Advanced Geopolymer Mortar System for the Structural Rehabilitation of Large Diameter Culvert and Sewer Infrastructure

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Abstract

As the state of infrastructure around the world decays, more cost-effective solutions to repair large diameter pipe systems are required. Typical dig and replace technology is often not practical because in most urban areas these degrading pipes are located directly under other critical infrastructure, such as major roadways, buildings or other assets. As the diameter of these pipes becomes larger (more than 48 inches), the cost of many of the traditional trenchless technologies becomes exponentially more expensive and often requires significant excavation around access points that present additional issues related to community disturbance, traffic control, noise and general disruption. For example, if a 48-inch diameter sewer pipe was located in the center of town, and a standard 30- or 36-inch manhole was the access point, a cured-in-place pipe (CIPP) repair would require an access hole of at least at least the least the diameter of the host pipe, which can be significantly larger than as standard manhole. While other techniques, such as slip-lining, would require an even greater excavation diameter for an access hole to install new liners. Additionally, with many of the standard trenchless repair technologies, other issues related to either the shape (round, arched, elliptical) or the layout (straight, curved, bends of various radius) can make these repair technologies impractical, while based on application method spray applied linings can generally be applied around these various anomolies.[1,2]

Over the last decade, additional trenchless technologies have been developed to help fill the need for larger diameter pipe repairs at effective costs with little or no excavation requirements and minimal community disruptions. One such technological advance is the use of centrifugally cast geopolymer mortars to create a new pipe inside of the existing pipe.[3] This technique allows for a cementitious pipe to be created within the existing structure, using the existing pipe as a form, and can be designed so that a new fully structural pipe is created. The flexibility of the technique allows for pipes of all shapes and layouts to be repaired either using automated mechanical casting or manually controlled material placement. The necessary equipment can easily fit down standard manholes and all excavation can be avoided if there are access points at least every 800 linear feet.

This paper reviews a geopolymer mortar system that has been used in North America since 2011 and is becoming a preferred solution for trenchless conduit rehabilitation. The system is spray cast either by a rotary nozzle or traditional shotcrete delivery systems inside of existing structures to create whole new structure that does not depend on the existing structure but uses it as formwork. This paper also highlights three culvert rehabilitation projects that demonstrate the viability, effectiveness and implementation of the geopolymer lining technology inside an existing deteriorated structure. The case studies represent projects where multiple trenchless options such as cured in place pipe (CIPP) and slip-lining were considered and evaluated.

Introduction

The former Milliken Infrastructure Solutions, LLC (now ClockSpring | NRI) developed a geopolymer mortar material (GeoSpray® mortar) for use as a trenchless technology repair method. Since this time other geopolymer materials have come into the market place. Geopolymers are styrene free, spray-applied cementitious mortars that produce a standalone structural lining within existing deteriorated conduits.[1] The technology can be employed regardless of the condition of the original pipe. Geopolymer mortars allows a contractor to reconstruct a new structural culvert or sewer pipe on-site using spray technology often referred to as centrifugally cast cementitious pipe (CCCP). The "new-pipe-within-a-damaged-pipe" technology results in improved strength and often improved flow characteristics. The environmental benefits of the geopolymer systems include:[3]

(1) Use of industrial waste materials that would otherwise be landfilled
(2) Substantial reduction in environmental disruption from the use of a trenchless technology
(3) Significantly reduced CO_2 when compared to standard cement materials
(4) Replacement of styrene-based resin alternative CIPP solutions

Geopolymers in general have been used since the mid-1970s as an alternate to OPC. To date, geopolymer material has been used to line over 140,000 linear feet of large diameter decaying conduit infrastructure and well over 200 individual projects.

Geopolymer History and Chemistry:

In various parts of the world, geopolymers are also industrially known as "alkali-activated cement" or "inorganic polymer concrete." Geopolymers provide comparable or better performance to traditional cementitious binders in terms of physical properties such as compressive or tensile strengths but with the added advantages of significantly reduced greenhouse emissions, increased fire and chemical resistance and reduced water utilization.

The structure of a geopolymer is a cross-linked inorganic polymer network consisting of covalent bonds between aluminum, silicon and oxygen molecules that form an alumniosilcate backbone with associated metal ions. While any specific geopolymer structure, such as the one represented here in Figure 1, will be significantly more complicated based on the chemical makeup of the starting raw materials, the generic structure shown provides an excellent representation of how a geopolymer network is constructed. In contrast, OPC, Figure 2, is a hydrated complex of small molecules that are not covalently bonded but rather associated.

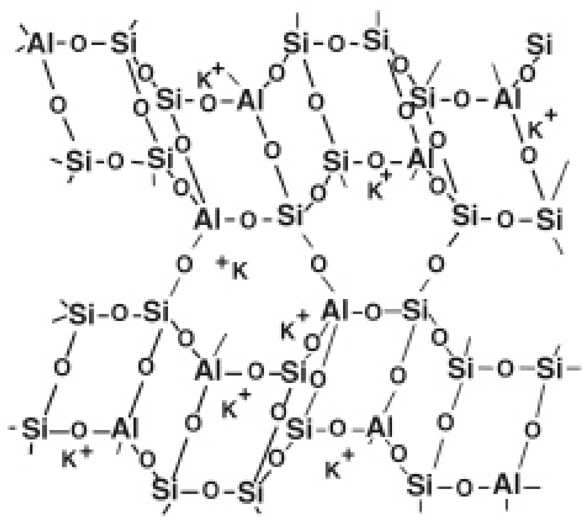

Figure 1 – Simplified Geopolymer Structure [4]

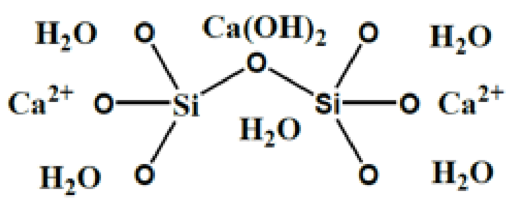

Figure 2 – Simplified Example of Molecular Structure of Hydrated OPC

Geopolymer Materials:

Geopolymers for trenchless pipeline repair have been commercially available since 2011. These materials are typically formulated for field performance requirements, specifically the physical and chemical requirements for rehabilitating sewer and stormwater structures, which are defined by the pipeline owner or engineering consultant. Water is added to the geopolymer at the job site where it can simply be centrifugally sprayed inside an existing structure that has been properly prepared. The exact formulation of most products is considered a trade secret, but generally speaking, geopolymers contain a mixture of the standard materials that are used in the production of calcium-aluminosilicates. Other components include, but are not limited to, blast furnace slag, reactive silicas, metal oxides, mine tailings, coal fly ash, metakaolin, calcinated shale, natural pozzolans and natural/processed zeolites.[7] Additional bio-based admixtures are included in the formulation to allow the composite material to set-up quickly and easily hydrate with a single addition of water. The "just add water" aspect of this class of geopolymer has been specifically developed to avoid the typical alkaline activation mechanisms and order of addition complexities of traditional geopolymers, which have significantly limited the ability of most contractors and asset owners from using geopolymers commercially. The material is mixed the same as standard cementitious material and no special curing or top coating is needed in most standard applications. A summary of the physical properties of geopolymers required for sewer rehabilitation is detailed in Table 1.

Table 1: Example Geopolymer Mortar Physical Properties

Test Method	Property	Duration	Typical Minimum Test Values
ASTM C39	Compression Strenght	1 Day	2500 psi
		28 Day	8000 psi
ASTM C78	Flexural Strength	7 Day	700 psi
		28 Day	1500 psi
ASTM C496	Moldulus of Elasticity	1 Day	3,000,000 psi
		28 Day	5,000,000 psi
ASTM C882	Bonding Strength	1 Day	900 psi
		28 Day	2500 psi
ASTM C807	Initial Set	N/A	60-75 minutes
	Final Set		90-120 minutes
ASTM C666	Freeze Thaw	300 Cycles	98%
ASTM C1090	Shrinkage	28 Day	0.00%
ASTM C496	Tensile Strength	28 Day	800 psi
ASTM C418	Abrasion Coefficient	28 Day	0.06 cm^3/cm^2

With most geopolymers, the entire system is contained within original powder formulation, which allows a single step addition. Mortars can typically be pumped up to 750 ft (229 m) within a pipe and still be centrifugally cast without clogging or damaging nozzle performance. To achieve this standard of performance, traditional cement or geopolymer formulations would require much higher water ratios, which would degrade their ultimate strength and require a much thicker final product during the installation to meet the flexural strength requirements of the rehabilitation.

Geopolymer Advantages:

Cold Joints

On real world construction sites, unexpected and unanticipated circumstances can result in delays or work stoppages. Additionally, many job sites can be subject to restricted work hours due to local traffic issues or community related ordinance. When working with the placement cement, these types of work stoppages or delays can result in the formation of a cold joint. A cold joint is an undesired discontinuity between two layers of concrete. A cold joint occurs due to the inability of a freshly poured wet cement to intermingle and bind with an already hardened cement. A typical cold joint in a poured structure is shown in Figure 3.

Cold joints can result in multiple problems ranging from minor to catastrophic. The spectrum of resulting issues includes: minor cosmetic visual differences between layers, possible moisture intrusion into the joint resulting in degradation from environmental conditions, and areas of significantly compromised strength within a structure. When water is mixed with Portland cement (OPC) the cement reacts with the water to form a hydrate allowing the cement to harden around aggregates and form concrete. The chemistry of the reaction uses a hydration mechanism to create a hardened solid phase structure. However, once the hydration is complete and the structure is solid, it will not physically or chemically intermingle with additional cement.

Figure 3: Typical Cement Cold Joint

Geopolymers undergo a completely different set of reactions classified as condensation. This process creates large polymer molecules that react to form large chain molecules that create the solid structure. When a hardened geopolymer is contacted with a freshly poured geopolymer mixture the polymer molecules from the hardened geopolymer are still active and will chemically bond with the new mixture preventing a cold joint from forming.

To demonstrate the superior properties of geopolymer mortar as compared to OPC materials with respect to cold joints, a series of compression test were conducted using 2 inch by 4 inch cylinders using a commercial geopolymer formulation. On the first day of the experiment, full cylinders of both geopolymer and commercially available competitive material based on OPC, both designed for use in structural pipe repair, were poured. In addition to the full cylinders, ½ pours of the same size were produced with both materials and vibrated on a slant to create an approximately 45° angle in the lower portion of the cylinder (as shown in Figure 4). A second pour atop the first pour (of the same material) was then done with intervals of 1, 7, 14 & 28 days. All samples where then compression tested according to ASTM C39.

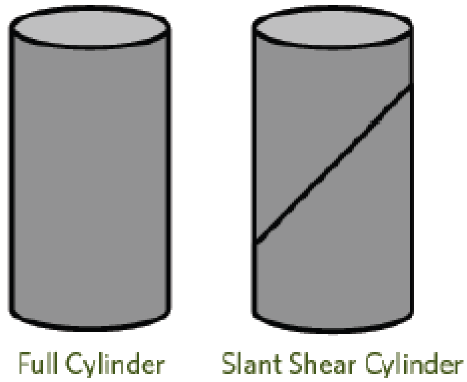

Figure 4: Schematic Illustration of Cold Joint Compression Experiment

For all combinations, the full cylinders poured on day 0 have no joints and break in a standard compression failure throughout the cylinder. For the geopolymer samples with the 45° joint, compression failure mode is the same as the full cylinder even when 28-days have elapsed between pours. The leading OPC competitive material breaks along the cold joint in all the test intervals, showing that the cold joint formed in the OPC between the pours is the weakest part of the structure. Detailed images of the experiments are shown in Figure 5.[5]

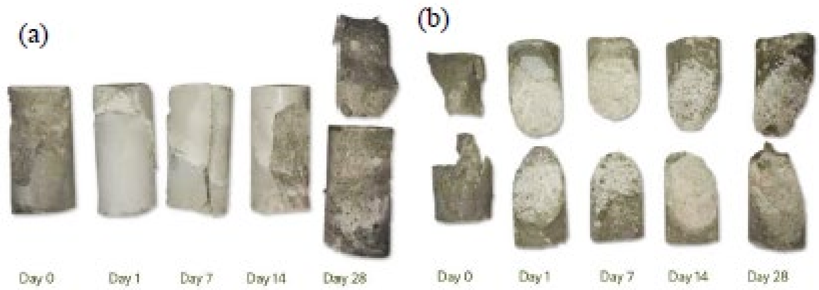

Figure 5: (a) Geopolymer samples showing compression failures located away from the joint (b) OPC samples with compression failure located at the joint.

Chemical Resistance

In sanitary sewers and other wastewater environments, the general corrosion mechanism of cementitious based materials is well known and widely documented. It is often referred to as Microbial Induced Corrosion (MIC). The process of MIC involves a three-step mechanism (shown schematically in Figure 6):

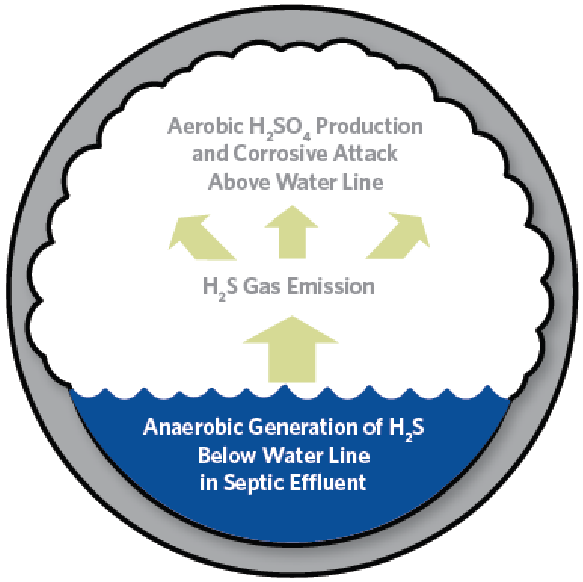

Figure 6 – MIC Process

The chemical makeup of geopolymers makes them inherently more acid resistant to the MIC mechanism found in many sewer environments. Where concrete pipes and structures exhibit the effects of microbial induced corrosion, geopolymers should result in significant resistance improvement over OPC.

While various test methods exist for testing of chemical resistance of cementitious materials including ASTM C267 and the so call California Pickle jar test, these tests are not truly standard and can vary based on concentration, sample size, and how often samples are adjusted. The only true standard currently in adoption anywhere in the world is DIN 19573 which is a German standard for testing of mortars for adoption into sewer system use. The standard consists of 3 test where small beams of 40mm x 40 mm x 160 mm are exposed to various concentrations of sulfuric acid which are constantly monitored and dosed to maintain their pH and then residual compressive strength is measured. The tests include (a) exposure of samples to pH 0.0 sulfuric acid for 14 days, (b) exposure to pH 1.0 sulfuric acid for 70 days and (c) exposure of samples to pH 4.0 sulfuric acid for 1000 hrs. The requirements to pass test (a) & (b) are to maintain 55% and 75% residual compressive strength after the exposure time. If tests (a) & (b) are passed a material is given a classification of XWW4 by the standard and is certified for the highest corrosive sewer environments. Under test (c) based on the residual strength remaining there are 3 additional classifications XWW1, XWW2 & XWW3, with classification 3 being the highest, for which products can be accepted for lower levels of exposure. This classification is strictly adhered to across most of mainland Europe. To date the two geopolymers on the market have received the highest XWW4 classifications along with calcium aluminate materials that are typically used only in manhole applications. No OPC based materials currently pass the highest classifications due to the high concentrations of residual $Ca(OH)_2$ found those samples.[6]

Geopolymer Application & Design

The damaged pipe is cleaned in place, typically with high pressure water blasting of 3500 psi or more. In order to ensure adhesion of the geopolymer to the damaged substrate, it is sometimes necessary to perform an additional cleaning with an environmentally friendly detergent to remove excess oils and grease from the existing pipe walls. If there are large leaking holes, the pipe can be plugged with a thin application of the material, a plugging compound or hydraulic cement. Any flow in the conduit will need to be diverted or bypassed possibly through the pipe before lining can begin. Finally, the geopolymer mortar is centrifugally cast from atop a sled, which is slowly removed from the pipe to provide a uniform application. Typical application thicknesses range between 1.5 – 3 inches (38 to 75 mm), depending on the type of pipe, local soil and water conditions, current condition of the existing pipe and the design life requirements of the particular pipe in question. Figure 7 show a series of images in the repair of a stormwater culvert made of corrugated metal from the original deteriorated pipe to the completely restored system.

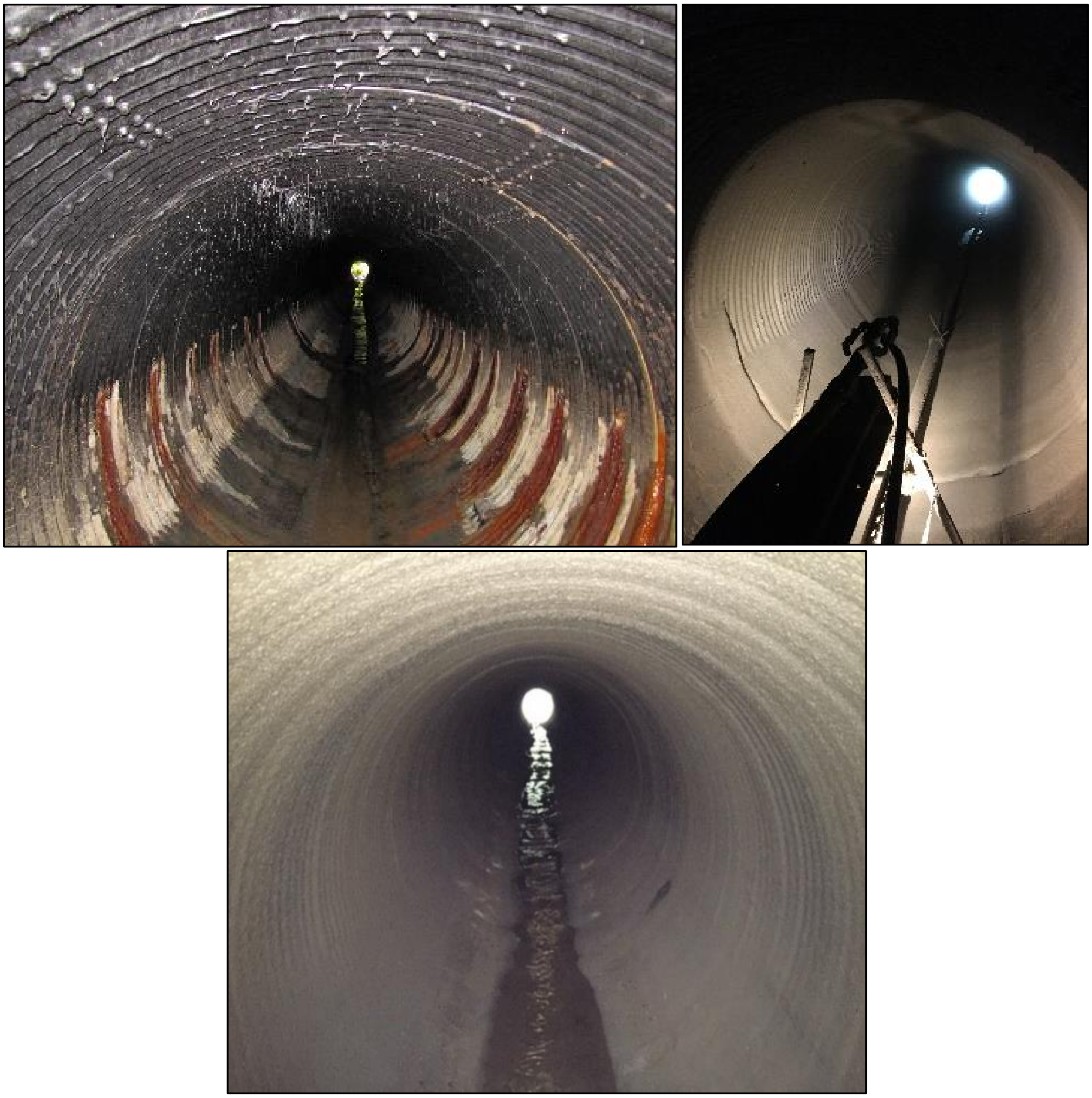

Figure 7 – Repair of a Stormwater Culvert made of Corrugated Metal

Additionally, significant work has been performed to develop a design methodology that is based on actual testing of deteriorated and lined pipe samples. The method has recently gained approval from the WRc in England and a detailed review of the engineering and design equations can be found elseware.[7]

Installation Case Study: SR 446 Culvert – Indiana Department of Transportation (IDOT):

The IDOT recently implemented a proactive culvert inspection and management program. The inspection of the SR 446 culvert revealed an 84 inch (2134 mm) corrugated steel pipe experiencing moderate deterioration in the invert from abrasion and corrosion. The culvert was buried under 30 feet (9 meters) of fill so replacement was not a practical option. Figure 8 shows the existing culvert and Figure 9 shows the roadway above. The IDOT tendered the project with the cured in place (CIPP) trenchless lining system as the preferred option. Access to the pipe ends at the bottom of the fill slopes made this option challenging for the applicator. The general contractor proposed the geopolymer lining option through the value engineering process. The DOT reviewed and accepted this option. This option proved to be more cost effective and less disruptive to the surrounding roadway.

Figure 8 – Existing Culvert at SR 446

Figure 9 – SR 446 above Culvert needing Repair

The use of geopolymer mortar is to create a new pipe within the existing CMP structure. The 1.5 inches (38 mm) of structural geopolymer lining was completed in two weeks in October 2015. The new rehabilitated pipe was ready to handle the Midwest extreme weather and heavy stream flows for many years of service. Figure 10 shows the culvert with the completed geopolymer lining.

Figure 10 – Completed Geopolymer Mortar Lining

Installation Case Study: Wattles Road Arch Culverts – Troy, Michigan
Twin 12.83 ft x 8.33 ft corrugated steel arch culverts were located in a northern Metropolitan Detroit suburb. During recent inspections in 2013 and 2015, the city of Troy discovered severe corrosion of the inverts of these arches built in 1967. In addition, one culvert was experiencing structural distress requiring stabilizing struts. Figure 10 shows the culverts prior to rehabilitation.

Figures 11 – Culverts prior to Rehabilitation

The city investigated replacing the culverts with a single span bridge. This option was rejected due to high costs and significant anticipated traffic delays on this high volume road from long closure. Other rehabilitation options such as CIPP and slip lining were eliminated because of the non-round shapes. The geopolymer spray option was decided on based on lining cost and minimal roadway disruption.

The twin culverts' combined spans exceeded 20 feet (6 meters) and were considered a bridge by the state of Michigan and as such required load rating analysis. The final design determined a 2.5 inch (64 mm) structural geopolymer lining was needed. The application of the lining was done in multiple passes over a period of three weeks during November and December 2016. Flow in the stream channel was maintained during lining by diversion into adjacent barrels (see Figure 12). The completed lining is shown in Figure 13.

Figure 12 – Flow in the Stream Channel was Maintained by Flow Diversion

Figure 13 – Completed Culvert Lining

Installation Case Study: Twin Box Culverts – City of Memphis, Tennessee

In 2015, the city of Memphis initiated the design of a rehabilitation solution for the Sears Crosstown Box Culvert System. Inspections of a section of twin 8.5 ft x 8 ft concrete box culverts revealed severe concrete spalling and corrosion of underlying steel reinforcement. The box structures were considered structurally sound despite deterioration of the interior walls (see figure 14).

Figure 14 – Deterioration of Interior Walls in Box Culverts

While considering rehabilitation options, the design consultant determined that slip lining with a circular pipe would have too great of an impact on hydraulic flow performance. Replacement was deemed too costly and impractical due to existing overlying building structures. The final decision was to structurally enhance the box walls with a geopolymer mortar lining. The culverts were pressured-washed to remove loose spalling concrete and exposed steel reinforcement was cleaned and coated. All active infiltration was stopped using hydrophobic grouts. Figure 15 shows a cleaned wall section ready for lining.

Figure 15 – Cleaned Wall Section Ready for Lining

A 1.5-inch (38 mm) geopolymer coating was applied to the culvert walls starting at the bottom of the vertical walls, moving overhead and finishing with the bottom. Flow was diverted into an adjacent box during the preparation and lining work. Figure 17 show the completed culverts.

Figures 17 – Completed Box Culverts

Conclusions

Geopolymer mortar repair systems have been developed to be a cost-effective alternative to other trenchless repair systems for large diameter culvert and sewer pipes. Geopolymers have advantages over OPC systems relating to the chemistry of the materials and how they are reacted that include:

(1) Lower CO_2 footprints
(2) Reduced tendency for cold joints
(3) Enhanced chemical resistance

Multiple case studies have been shown where structural pipe and box repairs were designed and cost effectively completed for culvert drain applications.

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