SPRAYED-ON LINERS

Concrete Culvert Overview Flowchart
Structural Defects Flowchart (Concrete)
Bedding Deficiencies Flowchart (Concrete)
Hydraulic Capacity Flowchart (Concrete)

1. CEMENTITIOUS LINERS (SHOTCRETE)

1.1. OVERVIEW

Shotcreting is the method in which cement mortar or concrete is pneumatically applied (jetted at high velocity) onto the surface of the structure being repaired. Shotcreting can be classified as a wet-mix process (all the ingredients including the water are mixed prior to introduction into the delivery equipment) or a dry-mix process, also known as gunite (all ingredients except the water are mixed and fed into the delivery equipment, and the water is added at the nozzle) as shown in Figure 86 (Hilton, 1990). The choice between gunite and the wet-mix process depends on various factors, e.g., project size (quantity of shotcrete required), application rate required (cubic yards per hour or shift), dust (could be an issue in a confined space and less is produced by wet-mix shotcrete), rebound (wet-mix shotcrete generally generates less material bouncing off the shooting surface), and required pumping length (Sulman, 2009).

Wire mesh reinforced cement mortar lining involves application of two layers of cement-mortar that are separated by a wire mesh (Figure 88). The first layer of cement-mortar (0.5 in. thick) is applied to the inner wall of the host pipe in the conventional manner (i.e., using gunite). A wire mesh is placed against the first coat of lining using overlapping joints, and the second layer of cement-mortar (0.5 in. thick) is applied by trowel over the wire mesh (AWWA, 2001).

Figure 1. Gunite application (REED, 2009)

Figure 2. Gunite lining inside the pipe (Queensland Gunite, 2009)

Figure 3. Wire mesh installed in the pipe; guniting will follow the mesh level and trowelling will complete the liner above it (Queensland Gunite, 2009)

Cement mortar lining can also be installed by spincasting whereby the equipment traversing through the pipe (Figure 89) applies a continuous thin layer of cement mortar (thickness typically between 0.25 in. and 0.5 in., and up to 2 in. if multiple layers are used) onto the interior of a deteriorated culvert pipe (Figure 90). A high-speed rotating applicator device is used to provide a densely compacted liner of uniform thickness and thorough coverage of the pipe interior surface. In the same pass through the pipe, the sprayed layer can be trowelled by either rotating spatulas fitted to the spraying machine or a simple tubular shield pulled behind the spraying machine (ISTT, 1998). However, no additional trowelling or surfacing is necessary with some centrifugal casting systems (AP/M Permaform, 2009). In small diameter pipes, the equipment is remotely operated. For large diameter pipes, an operator of the machinery can enter the pipe and control the flow of mortar, speed of travel, and the speed of rotation for the lining machine head. An example of a large diameter lining machine is shown in Figure 91.

Figure 4. High-speed rotating applicator device for centrifugal casting of cement mortar inside the culvert (Henning, 2009)

Figure 5. A thin layer of cement mortar applied by spincasting onto the cleaned concrete culvert pipe (Henning, 2009)

Figure 6. Large diameter cement mortar lining machine (Proline Pipeline Protection, 2008)

1.2. MATERIALS USED (SHOTCRETE MORTARS AND CONCRETES)

Morgan et al. (1989) reviewed conventional and specialty shotcretes (steel fiber reinforced, polypropylene fiber reinforced, and wire mesh reinforced). ACI (1991) presented state of the art on fiber reinforced shotcrete. US Army Corps of Engineers (1993) provided guidance on the shotcrete selection and proportioning.

Conventional shotcrete concretes are made of Portland cement, aggregates and chemical admixtures. Gunite mixture is made from 1 part Portland cement and 4 parts sand (REED, 2009). Special concretes often employ admixtures (e.g., polymer modifiers) that inhibit corrosion and enhance chemical resistance. For producing a freeze-thaw durable shotcrete, aggregates susceptible to frost attack should not be used and the maximum size of the aggregate should be lowered to reduce susceptibility to freeze-thaw deterioration (Hilton, 1990).

US Army Corps of Engineers (1993) outlined benefits of adding fibers to the shotcrete mixture, i.e., the added ductility of the material (unreinforced shotcrete is a brittle material that experiences cracking and displacement when subjected to tensile stresses or strains), as well as added energy absorption capacity and impact resistance. Fibers used in shotcrete include steel fibers, glass fibers, and synthetic fibers.

Steel fiber reinforced shotcrete (SFRS) is a mortar or concrete containing discontinuous discrete steel fibers, which are pneumatically projected at high velocity onto a surface (Indian Concrete Journal, 2003). Typical fiber lengths for shotcrete range between 0.75 in. and 1.5 in., and the fibers are used in the amount of 2% by volume of shotcrete (US Army Corps of Engineers, 1993). Banthia et al. (1992) assessed the influence of fiber geometry in steel fiber reinforced dry-mix shotcrete on the rebound characteristics and hardened shotcrete properties. Properly designed, SFRS can reduce or even eliminate cracking, a common cause for concern in plain shotcrete (Indian Concrete Journal, 2003).

Glass fiber reinforced shotcrete (GFRS) is made by adding glass fibers to the cementitious mix to improve flexural, tensile and impact strength. Alkaline resistant glass fibers are used. For glass fiber reinforced concrete (GRFC) spray-up, the optimum fiber length is 1.5 in. to 2 in. The properties and proportional mixes are discussed in PCI (2001).

Girard (2006) provided an introduction to GFRS. The material is often used to make large, lightweight panels (considered lightweight because of the thinness of the material; GFRC concrete weighs on average about the same as ordinary concrete on a volume basis). When spray-applied, the fluid concrete mixture (minus fibers) is sprayed out of a gun-like nozzle that also chops and sprays a separate stream of long fibers. The concrete and fibers mix when they hit the form surface. Glass fiber is fed off of a spool in a continuous thread into the gun, where blades cut it just before it is sprayed. Chopped fiber lengths tend to be much longer (about 1.5 in.) than fibers that get mixed in, since long fibers would ball up if they were mixed into the concrete before spraying. Typically spray-up is applied in two layers. The first layer is the face coat, much like a gel-coat in fiberglass. This face coat usually has no fibers in it and is

thin, often only about 0.125 in. thick. The second, or backer layer, has the fiber in it. The action of spraying on the fibers results in random orientation, much like the layers in plywood. Spray-up permits very high fiber loading using very long fiber length. GFRC made using the spray-up method yields the greatest strength. However, the equipment required to do spray-up is expensive, often costing more than $20,000.

Polypropylene fiber-reinforced shotcrete (FRS) is made by adding polypropylene fibers to the cementitious mix to improve strain capacity, toughness, impact resistance, and crack control. Collated fibrillated polypropylene (CFP) fibers with fiber lengths between 0.5 in. and 2.5 in. are used, having the primary benefit of control over thermal and drying shrinkage cracking when added in the amount of 1 to 2 lbs of fibers per cubic yard of shotcrete and increased shotcrete toughness when added up to 10 lbs of fibers per cubic yard (US Army Corps of Engineers, 1993). Loevlie (2008) stated that this kind of mortar develops a high compressive strength (6,000 psi in 7 days), and that is more acid and abrasion resistant and more impermeable than ordinary concrete. Fiber-reinforced shotcrete (FRS) proportional mixes are discussed in Morgan et al. (1989).

1.3. METHOD REVIEWS

Hilton (1990) prepared a brief state-of-the-art review of shotcrete covering material properties, applications, finishing, curing, durability, and failures in shotcrete installations. Most shotcrete failures are found to be related to poor preparation of the substrate surface, and the general consensus is that good quality shotcrete is a durable material even when used in severe environmental situations.

Walker and Guan (1997) found that cement mortar lining systems were very economical but provided limited corrosion protection in a corrosive environment. Furthermore, they concluded that cement mortar did not bond to the steel surface but was instead held in place by its rigidity and shape.

New York DOT recommends lining with shotcrete if the structural integrity of culvert is sufficient and corrosion on the entire circumference of culvert is minor, generally less than 20% total perforations. If signs of minor corrosion are limited to the bottom of culvert (i.e. less than 30% of the bottom one-fourth of the pipe is perforated), paving the invert with Portland cement concrete (PCC) is the preferred method (NYDOT, 2001).

1.4. APPLICABILITY

The method is applicable in circular pipes ranging in diameter from 12 in. to 140 in. Reinforced cement mortar lining is only applicable in many-entry pipes.

Maximum installation length is about 650 ft in robotic applications and about 50 to 60 ft in man-entry applications for practical reasons (this also depends on safety regulations) (Caltrans, 2003).

1.5. EXAMPLE CASE HISTORIES

Loevlie (2008) reported several case histories of relining culverts using fiber-reinforced shotcrete (FRS) such as:

- In Milwaukee, WI, approx 9,000 ft of pipe with 60 in. ID was relined applying a 0.5 in. thick shotcrete lining. The individual runs were up to 500 ft long (Kristian Loevlie, Shotcrete Technologies, Inc, personal communication)
- In Grand Junction, Mesa County, CO, a 36 in. diameter culvert 110 ft long was relined in less than two hours

In Oldman River Dam in Alberta, Canada, a drainage tunnel, 10 ft in diameter, was relined using fiber-reinforced shotcrete (FRS) in 1987 (Morgan, 2000a).

1.6. ADVANTAGES AND LIMITATIONS

The main advantages of cement mortar lining are the ability to provide protection against corrosion and abrasion, restore flow capacity, and provide structural repair if sufficient material thickness is used. No excavation is required.

The main limitations include the relatively long setting time and the relatively slow strength gain of the installed liner. The culvert must be completely free of water and flow bypass may be required. Extensive surface preparation is needed in most cases.

2. POLYMER BASED COATINGS AND LINERS

2.1. OVERVIEW

Polymer based coatings and liners involve the application of a layer of polymer material by either spincasting (Figure 92) or manual spraying using spray guns (Figure 93). ASCE (2009) defines coatings as applications where only a corrosion barrier is created, and liners as applications where a corrosion barrier and/or a structural repair are provided.

Figure 7. The spincast system uses centrifugal force to apply the material to pipe walls over lengths up to 700 ft (RLS Solutions, 2009)

Figure 8. A spray gun is used for applying the material to pipe walls in man-entry pipes (Warren, 2007)

2.2. MATERIALS USED

2.3. EPOXY

Although spray-on epoxy is mostly used for rehabilitation of potable water pipes, it can also be effectively used to line culverts (Thornton et al, 2005). Epoxy can be applied as protective coatings against corrosion and for eliminating infiltration/exfiltration.

Epoxy coatings are typically100% solids and solvent-free (i.e., they do not require a solvent to keep the binder and filler parts in a liquid suspension form). There are several advantages of such coatings over conventional liquid coatings: they emit zero or near zero volatile organic compounds; they can produce much thicker coatings than conventional liquid coatings without running or sagging; they produce less hazardous waste than conventional liquid coatings; generally they have fewer appearance differences between horizontally coated surfaces and vertically coated surfaces than liquid coated items (Walker and Guan, 1997).

Fiber reinforced polymer composites (FRPCs) contain high performance fibers embedded in a polymer matrix (Figure 95). The matrix serves to provide continuity to the composite, distribute applied loads among fibers, support the slender fibers against buckling, and protect the fibers from physical and environmental damage. FRPC materials have high strength-to-weight ratios, are generally resistant to corrosion, and are lightweight and thus relatively easy to apply (Warren, 2002)

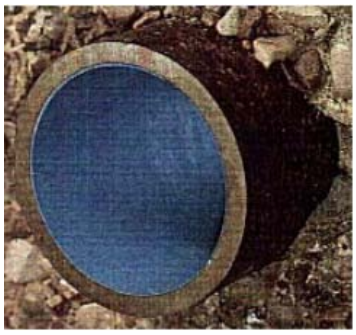

Figure 9. Epoxy-lined pipe (Proline Pipeline Protection, 2008)

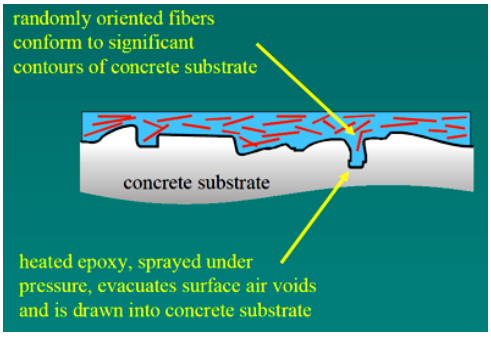

Figure 10. Spraying of fiber reinforced polymer composites (Warren, 2002)

2.4. POLYURETHANE

Sprayable polyurethanes are polyol based products blended with isocyanate. When mixed in a 2:1 ratio (2 parts of "B" polyol to 1 part of "A" isocyanate, proportioned by weight), a rigid coating is produced (permitting up to 4% elongation by ASTM D638) that provides both structural enhancement and corrosion protection. A 1:1 mixing ratio produces a flexible coating (permitting 43% elongation as assessed by ASTM D638) that offers only corrosion protection (Jerry Gordon, Sprayroq, personal communication).

Guan (2003a, 2003b) reviewed the chemistry, history and developments of 100% solids elastomeric polyurethane and 100% solids rigid polyurethane. Most pipe rehabilitation field applications have been traditionally based on 100% solids elastomeric polyurethane, but since the mid 1990s, the trend in North America has been towards the development and use of 100% solids rigid polyurethane coatings.

2.5. POLYUREA

Polyurea coatings and liners are based on isocyanates/amines (Primeaux, 1989). They combine application characteristics such as rapid cure, even at temperatures well below 0°C, and insensitivity to humidity, with physical properties such as high hardness, flexibility, tear strength, tensile strength, chemical and water resistance. The resulting surface offers good weathering and abrasion resistance. The systems are 100 percent-solids, making them compliant with the strictest VOC regulations (Broekaert, 2002).

For structural enhancement, the liner is sprayed "high build" (the term typically implies thickness roughly between 0.25 and 1 in.) as the liner is designed to resist soil loads, traffic loads and hydrostatic groundwater pressure. Like cement mortar lining, polyurea lining of this thickness, holds in place as a result of its rigidity and shape, and the adhesion (i.e. surface preparation) is not as critical as with protective coatings (Donald Dancey, Innovative Painting & Waterproofing Inc, personal communication).

Figure 11. High build polyurea lining in pipe (Joseph, 2009)

2.6. APPLICABILITY

The technology is applicable in all pipe shapes and types (steel, concrete, PVC, cast and ductile iron, asbestos cement, wood, corrugated metal pipes) but the pipes must be completely empty of water, dry and clean (Stephane Joseph, Acuro, personal communication). Spincasting is applicable in small diameter circular pipes, typically in a diameter range between 3 in. and 36 in., and up to 700 ft in distance (RLS Solutions, 2009). In man-entry pipes, the method is applicable in any pipe size and shape, and the installation length is typically limited to 450 ft (Thornton et al, 2005). Safety regulations can also limit the installation length.

2.7. INSTALLATION

2.7.1. EPOXY

Epoxy liners are predominantly installed in man-entry pipes with manual spraying.

One system on the market (two components and 100% solids) is installed with a plural component spray application system, which pre-heats the product, mechanically ratios the two components, mixes and delivers the homogeneously blended product to the spray gun (airless or air-assisted). Application thickness is between 0.06 in. and 0.25 in. per application layer. For quality assurance, at least two coats are recommended. When applying multiple coats, no more than 18 hours at 70°F should be permitted to pass between coats. Recoating is usually performed between 2 and 18 hours after the previous coat. Initial set generally occurs within 6 hours at 70°F. Curing continues for 7 to 14 days (Jim Henke, RLS Solutions, personal communication).

Another system is also using a plural component spray-on system for spraying the material. The epoxy component utilizes a 2 parts base to 1 part activator mix ratio by volume. No thinners are utilized. The coating is applied in thickness up to 0.750 in., and multiple coats can be applied to a max thickness of 1 in. The cure time is about 2 hours at 77°F. Additional coats are applied within one hour (Jane Warren, Warren Environmental Inc, personal communication).

2.7.2. POLYURETHANE

This material is sprayed onto the prepared surface through an airless spray gun using appropriate ratio system for mixing the components (see 3.1.7.2_2b). Application thickness is up to 1 in. or greater. The material begins to gel in about 8 seconds, with a tack free condition after one minute. Within 30 to 60 minutes, the initial cure is completed and the structure is capable of accepting flow. The complete curing continues for the next 4 to 6 hours (Jerry Gordon, Sprayroq, personal communication).

Surface preparation is essential for successful application. The surface must be clean (free of oil, grease, rust) and dry (polyurethanes react to water instantly having bubbling and blistering reaction) (Baron**,** 2007).

2.7.3. POLYUREA

Polyurea is applied in thickness between 0.020 in. and 1 in., though maximal thickness is theoretically unlimited (Stephane Joseph, Acuro, personal communication).

The product cures rapidly with 5 to 8 seconds gel time, 12 to 15 seconds tack free time, and 24 hours return to full service. Application thicknesses from 0.125 to 1 in. can easily be achieved (for a high-built liner). The product can be sprayed directly onto concrete. If substrate is uneven or slightly damp, a

primer is recommended (e.g., water blown high density foam that fills voids and creates an even surface) (Donald Dancey, *Innovative Painting & Waterproofing Inc*, personal communication).

2.8. EXAMPLE CASE HISTORIES

2.8.1. EPOXY

Several case histories of applying fiber reinforced polymer composites (FRPCs) for spray-on lining of tunnels, sewer pipes, manholes, and aqueducts are listed on a web site (Warren Environmental, 2009) although no case history of culvert rehabilitation is included among them.

2.8.2. POLYURETHANE

2.8.3. POLYUREA

Several agencies have already approved polyurea coatings for rehabilitation of culverts and sewer pipelines, e.g., Virginia DOT, Florida DOT, Ohio DOT, whereas polyurea coatings are under review in 35 other states for DOT evaluation nearing final approval stage (Hunting, 2008).

In 2008, City of Vaudreuil-Dorion, near Montreal, Canada, used a high-built polyurea to rehabilitate over 5,000 ft of cast and ductile iron water mains. The liner was applied in thickness of 0.12 and 0.2 in., in pipe diameters of 6 and 10 in. respectively (Joseph, 2009).

In Springerville, AZ, Tucson Electric Power (TEP) rehabilitated a water pipe intake into the power plant applying a polyurea lining in 2009. The pipe consisted of 1,800 ft of 96 in. and 620 ft of 72 in. diameter steel pipe. The existing mortar lining was first demolished and hydro/abrasive blasting was performed on the pipe interior surface to prepare it for the polyurea lining. The lining was applied in thickness of 0.06 in. using a combination of robotic plural-component spray equipment and hand-spray methods in areas inaccessible to robotic systems (Allouche and Steward, 2009).

In Chicago, IL, a partially deteriorated concrete storm line was experiencing large infiltration (caused by the acidic degradation of the joint seals and several radial cracks in the elliptical pipe that occurred due to the loss of soil stabilization) causing soil loss and voids around the pipe. The pipe was rehabilitated in 2000 by spray-applying a 0.75 in. thick semi-structural polyurea lining (Inspar Robotic Technologies, 2005).

2.9. ADVANTAGES AND LIMITATIONS

The main advantage of polymer-based coatings and liners is the ability to provide protection against corrosion. Some also provide structural enhancement. No excavation is required.

The main limitation is that the culvert must be completely free of water and flow bypass may be required. An extensive surface preparation is essential for successful application with some systems.

3. QA/QC CONSIDERATIONS FOR SPRAYED-ON LINERS

NASTT (2006a) outlined QA/QC issues for coatings and lining (cementitious, epoxies, urethanes and ureas). Referenced were material standards, most important installations issues (surface preparation, variables such as weather, safety, confined spaces, product viscosity, moisture tolerance, etc), and measures to ensure proper application (training of qualified applicators and proper equipment). The importance of testing and inspection of applied coatings and linings was recognized.

Muenchmeyer (2004) discussed elements of a QA/QC program that can minimize or prevent coating failures (Table 8), and outlined key specification issues and customer acceptance criteria. Good verifiable quality controls and testing documentation during construction were identified as critical components for the long term success of corrosion protection coatings. The paper also discussed warranties and the importance of regular project inspections.

Table 1: QA/QC for polymer coating (based on Muenchmeyer, 2004)

Quality assurance plan	Quality control plan
▪ Complete description of the project site and structure condition specifying precautions, if applicable	▪ Written verification that all QA requirement have been met
▪ Defined QA criteria	▪ Documentation that all safety requirements have been implemented
▪ Defined QC verifications during construction	▪ Verification of coating materials submittals, delivery and use
▪ Proposed safety plan for the work execution	▪ Pre-construction inspection of surfaces documenting their condition
▪ Schedule for product sampling	▪ Inspection of equipment for surface preparation and coating application (applicability, operational condition, and manufacturer's approval)
▪ Required submittals and certifications for the project and on the products to be used	▪ Documentation of environmental and service condition (temperature, humidity, pH, flow, infiltration, etc)
▪ Training certifications for the Applicator	▪ Inspection and verification of surface preparation
	▪ Measurements of film thickness of applied coating
	▪ Inspection of film continuity (visual and holiday testing)
	▪ Adhesion testing
	▪ Inspection and documentation of post-inspection repair procedures
	▪ Re-testing requirements of areas found to be deficient and repaired
	▪ Other test requirements recorded and verified by the inspector

Muenchmeyer (2005) evaluated a failure of coatings installed in one rehabilitation project in 1996, and described lessons learnt for future applications. The project included the use of epoxy coating in approximately 50 large diameter manholes (the conclusions apply to coatings in general), which failed soon after the 5-year warranty expired for the following principal reasons: 1) the coating was installed with non-uniform thickness that varied between 0.06 in. and 0.30 in. (thinner non-monolitic areas failed), and 2) the exposed aggregate was in many areas left un-coated and the pinholes were not repaired thus leaving underlying concrete to corrode at more rapid rate. Prior to the 5-year warranty expiration, the coatings were inspected by non-experienced inspectors who did not identify any problems. Among the lessons learnt are: 1) experienced inspectors and regular annual inspections are essential (extended warranty has no value otherwise), and 2) good field advice should be considered (the applicator indeed recommended a cementitious coat prior to epoxy coating that the owner disregarded).

4. STANDARDS AND SPECIFICATIONS

Morgan (2000b) listed shotcrete guides and specifications.

AWWA C602 covers cement-mortar lining of pipelines from 4 in. to 144 in. in diameter.

ACI 506.2 provides a useful basis (but only limited guidance) for the preparation of detailed specifications for a variety of different shotcrete constructions

ACI 506R provides detailed information on materials and properties of both dry-mix and wet-mix shotcrete. Most facets of the shotcrete process are covered, including application procedures, equipment requirements, and responsibilities of the shotcrete crew.

European Specification for Sprayed Concrete (EFNARC, 1996a) deals with concrete or mortar which is pneumatically placed onto a surface. Both wet and dry processes are covered. The appendix covers the admixtures for sprayed concrete: definitions, specifications, requirements, reference concrete mixes and

test methods. EFNARC (1996b) covers the execution of spraying of concrete or mortar. EFNARC (1999) provide a commentary on the Specification by giving an explanation of the requirements.

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