was recorded in L/minute. Based on the known portland cement content in the shotcrete mixture and the specific gravities of the cement and accelerator, a desired accelerator addition rate was calculated. Measuring just the flow rates at different dial settings alone, however, did not provide an accurate accelerator addition rate (as a percent by mass of cement) due to back pressures from the airflow in the nozzle impacting the accelerator injection into the shotcrete stream. The accelerator dosing pump dial had to be set at a suitable pump motor speed (rpm) to overcome this back pressure, but without overdosing the accelerator amount entering the shotcrete stream.

Fig. 11: Slump of approximately 9 in. confirmed based on testing in accordance with ASTM C143/C143M

The calibration procedure was completed by the contractor prior to shooting the mockups and the production on-site. The time measured to completely fill the 4 ft^3 box and the volume of accelerator pumped from sufficiently sized measuring flasks was recorded. The calibration procedure included testing for the initial and final set times (Fig. 12) and early-age compressive strengths measured at 2, 4, 6, 8, and 24 hours (Fig. 13) to confirm the addition of the appropriate amount of accelerator necessary to shoot the draft tube ceiling safely.

Fig. 12: Determination of initial and final set based on testing in accordance with ASTM C403/C403M

Fig. 13: Determination of early-age compressive strength based on testing in accordance with ASTM C116

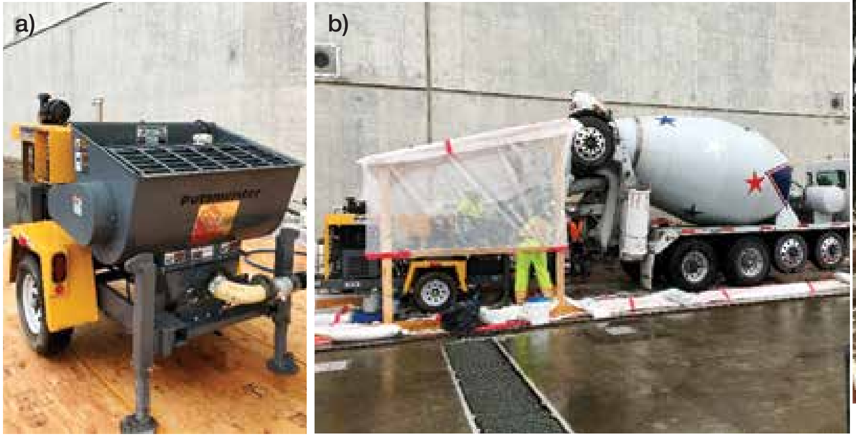


Fig. 14(a) and (b): Shotcrete pump and supply setup outside powerhouse

CONSTRUCTION

Equipment and Crew

Shotcrete equipment included a Putzmeister TK20 Shotcrete pump (Fig. 14), a 325 ft^3/minute (9200 L/minute) air compressor, 3 in. (75 mm) steel slick lines, and 2 in. (50 mm) rubber hoses. Three nozzlemen and eight laborers made up the crew. Shotcrete was pumped into a long 3 in. diameter steel line which fed shotcrete into the power house, down a 50 to 75 ft (15 to 23 m) vertical shaft to a narrow corridor leading to an egress to access a 50 ft high scaffold stairway down to the bottom of the draft tube (Fig. 15 and 16). The steel line contained several turns and 90-degree elbows to reach the bottom of the draft tube from the power house. The steel line transitioned into a 2 in. rubber hose at the shotcrete work area. Approximately 200 ft (60 m) of slickline

Fig. 15: Steel line entering draft tube from powerhouse

Fig. 16: Steel line entering shotcrete application area inside draft tube

Fig. 17: Nozzleman shooting overhead on scaffold platform in crouching position maintaining adequate shooting angle and distance to receiving surface and building out shotcrete to shooting wires

Fig. 18: ICRI CSP7 surface roughness profile

and rubber hoses were used to feed the shotcrete to the nozzlemen in the draft tube. The shotcrete work area had several levels of scaffold decks supported on a sloped floor (Fig. 17). The scaffold decks were adjusted up or down so that the nozzlemen could apply shotcrete overhead while shooting in an upright position where possible. Nozzlemen found that shooting in a crouching position was necessary at some locations to enable an adequate shooting angle during application to the sloped ceiling (Fig. 17).

Scaffold Setup

Several scaffold platforms were set up consecutively and in a stepped pattern to complete the overhead shotcrete application. Each platform was positioned at an elevation dictated by the slope angle of the existing concrete ceiling and required adjusting following installation of anchors, reinforcing bar, and the thickness of daily shotcrete application. Scaffold platform elevations were adjusted as necessary so that nozzlemen could shoot in a position that enabled satisfactory shooting techniques.

Concrete Surface Preparation

The existing concrete ceiling surfaces of the draft tubes located in Barrels A and C were generally found to be in good condition based on visual inspection of the concrete surfaces. Abrasive blasting using silica glass provided an ICRI CSP 7 surface roughness profile (Fig. 18). Visual inspection and hammer sounding techniques were completed by Wood Environment & Infrastructure Solutions to ensure a sound and clean surface was provided. Surfaces were brought to a saturated surface-dry (SSD) condition prior to shotcrete application.

Reinforcing Steel and Anchors

The reinforcing steel was inspected for size, spacing, and rigidity prior to shotcrete application. Positioning of anchors into the concrete ceiling required some offsetting to avoid existing reinforcing bar following ground-penetrating radar scanning. Anchor Types 1 and 2 were required to be drilled at 3 ft (1 m)

Fig. 19: Concrete substrate, formwork, 1 in. anchors, and No. 5 reinforcing bars installed and ready for shotcrete application

Fig. 20: A 1 in. diameter anchor embedded in shotcrete and shooting wire positioned to show nozzleman how thick to build out next layer of shotcrete

Fig. 21: A 1/2 in. anchor embedded in shotcrete

on-center and 18 in. (460 mm) spacing, respectively. The drawings allowed for a tolerance of ±4 in. spacing for anchors. The No. 5 and No. 9 reinforcing steel bars were spaced at 12 in. (300 mm) each way. Refer to Fig. 19 through 23.

All reinforcing steel inspected generally satisfied the design requirements in the structural drawings and was secure for overhead shotcrete application. A compressed air blowpipe was used during shotcrete application to enable removal of overspray from the reinforcing bars adjacent to the shotcrete placement. In addition, the anchors were protected from overspray by plastic wrap.

Placement Sequence

The original draft tube concrete substrate and the most recently applied shotcrete layer were cleaned using a pressure washer and allowed to dry back to an SSD condition

Fig. 22: Number 9 reinforcing bars installed and ready for shotcrete application

Fig. 23: Nozzleman ready to begin shotcrete application to prepared concrete substrate

immediately prior to shotcrete application. A compressed air blowpipe was used to accelerate drying of the surfaces where necessary.

At the start of each day, initial and final set times were tested to confirm the accelerator addition rate was adequate for overhead shotcrete application. Beam molds were shot to provide specimens for testing early-age compressive strength at 2, 4, 6, 8, and 24 hours. A square test panel was shot to test for compressive strength at 7, 28, and 56 days, and boiled absorption and volume of permeable voids to ASTM C642.

Shotcrete nozzlemen began shooting the prepared concrete substrate behind the No. 5 reinforcing bar by "picture framing" the edge of the work. Nozzlemen would fill in behind the reinforcing bar and wrap the bars with shotcrete by manipulating the nozzle in a side-to-side motion, adjusting the angle of the nozzle so that shotcrete would wrap around the reinforcing bar adequately. After the edge of the work was shot, the nozzlemen would work inward from the edge, using the same sequencing as described previously.

Anchor rod extensions were installed and protected with plastic wrap and shotcrete was built out in maximum 4 in. layers beyond the No. 5 bars. Shooting wires installed at a 3 ft spacing provided guidance to the nozzlemen on how thick the work should be built out in a single pass. Nozzlemen generally shoot at 90 degrees to the receiving surface, manipulating the nozzle in a slight side-to-side movement and with a small circular motion to fully encapsulate reinforcing bar and anchors.

Nozzlemen were required to wait until the shotcrete had reached final set prior to shooting the next layer of shotcrete, as confirmed by testing for initial and final set times. Surfaces of shotcrete were also evaluated by touch prior to applying the next layer of shotcrete to confirm the set.

Number 9 bars were installed approximately 10 in. (250 mm) from the final finish surface.

A dry-mix shotcrete mixture with synthetic fibers (without accelerator) was used to shoot the final layers around the No. 9 bars instead of the accelerated steel fiber reinforced wet-mix shotcrete mixture. With the lower-volume output provided by the dry-mix shotcrete process, the nozzlemen were able to work carefully around the No. 9 bars and provide full encapsulation of this heavily congested reinforcing bar (Fig. 24).

Nozzlemen applied dry-mix shotcrete out to the final shooting wires to provide the 4 in. specified cover for the No. 9 reinforcing bar. The shotcrete was trimmed to the wires with a cutting screed, troweled, and sponge floated. The final finish was a sponge float finish and satisfied the specification surface tolerance requirements of 2 in. over a 10 ft (3 m) straight edge (Fig. 25).

Thickness Control

Piano wire installed at a 3 ft spacing was offset approximately 4 in. from the surface of the preceding layer of shotcrete to control line and grade.

Fig. 24: Nozzleman shooting dry-mix shotcrete at the No. 9 reinforcing bar

Fig. 25: Sponge float finish satisfying specification requirements for finishing tolerance

Curing

Sprinklers were set up on the scaffold deck to apply water to the surface to cure the freshly applied shotcrete overnight. High humidity in the work area and no sun or wind exposure made the shotcrete curing conditions favorable.

CHALLENGES ENCOUNTERED

Due to using a different shotcrete setup than the one used during the initial calibration of the peristaltic accelerator dosing pump, accelerator consumption was measured daily from the accelerator tote to verify accelerator addition rates. The dial setting was adjusted based on observed flow rates at different dial settings, initial and final set times achieved at various dial settings, and the accelerator consumption measured daily at the selected dial setting used during production. This method was repeated on several occasions to confirm that a suitable addition rate of accelerator was being provided by the accelerator dosing pump so that shotcrete would stick overhead without sloughing or fallouts at the target maximum thickness of 4 in.

Balls or clumps of material were sometimes observed coming off the concrete truck delivery chute. These clumps occasionally plugged up the steel line at the reducer where the steel line transitions to a rubber hose. This issue was corrected by adjusting the silica fume and steel fiber material addition techniques at the batch plant.

Blockages in the shotcrete delivery lines sometimes occurred. A regular preventative maintenance routine of opening up the steel lines and rubber hoses at the connections and removing any buildup of mortar proved helpful in reducing line plugging.

Fallouts were occasionally observed when nozzlemen attempted to shoot at thicknesses greater than the target maximum 4 in. in a single layer. When fallouts occurred, the fallout area was prepared for reapplication with shotcrete by using a compressed air blowpipe to remove any loosely bonded shotcrete or carefully scraping any loose shotcrete around the perimeter of the fallout area with a steel trowel. Shotcrete was required to achieve initial set before reshooting in the fallout area.

Entry into the draft tube was designated as a confined space and this required all personnel who entered into the draft tube to follow USACE safety regulations for confined space entry. Lockouts and sign-in/sign-out reports were required to ensure that everyone inside the draft tube was accounted for.

QUALITY CONTROL

Preconstruction Testing

Two different alkali-free accelerator brands were investigated during the preconstruction mockup trials. Initial and final set times, early-age compressive strength, and compressive strength at 7, 28, and 56 days were evaluated using each brand of accelerator and at several dosages measured in percent by mass of cement: 0, 4, 6, and 8%.

Evaluation of the initial and final set times and compressive strength testing of cores from test panels was completed on every load of shotcrete used to construct the mockups. Compressive strength of shotcrete cores without any accelerator addition was found to be significantly higher than in shotcrete with accelerator. The lowest compressive strength was found to occur in shotcrete with 8% accelerator.

Production Testing

Tests were conducted to record the ambient temperature, shotcrete temperature, as-batched and as-shot air contents, and initial and final set times. End beam tests were carried out to determine early-age compressive strength development.

The contractor shot one production test panel for every 50 yd^3 (38 m^3) of shotcrete placed, or one per day, whichever occurred more frequently. Cores were extracted from these test panels to determine:

- Compressive strength at 7, 28, and 56 days; and
- Boiled absorption and volume of permeable voids to ASTM C642 at 28 days.

The contractor performed bond pulloff testing to determine the shotcrete bond strength to the prepared concrete substrate. Bond strength testing was conducted after the shotcrete shot on the original prepared concrete substrate had cured for a minimum of 7 days. Bond strength tests were also performed to measure bond between shotcrete layers.

COMPRESSIVE STRENGTH TEST RESULTS

Wet-Mix Shotcrete

Compressive strength tested at 7 days ranged between 4470 psi and 6220 psi (30.8 and 42.9 MPa), and averaged 5180 psi (35.7 MPa) in Barrel A. Compressive strength tested at 28 days ranged between 7240 and 9500 psi (49.9 and 65.5 MPa), and averaged 8150 psi (56.2 MPa) in Barrel A. Refer to Table 1.

Table 1: Compressive Strength of Shotcrete Cores

Turbine Unit No. 2 Barrel A					
Compressive strength, MPa					
			Age, Days		
	Panel No.	Date shot	7	28	56
Wet-mix	1	24-Mar-17	33.0	58.4	64.2
	2	24-Mar-17	35.0	53.1	59.2
	3	24-Mar-17	31.9	50.2	58.9
	4	27-Mar-17	32.2	49.9	54.8
	5	29-Mar-17	34.1	57.2	62.9
	6	31-Mar-17	37.0	56.2	61.1
	7	24-Mar-17	39.7	60.6	60.4
	8	4-Apr-17	42.9	65.5	67.9
	9	6-Apr-17	33.8	55.9	55.6
	10	7-Apr-17	30.8	54.5	58.9
	11	10-Apr-17	41.4	61.2	65.2
	12	11-Apr-17	37.4	56.1	59.7
	13	19-Apr-17	35.5	52.4	54.0
	Mean		35.7	56.2	60.2
	Standard deviation		3.7	4.5	4.1
	Specs		—	Min 34.5	—
Dry-mix	14	24-Apr-17	38.5	49.5	51.0
	15	25-Apr-17	39.8	52.4	54.3
	16	26-Apr-17	38.9	58.1	59.6
	17	27-Apr-17	38.1	51.4	56.8
	18	28-Apr-17	38.9	52.5	54.6
	19	29-Apr-17	38.6	52.4	54.7
	20	3-May-17	43.6	56.0	59.0
	21	5-May-17	39.4	47.9	50.2
	22	6-May-17	42.4	53.3	56.3
	23	13-May-17	61.0	64.1	67.1
	24	19-May-17	52.8	62.1	63.8
	25	20-May-17	53.9	62.3	64.5
	Mean		43.8	55.1	57.6
	Standard deviation		7.70	5.32	5.33
	Specs		—	Min 34.5	—

Turbine Unit No. 2 Barrel C					
Compressive strength, MPa					
			Age, Days		
	Panel No.	Date shot	7	28	56
Wet-mix	1	1-May-17	31.8	45.0	48.5
	2	2-May-17	23.3	43.8	47.9
	3	4-May-17	41.3	52.7	54.0
	4	8-May-17	39.4	54.5	57.3
	5	9-May-17	36.8	61.4	66.4
	6	10-May-17	34.9	56.4	58.9
	7	11-May-17	39.3	49.1	50.5
	8	11-May-17	34.8	50.8	51.9
	9	12-May-17	32.2	39.8	54.9
	10	15-May-17	32.0	36.0	52.9
	11	16-May-17	29.2	55.4	58.6
	12	17-May-17	44.9	55.7	65.3
	13	18-May-17	37.4	54.8	65.3
	Mean		35.2	50.4	56.3
	Standard deviation		5.6	7.3	6.2
	Specs		—	Min 34.5	—
Dry-mix	14	22-May-17	51.1	59.8	61.2
	15	23-May-17	44.3	66.1	69.8
	16	24-May-17	56.4	60.0	64.8
	17	25-May-17	51.5	59.6	68.7
	18	30-May-17	43.8	61.1	68.3
	19	31-May-17	41.7	60.6	61.5
	20	1-Jun-17	43.3	47.9	54.8
	21	2-Jun-17	38.1	52.4	64.6
	Mean		46.3	58.4	64.2
	Standard deviation		6.09	5.65	4.97
	Specs		—	Min 34.5	—

Note: 1 MPa = 145 psi

Compressive strength tested at 7 days ranged between 3380 and 6510 psi (23.3 and 44.9 MPa), and averaged 5110 psi (35.2 MPa) in Barrel C. Compressive strength tested at 28 days ranged between 5220 and 8910 psi (36 and 61.4 MPa), and averaged 7310 psi (50.4 MPa) in Barrel C. Refer to Table 1.

As shown in Table 1, the 28-day compressive strength test results well exceeded the specified minimum compressive strength requirement of 5000 psi at 28 days.

Dry-Mix Shotcrete

Compressive strength tested at 7 days ranged between 5530 and 8850 psi (38.1 and 61.0 MPa), and averaged 6250 psi (43.8 MPa) in Barrel A. Compressive strength tested at 28 days ranged between 6950 and 9300 psi (47.9 and 64.1 MPa), and averaged 7990 psi (55.1 MPa) in Barrel A. Refer to Table 1.

Compressive strength tested at 7 days ranged between 5530 and 8180 psi (38.1 and 56.4 MPa), and averaged 6720 psi (46.3 MPa) in Barrel C. Compressive strength tested at 28 days ranged between 6950 and 9590 psi (47.9 and 66.1 MPa), and averaged 8470 psi (58.4 MPa) in Barrel C. Refer to Table 1.

As shown in Table 1, the 28-day compressive strength test results well exceeded the specified minimum compressive strength requirement of 5000 psi at 28 days.

BOILED ABSORPTION AND VOLUME OF PERMEABLE VOIDS

Wet-Mix Shotcrete

Boiled absorption tested at 28 days ranged between 6.4 and 10.0%, and averaged 7.6% in Barrel A. Volume of permeable voids tested at 28 days ranged between 14.2 and 21.9%, and averaged 17.0% in Barrel A. Refer to Table 2.

Boiled absorption tested at 28 days ranged between 4.6 and 8.7%, and averaged 7.6% in Barrel C. Volume of permeable voids tested at 28 days ranged between 10.2 and 19.3%, and averaged 17.1% in Barrel C. Refer to Table 2.

Dry-Mix Shotcrete

Boiled absorption tested at 28 days ranged between 4.3 and 7.4%, and averaged 5.5% in Barrel A. Volume of permeable voids tested at 28 days ranged between 9.8 and 16.6%, and averaged 12.2% in Barrel A. Refer to Table 2.

Boiled absorption tested at 28 days ranged between 4.3 and 6.6%, and averaged 4.9% in Barrel C. Volume of permeable voids tested at 28 days ranged between 9.7 and 14.3%, and averaged 12.1% in Barrel C. Refer to Table 2.

While the USACE specification did not have a requirement to test the shotcrete to ASTM C642 for boiled absorption and

Table 2: ASTM C642 Boiled Absorption and Volume of Permeable Voids Data

Turbine Unit No. 2 Barrel A				
	Panel No.	Date shot	Boiled absorption, %	Volume permeable voids, %
Wet-mix	1	24-Mar-17	7.8	17.0
	2	24-Mar-17	8.6	19.0
	3	24-Mar-17	8.2	18.3
	4	27-Mar-17	6.9	15.5
	5	29-Mar-17	10.0	21.9
	6	31-Mar-17	7.9	17.9
	7	24-Mar-17	6.2	14.2
	8	4-Apr-17	7.2	16.3
	9	6-Apr-17	7.3	16.5
	10	7-Apr-17	7.4	16.7
	11	10-Apr-17	6.4	14.6
	12	11-Apr-17	6.9	15.6
	13	19-Apr-17	7.9	17.6
	Mean		7.6	17.0
	Standard deviation		1.0	2.0
	ACI 506		Max 9.0	Max 17.0
Dry-mix	14	24-Apr-17	5.4	11.9
	15	25-Apr-17	6.0	13.0
	16	26-Apr-17	4.7	10.6
	17	27-Apr-17	5.6	12.4
	18	28-Apr-17	6.3	13.7
	19	29-Apr-17	5.4	11.8
	20	3-May-17	4.9	11.0
	21	5-May-17	5.3	11.7
	22	6-May-17	7.4	16.6
	23	13-May-17	4.9	10.8
	24	19-May-17	4.3	9.8
	25	20-May-17	5.8	12.9
	Mean		5.5	12.2
	Standard deviation		0.81	1.79
	ACI 506		Max 9.0	Max 17.0

Turbine Unit No. 2 Barrel C				
	Panel No.	Date shot	Boiled absorption, %	Volume permeable voids, %
Wet-mix	1	1-May-17	7.0	15.6
	2	2-May-17	8.7	18.8
	3	4-May-17	4.6	10.2
	4	8-May-17	7.8	17.8
	5	9-May-17	7.2	16.6
	6	10-May-17	8.1	18.1
	7	11-May-17	8.1	18.3
	8	11-May-17	8.6	19.3
	9	12-May-17	8.3	18.5
	10	15-May-17	8.2	18.3
	11	16-May-17	7.8	17.4
	12	17-May-17	7.4	16.7
	13	18-May-17	7.5	17.1
	Mean		7.6	17.1
	Standard deviation		1.1	2.3
	ACI 506		Max 9.0	Max 17.0
Dry-mix	14	22-May-17	5.2	12.7
	15	23-May-17	5.0	12.6
	16	24-May-17	5.1	12.7
	17	25-May-17	4.8	11.7
	18	30-May-17	4.3	9.7
	19	31-May-17	6.6	14.3
	20	1-Jun-17	4.9	10.9
	21	2-Jun-17	5.7	12.6
	Mean		4.9	12.1
	Standard deviation		0.38	1.39
	ACI 506		Max 9.0	Max 17.0

volume of permeable voids, it has been found to be a useful test to evaluate the inherent durability of concrete and shotcrete.[1] ACI 506R-05 states that "Typical Boiled Absorption values are 6-9%." All the wet-mix shotcrete test results (with one exception) are within this range and test results for the nonaccelerated dry-mix shotcrete are even lower, as shown in Table 2.

BOND TESTING

Shotcrete bond strength to the prepared concrete substrate was tested after a minimum of 7 days in Barrel A. Bond strength tested at 9 days ranged between 129 and 174 psi (0.89 and 1.20 MPa), and averaged 152 psi (1.05 MPa) in Barrel A. Bond strength tested at 15 days ranged between 184 and 273 psi (1.27 and 1.88 MPa), and averaged 231 psi (1.59 MPa) in Barrel A.

Shotcrete bond strength to the prepared concrete substrate was tested after a minimum of 7 days in Barrel C. Bond strength tested at 9 days ranged between 151 and 244 psi (1.04 and 1.68 MPa), and averaged 194 psi (1.34 MPa) in Barrel C. Bond strength tested at 11 days ranged between 183 and 189 psi (1.26 and 1.30 MPa), and averaged 186 psi (1.28 MPa) in Barrel A.

As shown in Table 3, the bond strength test results exceeded the specified minimum shotcrete bond strength requirement of 100 psi.

CONCLUSIONS

This article demonstrates that a successful execution of such challenging projects requires a rigorous design specification and comprehensive preconstruction mockup construction which includes the prequalification of the:

a. Shotcrete mixture design;
b. Shotcrete accelerator brand and dispensing system and calibrate the accelerator addition rate;
c. Shotcrete nozzlemen, shotcrete application, and finishing system; and

Table 3: Bond Pull Off Testing Results

Turbine Unit No. 2 Barrel A		
Bond strength, MPa		
Test No.	Age, Days	
	9	15
1	1.20	—
2	0.89	—
3	—	1.88
4	—	1.69
5	—	1.27
6	—	1.52
Mean	1.05	1.59
Standard deviation	0.219	0.259
Specs	Min 0.7	
ACI 506	Min 1.0	

Turbine Unit No. 2 Barrel C		
Bond strength, MPa		
Test No.	Age, Days	
	9	11
1	1.47	—
2	1.68	—
3	1.04	—
4	1.18	—
5	—	1.30
6	—	1.26
Mean	1.34	1.28
Standard deviation	0.288	0.028
Specs	Min 0.7	
ACI 506	Min 1.0	

Note: 1 MPa = 145 psi

d. Shotcrete quality assurance monitoring, quality control inspection, and testing plan.

This project showcased that with proper materials, equipment, and placement techniques, a high-quality, accelerated, wet-mix, steel fiber-reinforced, silica fume shotcrete up to 6.5 ft thick overhead is achievable. The USACE approved the results of the mockup construction and authorized construction of the work in the draft tube.

There were logistical, access, and scaffolding challenges in the draft tube, but the shotcrete subcontractor successfully overcame these challenges and completed the reshaping of the draft tube to the satisfaction of the USACE. This is the first of three draft tubes to be reshaped on the Ice Harbour Lock and Dam and it is expected that the same products and processes will be used for reshaping the next two draft tubes.

References

1. Zhang, L.; Morgan, D.R.; and Mindess S., "Comparative Evaluation of the Transport Properties of Shotcrete Compared to Cast-in-Place Concrete," *ACI Materials Journal*, V. 113, No. 3, May-June 2016, 373-384 pp.

PROJECT TEAM FOR DESIGN AND CONSTRUCTION OF THE STRUCTURAL MODIFICATION OF THE DRAFT TUBE EXITS

Owner and Design Engineer
United States Army Corps of Engineers

General Contractor
Voith Hydro

Shotcrete Subcontractor
PCiRoads, LLC

Wet-Mix Shotcrete Supplier
American Rock Products

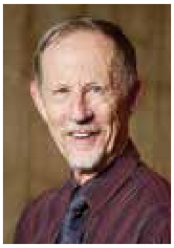
Steel Fiber Supplier
FRC Industries

Dry-Mix Shotcrete Supplier
TCC Materials

Steel Fiber-Reinforced Accelerated Wet-Mix Shotcrete Mixture Design Development, Technical Submittal Reviews, Inspection and Monitoring of the Shotcrete Preconstruction Mockups, and Shotcrete Application in the Draft Tube
Wood Environment & Infrastructure Solutions

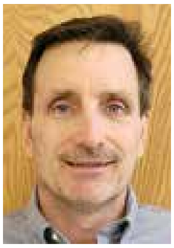
Accelerator Dosing Pump Calibration and Shotcrete Quality Testing for the Preconstruction Mockups and for the Draft Tube Application
LZhang Consulting and Testing

Shaun M. Radomski *is a Civil Materials Engineer specializing in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructure. He has 15 years of civil materials engineering and testing experience in Canada and the United States. Radomski received both his BEng and MSc in civil engineering from Ryerson University, Toronto, ON, Canada.*



Dudley R. (Rusty) Morgan*, FACI, is a Civil Engineer with over 50 years of experience in the concrete and shotcrete industries. He served as a member and Secretary of ACI Committee 506, Shotcreting, for over 25 years. He is a past member of ACI Committees 365, Service Life Prediction, and 544, Fiber-Reinforced Concrete. Morgan is a founding member and Past President of ASA. He is an ASA/ACI C660-approved Shotcrete Nozzleman Examiner. Morgan is a past member of the Canadian Standards Association Concrete Steering Committee and was a Canadian Representative on the International Tunneling and Underground Space Association Committee, Shotcrete Use. He has worked on over 1000 concrete and shotcrete projects around the world during his consulting career and has edited five books and published over 150 papers on various aspects of concrete and shotcrete technology. In 2001, Morgan was elected as a Fellow of the Canadian Academy of Engineering.*

Lihe (John) Zhang *is an Engineer and Owner of LZhang Consulting & Testing Ltd. He received his PhD in civil engineering from the University of British Columbia, Vancouver, BC, Canada, where he conducted research on fiber-reinforced concrete. He has over 15 years of experience in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructure. Zhang is a member of the American Concrete Institute. He is Chair of ACI Subcommittee 506-F, Shotcreting-Underground, and a member of ACI Committees 130, Sustainability of Concrete; 506, Shotcreting; and 544, Fiber-Reinforced Concrete. He is an ASA/ACI C660-approved Shotcrete Nozzleman Examiner. Zhang is a member of ASTM Committee C09, Concrete and Concrete Aggregates. With ASA, he serves as the 2018 ASA Past President, member of the Board of Direction, and Chair of the Technical Committee.*



David Graham*, Project Manager for PCiRoads, LLC, since 2007, is an ACI Certified Nozzleman for both dry- and wet-mix shotcrete. With over 30 years of experience in the shotcrete industry, he has managed numerous projects nationwide that include the use of shotcrete on buildings, bridges, tunnels, dams, silos, tanks, and soil stabilization.*