Shotcrete in Liquid-Containing Concrete Structures

By Charles S. Hanskat

Since its development nearly a century ago, shotcrete has been used for building concrete liquid-containing structures (LCS). An article by George D. Yoggy, "The History of Shotcrete, Part I,"[1] mentions that soon after the development of the cement gun in 1910, gunite was used in a variety of water/wastewater infrastructure applications including reservoirs, dams, sewer tunnels, and water tanks. Figure 1 shows typical tank construction with gunite in 1919 with a nozzleman shooting a sloped wall of a conical floor for a tank.

Today, shotcrete remains a vital part of construction of concrete LCS. The largest use of shotcrete in LCS today is in the construction of circular-wrapped prestressed concrete tanks. In 1942, J.M. Crom Sr. first wrapped high-strength wire in a continuous spiral on the exterior of cylindrical concrete tanks. The "wrapping" method tensioned the prestressing wire before it was placed on the wall, thus avoiding prestressing friction losses (refer to Fig. 2). After placement, the wrapped prestressed reinforcement is encased in shotcrete to provide fully bonded reinforcement, mechanical protection, and corrosion protection (refer to Fig. 3). More than 9000 wrapped prestressed tanks of various sizes and shapes have been constructed to date.

Though not common, some circular concrete tanks have been prestressed by the use of externally-positioned prestressing strands that are tensioned in-place on the wall. The prestressing tendons are then either left exposed on the wall or preferably encased with shotcrete for bonding and protection. This same approach is occasionally used for the repair of concrete tanks.

Fig. 1: Nozzleman applying gunite for a water storage facility in Pittsburgh, PA, 1919

Governing Codes and Standards

In the U.S., both the American Concrete Institute (ACI) and American Water Works Association (AWWA) have technical committees that develop and maintain codes and standards that cover design and construction with shotcrete specifically in LCS. These include:

- ACI 350, "Code Requirements for Environmental Engineering Concrete Structures and Commentary";

Fig. 2: Wrapping prestressing wire on circular prestressed tank
Photo courtesy of Preload Company

Fig. 3: Shotcreting of wrapped prestressing wires
Photo courtesy of Natgun Corporation

- ACI 372R, "Design and Construction of Circular Wire- and Strand-Wrapped Prestressed Concrete Structures";
- ACI 373R, "Design and Construction of Circular Prestressed Concrete Structures with Circumferential Tendons";
- AWWA D110, "Wire & Strand Wound, Circular, Prestressed Concrete Water Tanks"; and
- AWWA D115, "Tendon-Prestressed Concrete Water Tanks."

In general, these ACI and AWWA documents address the requirements for shotcrete materials, placing, cover, and allowable design stresses. The ACI 350 code and the two AWWA standards are mandatory language documents. ACI 372R and ACI 373R are nonmandatory reports that provide guidance for the designer and builder of LCS. Most of these ACI and AWWA documents also reference specific ACI 506 reports or specifications that are applicable to LCS. Both dry- and wet-mix shotcrete are covered.

AWWA documents cover only potable water tanks. ACI documents are more broad-based, covering all types of LCS. The ACI 350 code defines "environmental engineering concrete structures" as concrete structures intended for conveying, storing, or treating water, wastewater, or other liquids and nonhazardous materials such as solid waste, and for secondary containment of hazardous liquids or solid waste.

ACI Committee 350 is also nearing completion of a new construction specification for LCS. This new ACI 350 specification specifically addresses the requirements for the contractor building LCS and parallels ACI 301 for concrete building construction. This new ACI 350 specification specifically addresses the use of shotcrete in all types of LCS. Though intended for new construction, many of the provisions are applicable to the repair of concrete LCS.

Shotcrete in Circular-Wrapped Prestressed Tanks

There are five major builders of circular-wrapped prestressed tanks in the U.S. These companies are The Crom Corporation, DYK Incorporated, Natgun Corporation, Precon Corporation, and Preload Incorporated. Combined, they build several hundred wrapped prestressed concrete tanks each year. These tanks are predominately used in water treatment, water storage, wastewater collection, wastewater treatment, stormwater management, thermal energy storage, and industrial processes. Similar designs have also been used in construction of large liquefied natural gas (LNG) tanks, and in years past, some were used for the storage of low-level radioactive materials.

Some wrapped tank builders use shotcrete for the construction of the complete structural wall (Crom and Precon). Others build a composite wall with a combination of cast-in-place (DYK) or precast concrete (Natgun and Preload) in the structural core of the wall and then use shotcrete for encasing the wrapped prestressing. On large tanks, the cylindrical walls are often tapered, so they are thicker at the base than at the top of the wall. This is easily accomplished with shotcrete or precast, and provides maximum efficiency and economy of the concrete wall materials.

As large users of shotcrete equipment and materials, it is of interest to see how several of these companies produce shotcrete for their tanks. For this article, several of the tank builders were contacted to provide information on their shotcrete usage for tanks.

Crom Shotcrete Operations

The Crom Corporation places approximately 52,000 yd^3 (40,000 m^3) of shotcrete each year. The majority of Crom tanks use a tapered shotcrete wall for the structural core wall. The tanks are prestressed with a wrapped eight- or six-gauge prestressing wire. Crom requires all its nozzlemen to hold ACI Shotcrete Nozzlemen Certification. The majority of its shotcrete is placed using traditional shotcreting equipment as follows:

- Stationary concrete pumps capable of output of up to 50 yd^3 (38 m^3) per hour and maximum pressures of 1100 psi (7.6 MPa). These pumps are typically single-axle units and are sometimes pulled behind concrete trucks; however, increasingly, a central hub is used in the tank to deliver material while the pump remains stationary.
- Air compressors capable of over 600 ft^3/min (17 m^3/min) air output.

Material is delivered to the nozzle beginning with a 5 in. (130 mm) steel line off the back of the pump rock valve cylinder. Hoses are reduced quickly from steel to 3 in. (80 mm) reinforced rubber hose. The reduction of the hose diameter continues until the material reaches the 2 in. (50 mm) placement hose that the nozzleman typically controls. A rubber nozzle with a steel air ring body is located at the end of the hose to deliver uniform air pressure to the material to propel it onto the surface (refer to Fig. 4).

Shotcrete mixtures typically consist of 1:3 mixtures without coarse aggregate. Water cementitious material ratios (*w/cm*) are a maximum of 0.42 with slumps of 3 in. ± 1 in. (80 mm ± 25 mm). Mixtures are designed for a minimum 4000 psi (28 MPa) 28-day design strength; however, typical shotcrete mixtures contain 800 lb (360 kg) or greater of cementitious materials, so it is not uncommon to obtain compressive strengths that are much higher than the 4000 psi (28 MPa) design strength. It is also common to replace up

Fig. 4: Shooting core wall at the base of the tank
Photo courtesy of Crom Corporation

Fig. 5: Remotely controlled shotcrete nozzling of tank wall
Photo courtesy of Crom Corporation

to 20% of cement materials with fly ash. Typical air content is around 6% when tested at the point of discharge from the concrete truck.

In addition to traditional equipment, there is a small amount of shotcrete placed using more exotic equipment, including robotic equipment. This equipment is custom fabricated for tank construction and typically requires the use of more powerful concrete pumps and air compressors to achieve the high placement rate that is capable with this equipment (refer to Fig. 5).

Also, for more remote locations, a small amount of shotcrete is batched using on-site batching equipment. These small on-site batch plants with modified silos are capable of storing enough cement to shoot around 75 yd^3 (57 m^3) before it is necessary to recharge the silo. For more information on this type of tank, you can refer to an article in the ASA archives by Lars Balck.[2]

DYK Shotcrete Operations

The majority of DYK tanks use a cast-in-place concrete core wall built with traditional forming methods. DYK wraps a 3/8 in. (10 mm) diameter galvanized strand to prestress their tanks. Shotcrete is used for encasing and protecting the wrapped strands. DYK specifies a shotcrete using a one-part cement, three-part sand mixture for the full shotcrete thickness over the prestressing steel. Approximately 10,000 yd^3 (7650 m^3) of shotcrete are used annually.

To help control shrinkage, DYK uses polypropylene fibers in the shotcrete mixture. Polypropylene fibers help control cracking from shrinkage and thermal tensile stresses, and add to the toughness of the shotcrete. The fibers are manufactured in accordance with ASTM C1116. DYK uses 0.1% (1.5 lb/yd^3 [0.9 kg/m^3]) polypropylene fibers in each cubic yard of shotcrete material.

Wet-mix shotcrete is applied from a nozzle mounted on a mechanized tower that travels around the circular wall or dome ring at a controlled speed. DYK's equipment uses electro-servo travel speed controls to monitor the vertical nozzle travel. The remotely operated nozzle slowly moves around the tank circumference and up the wall in a uniform spiral path (refer to Fig. 6). To obtain a uniform cure and to help prevent shrinkage cracking, the full cover is built up in numerous layers approximately 3/8 in. (10 mm) thick.

DYK has also developed a machine application to encapsulate the shotcrete in plastic during the curing process (refer to Fig. 7). This innovation greatly improves the moisture retention of the shotcrete during its initial curing. An article on DYK's construction of a 35,000,000 gal. (130,000 m^3) tank can be found in the ASA archives.[3]

Natgun Shotcrete Operations

The majority of Natgun tanks use a precast concrete panel core wall. The tanks are prestressed with a wrapped eight- or six-gauge prestressing wire. Shotcrete is used for providing the final thickness of the core wall over the exterior of the precast panels, and for encasing and protecting the wrapped prestressing wires. Natgun currently uses wet-mix shotcrete on all new tank projects and restoration projects. In 2009, Natgun used a total shotcrete volume of 18,104 yd^3 (13,840 m^3). Prior to the late 1970s, the company used dry-mix shotcrete. All of Natgun's nozzlemen are trained and required to pass the ACI Shotcrete Nozzleman Certification Program.

Natgun has 19 diesel-powered hydraulic piston trailer concrete pumps. In general, these pumps have:

- 5 in. (130 mm) outlets;
- 5 to 6 in. (130 to 150 mm) material cylinders;

Fig. 6: Remotely operated nozzle on automated wrapping/shotcreting machine
Photo courtesy of DYK Incorporated

Fig. 8: Pump with multiple reducers
Photo courtesy of Natgun Corporation

Fig. 7: Plastic wrapping of shotcrete cover coat for curing
Photo courtesy of DYK Incorporated

Fig. 9: Shotcreting dome ring
Photo courtesy of Natgun Corporation

- 1300 to 1450 psi (9 to 10 MPa) maximum material pressure;
- Harsh or standard mixtures approximately 11 ft^3 (0.31 m^3) hoppers with remixers; and
- Maximum theoretical aggregate size is 1.5 in. (40 mm).

Natgun uses a 5 x 4 in. (130 x 100 mm) reducing elbow off the pump outlet, a straight 4 x 3 x 42 in. (100 x 80 x 1000 mm) reducer to a straight 3 x 2 x 42 in. (80 x 50 x 1000 mm) reducer and then to a 2 in. x 50 ft (50 mm x 15 m) high pressure hose, all with heavy-duty couplings (refer to Fig. 8). Typically, Natgun uses four to five lengths of hose for the average job. Smaller radius tanks will allow less hose and larger radius tanks may require multiple pump locations to shoot the exterior core wall, wire cover, and cover coat shotcrete. Natgun uses two styles of shotcrete nozzles. One employs a swivel air ring in the nozzle body assembly to prevent twisting and kinking of the air and material hose couplings. The other uses a fixed air ring in the nozzle body assembly. The rubber nozzle tips are 1 in. (25 mm) in diameter and fastened to the nozzle body with a conventional hose clamp (refer to Fig. 9).

Natgun's standard shotcrete mixes consist of:

- 1:3 shotcrete mixture—851 lb (386 kg) of cement and 2553 lb (1158 kg) of fine aggregate with air entrainment and water-reducing admixtures to obtain a maximum *w/cm* of 0.35 to 0.37 for a 3 to 4 in. (80 to 100 mm) slump at 6 to 8% air as delivered on site. This 1:3 cement-to-fine aggregate mixture is used primarily for the exterior core wall and prestress wire cover.
- 1:4 shotcrete mixture—665 lb (302 kg) of cement, 150 lb (68 kg) of Class F fly ash, and 2650 lb (1202 kg) of fine aggregate with air entrainment and water-reducing admixtures to obtain a maximum *w/cm* of 0.35 to 0.37 for a 3 to 4 in. (80 to 100 mm) slump at 6 to 8% air on site. This 1:4 cement-to-fine aggregate mixture is used primarily for cover coat and any other tank component or feature not in direct contact with prestressing wires such as pilasters and ladder

Fig. 10: Shotcreting final cover coat of a wrapped tank
Photo courtesy of Preload Incorporated

and antenna pads. To minimize plastic shrinkage, this mixture also incorporates 1.5 lb/yd^3 (0.9 kg/m^3) of 0.25 in. (6 mm) polypropylene fibers.

The gradation of the fine aggregate of these mixtures is critical to maintaining pumpability. Natgun works closely with the concrete supplier and local aggregate producers to obtain the desired gradation. It finds that when there is 18 to 28% of combined particles passing the No. 50 to 100 sieve, the pumpability of the shotcrete and grout mixtures is much better. When the local fine aggregates are too coarse or only manufactured or crushed sand is available, Natgun will occasionally increase the amount of fly ash in the mixture to a maximum of 25% of the total cementitious material to aid in pumpability.

Summary

Current codes and standards (ACI 350, ACI 372R, ACI 373R, AWWA D110, and AWWA D115) that cover concrete LCS have recognized the importance of shotcrete and directly address shotcrete in these documents. A new ACI 350 specification that includes shotcrete should be available later this year.

Currently, by far the most extensive use of shotcrete in LCS is in the construction of wrapped prestressed concrete tanks. The builders of wrapped prestressed concrete tanks in combined volume shoot well over 100,000 yd^3 (2831.7 m^3) of predominately wet-mix shotcrete annually (refer to Fig. 10). All of the tank builders are committed to using highly trained nozzlemen with ACI Shotcrete Nozzlemen certifications.

Shotcrete has a long, successful history in the construction of concrete LCS and is now approaching the century mark since its initial use for water and wastewater infrastructure. When properly used, quality shotcrete in both materials and placement has proven to equal or surpass the durability and serviceability of cast-in-place concrete LCS.

References

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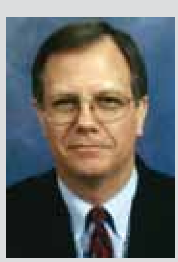

Charles S. Hanskat *is a Principal at Concrete Engineering Group, LLC, a firm he founded in 2008 located in Northbrook, IL. He received his bachelor's and master's degrees in civil engineering from the University of Florida. Hanskat is a licensed professional engineer in 22 states. He has been involved the design, construction, and evaluation of environmental concrete and shotcrete structures for nearly 35 years.*

Hanskat is an ASA Board member and Chair of the ASA Sustainability Committee. He is also a member of ACI Committees 301, Specifications for Concrete; 350, Environmental Engineering Concrete Structures; 371, Elevated Tanks with Concrete Pedestals; 372, Circular Concrete Structures Prestressed by Wrapping with Wire or Strand; 373, Circular Concrete Structures Prestressed with Circumferential Tendons; 376, Concrete Structures for Refrigerated Liquefied Gas Containment; 506, Shotcreting; and Joint ACI-ASCE Committee 334, Concrete Shell Design and Construction. He is a former member of the ACI Technical Activities Committee and the ACI Board of Directors.

Hanskat's service to the American Society of Civil Engineers (ASCE), the National Society of Professional Engineers (NSPE), and the Florida Engineering Society (FES) in over 50 committee and officer positions at the national, state, and local level was highlighted when he served as State President of FES and then as National Director of NSPE. He served as a District Director for Tau Beta Pi for 25 years from 1977 to 2002. He is a Fellow of ACI, ASCE, and FES, and a member of ASA, NSPE, ASTM, AWWA and ASHRAE.