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GEOSPRAY CASE STUDIES FOR CORRUGATED STEEL PIPE CULVERT REHABILITATION

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Abstract: As many corrugated steel Pipe (CSP) culverts will be approaching the end of their useful service life over the next 20 years, there is a growing demand to rehabilitate these aging infrastructures. Asset owners and engineers are in search of rehabilitation strategies to repair and restore the structural integrity of the CSP culverts such that the repair is cost-effective, environmentally friendly and have minimum impacts on highway's and freeways traffic volume. This paper reviews a geopolymer mortar system that has been used in the North America since 2011 for trenchless rehabilitation of CSP culvert. The system is spray cast either by rotary nozzle or via traditional shotcrete delivery systems placed inside the existing structures to create a new structure. This paper will share the experiences in design and implementation of the Geospray CSP rehabilitation technology, and report successes and lessons learned from two recently completed MTO projects.

1 INTRODUCTION

There is growing recognition that many of the corrugated steel Pipe (CSP) culverts conveying stormwater across embankments and roadways will be approaching the end of their useful service life over the next 20 years. As the need for investment in the repair and rehabilitation of the CSP culverts stormwater systems continues to increase, Asset owners and engineers around the world are in search of cost-effective and environmentally friendly solutions that solve these infrastructure challenges. The search for alternative technologies is particularly necessary regarding larger diameter pipe systems, as the selection of rehabilitation methods for these structures is limited and the cost per linear foot could be substantial. One technology that offers promise in this area is Geopolymer spray linings.

2 GEOPOLYMER LININGS

GeoSpray geopolymer mortar has been developed for use as a trenchless technology rehabilitation method. Geopolymer binders offer several advantages compared with portland cement-based cementitious materials including (a) enhanced chemical resistance, (b) enhanced resistance to elevated temperatures and (c) reduced CO2 greenhouse emissions due to the use of industrial waste streams as large percentages of the formulations. When geopolymer linings are applied to an existing pipe structure, it is typically done by a centrifugally casting method for smaller pipes or manual spray for bigger pipes. This “pipe-within-a-pipe” technology results in enhanced structural capacity and often improved flow characteristics. To date, 20 million pounds of GeoSpray geopolymer mortar have been installed to repair more than 200 deteriorated structures, which totals to more than 100,000 linear feet.

3 GEOPOLYMER CHEMISTRY AND PROPERTIES

The term “geopolymer” was originally coined by the French researcher Joseph Davidovits to describe a class of “cementitious binders” formed by the activation of aluminosilicates. Alternating terms used in the literature include “alkali-activated cement” or “inorganic polymer concrete” (2). While traditional portland cement relies on the hydration of calcium silicates, geopolymers form by the dissolution, gelation and condensation of aluminosilicates. The kinetics and thermodynamics of geopolymer networks are driven by covalent bond formation between tetravalent silicon and trivalent aluminum. The molar ratio of these key components along with the presence and concentration of alkali-metals (e.g., sodium, potassium) and calcium have been shown to affect setting time, compressive strength, bond strength, shrinkage and other desired properties of the resulting matrix. Geopolymers provide comparable or better performance to traditional cementitious binders in terms of physical properties such as compressive or tensile strengths (3-6) but with the added advantages of significantly reduced greenhouse emissions, increased fire and chemical resistance and reduced water utilization. Historically, the utilization of alkali-activated cements in the U.S. commenced in the late 1890s, with several structures built by the United State Army Corps of Engineers, including some that are still in service in southern Louisiana. In the early 1900s, however, the technology was abandoned with an increase in the use of ordinary portland cement (OPC).

The technology was revived by Glukhovsky and his co-workers in the Soviet Union post-WWII, who used the binder in the construction of several buildings in the Ukraine; the geopolymer was then known as “soil cements” (Royer & Matthews, 2019). Geopolymers have seen a revival over the past 20 years with several applications in the construction industry becoming increasingly popular based on both their intrinsic environmental and performance benefits. A typical aluminosilicate structure that is common among many geopolymer materials is represented below (Figure 1). 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 aluminosilicate backbone with associated metal ions. In contrast, OPC is a hydrated complex of small molecules that are not covalently bonded, but rather associated. OPC itself is sufficiently complex in that the structure is only a basic representation of the molecules, but no long-chain covalently bonded backbone or network structure exists in standard cementitious materials (i.e., particles are mechanically interlocked rather than presenting a continuous chemical structure) (Figure 2).

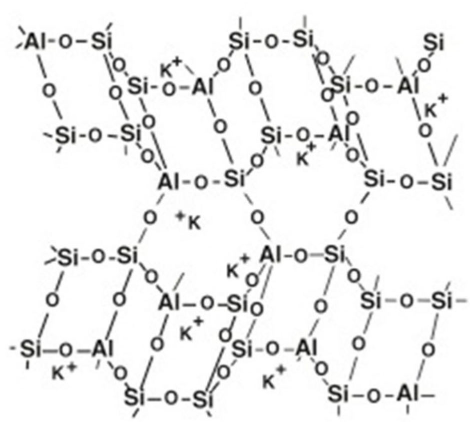

Figure 1: Typical Geopolymer Structure

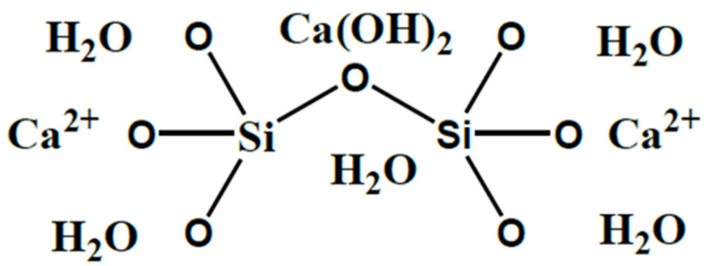

Figure 2: Typical Hydrated Ordinary Portland Cement (OPC) Structure

Figure 3 shows the major difference between Geopolymer and conventional repair mortar.

Test Method	Duration	GeoSpray	Conventional Repair Mortar
Compressive Strength ASTM C-39/C-109	1 Day 28 Days	Min. 2,500 psi / 17 MPa Min. 8,000 psi / 55 MPa	 5000 psi / 34 MPa
Flexural Strength ASTM C-78	7 Day 28 Days	750 psi / 5.2 MPa 1500 psi / 10.3 MPa	 500 psi / 3.4 MPa
Modulus of Elasticity ASTM C-469	1 Day 28 Days	3,000,000 psi / 20700 MPa 5,800,000 psi / 40000 MPa	 3,000,000 psi / 20700 MPa
Bond Strength to Concrete ASTM C-882	1 Day 28 Days	Min 900 psi / 6.2 MPa Min. 2,500 psi / 17 MPa	 N/A
Set Time ASTM C-807 Initial Cure Time	Initial Set Final Set	60 - 75 Minutes 90 - 110 Minutes	120 Minutes 300 minutes
Freeze Thaw Durability ASTM C-666	300 Cycles	100% Zero loss	80% to 90% 10% to 20% degradation
Shrinkage ASTM C-1090	28 Days	0.00% @ 65% R. H.	0.35% to 0.50% Shrinkage
Tensile Strength ASTM C-496	28 Days	Min. 800 psi / 5.5 MPa	400 psi / 2.7 MPa
Abrasion Resistance ASTM C-1138	5 Cycles @ 28 Day Maturity	2.7% Loss	4.7% Loss
Rapid Chloride Ion Permeability ASTM C-1202	28 Days	Very Low	N/A

Figure 3: Geopolymer Mortar vs Conventional Repair Mortar

4 LINER DESIGN

No consensus design standards exist for spray applied liner application at this point in time. For the design of geopolymer spray applied lining an extensive amount of research has been conducted on the proper design methodologies for the determination of liner thickness (Royer & Matthews, 2019). This research has developed a methodology for the design of spray on systems that has been shown to model both the original experimental conditions as well as additional data sets that have been recently generated. The conclusions of that work show that these systems when installed into CSP are no longer flexible systems so a rigid design methodology should be employed. Design methods such as ASTM F1216 or other design strategies for flexible systems are not acceptable as they rely on analysis of the buckling failure of the lining and the failure mode of the rigid structure is based on longitudinal cracking.

The first critical step related to the design of geopolymer liners is to determine the load that is applied to the structures. For many fully deteriorated pipe rehabilitation conditions which assume the host pipe is not capable of supporting any of the soil, hydraulic or live loads and they must all be supported by the liner. The live loads were calculated based on the Canadian loading standard (CL-625-ONT), while the soil and hydraulic loads were calculated based on the loading conventions of ASTM F1216 and other pipe standards. The critical design parameter in the geopolymer material is flexural strength which is conservatively measured by ASTM C78. The value used in the design of the lining was 10 MPa. This value has been repeatedly validated by field testing on a variety of different lining installations.

The final design thickness was then calculated by performing a moment analysis across the crown of the pipe using the pipe based on the moment of a fixed arch (Watkins, 2000) with the resulting equation [1]:

$$t = \sqrt{\frac{0.0744 r^2 q_t}{S_F} \frac{N}{C}} \qquad [1]$$

Where t is the minimum liner thickness, q_t is the total combined load of the system, r is the radius of curvature at the crown of the pipe, S_F is the flexural strength, N is the safety factor, C is the ovality reduction factor. Based on this methodology the design thickness and total loads calculated are determined.

The initial CSP culvert was assumed to have a Manning's coefficient (n) value of 0.021 which is conservative for corroded CSP pipes. The new lining was assumed to have an n value of 0.015 as much of the base corrugations were filled during application of the liner.

5 SITE & SURFACE PREPARATION

Surface preparation is critical to the success of a spray applied geopolymer lining. All active infiltration must be stopped as any running water will wash away the spray applied material while it is curing. If the pipe is coated, the coating does not need to be removed in advance as the design does not rely on adhesion to the host pipe or structure, but any peeled/delaminated coating or debris should be removed. Invert voids if present may be filled with flowable fill material and most active infiltration should be stopped with either hydraulic plug material or hydrophilic grouts. Once the infiltration is stopped, the pipe is pressure washed with a 15 MPa system to remove any loose materials, corrosion deposits, all foreign materials including dirt, grit, roots, grease, sludge that maybe attached to the barrels of the culvert. Geopolymer mortars can readily be applied to a damp pipe and so the host structure does not have to be completely dry prior to application.

It is often difficult based on the weather and ground water table to completely stop all infiltration as it simply migrates to the closest weak points. Water infiltration may occur post completion of geopolymer lining application through surface hairline stress cracks, that form during the curing process. Under standard saturated dry conditions, these cracks would self-heal and have no structural impact on the pipe segments.

Urethane grout injection along with a pre-packaged, fast-setting, concrete repair mortar containing industrial hydraulic cements are used to arrest any infiltration and make the structure watertight.

6 LINER INSTALLATION

The lining installation can be conducted by two different methods: Centrifugal spin casting and hand spray. Each single pass applies 20-25 mm of geopolymer thickness to the host pipe. The geopolymer mortar is mixed on the surface with a water to material ratio of 0.19 – 0.20 and then either spray applied via spin casting machine or manually hand applied on pipe sections of larger diameter.

The hand spray liner installation methodology is used for larger diameter CSP, the ends of the CSP culverts, irregular pipes, and culverts with narrow entries where the slopes of some sections exceeding 15%. The hand spray application typically uses 20-25% more material as it is not possible to follow the contours of the corrugations accurately by hand and therefore it fills in the corrugations on the pipe and t creating a smoother hydraulic finish.

Picture 4: Lining machine applying.

The lining can be completed in very challenging terrain with limited access, and poor weather conditions. As the lining application is completed inside the culvert and the application is independent of the traffic above the structure, there are minimum traffic restriction and staging involved to complete the rehabilitation work. Traffic restriction is only involved for the mobilization and demobilization. These challenging conditions are one of the key advantages of spray applied lining mortars and the small project footprints that can be maintained compared to other rehab technologies.

Picture 5: Hand Spray.

7 QUALITY CONTROL

As part of Geopolymer Liner sampling and testing process, field records are maintained with temperatures of materials, pipe and equipment, and material parameters as well as pipe conditions inside the pipe sections. The required QC properties are presented in Figure 6. CSA/ACI certified field sampling technicians will carry out sampling and delivery to the approved testing laboratory. Field sampling was conducted in the presence of the site inspector and each sample identified with Contract#, Date, Time, Location within Pipe and Layer/ Pass #. Per project specification. The required QC Tests are detailed in Table 3.

Table 3: QA/QC Log and Testing Requirements

Property	**Testing Req.**	**Required Value**	**Test Method**	**Frequency**
Slump	1	Mix slump will vary for pumpability & application. Mfr. Recommendation W:C ratio not to exceed 0.20.		
Compressive Strength	7 Days	Min. 2,500 psi/ 17 MPa	ASTM C-39	01st Day & then Every Other Day
	28 Days	Min. 8,000 psi/ 55 MPa		

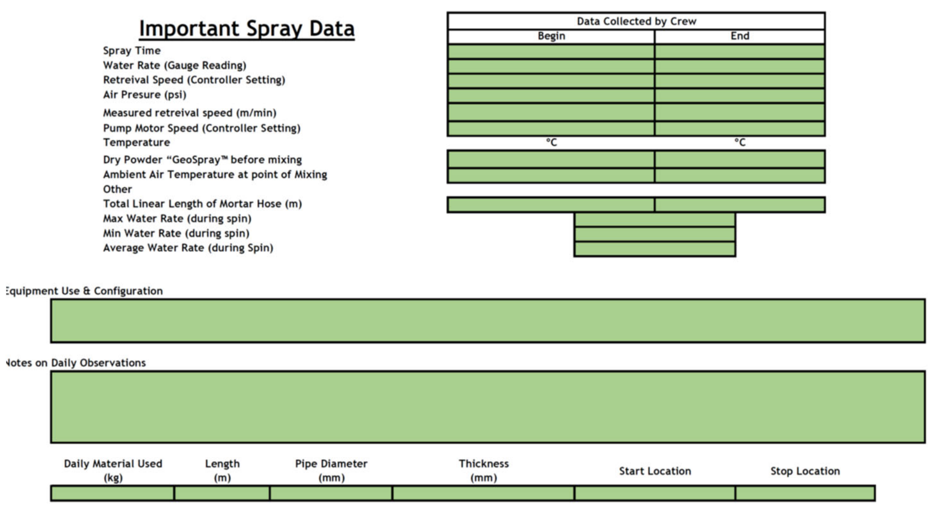

Figure 6: Extract of QA/QC Log Example

A Typical Geospray specification requires compression cylinders to be tested every day of spray application or every 18,000 kgs (40,000 lbs.). A minimum of six (6) 100 mm x 200 mm cylinders are collected by an independent testing lab at each day. The cylinders are cured in the laboratory and are tested as per ASTM C39 specifications. The first two (2) cylinders are tested at 7-days of cure. These two cylinders are helpful to identify any testing issues or concerns prior to the full-strength tests at 28-days. Subsequently three (3) cylinders are tested at the full cure time of 28-days and are required to exceed the minimum requirements of 55 MPa The final cylinder is used for back up and it is tested at 56-days as needed.

To monitor the mixing and application the contractor maintains a log of ambient temperature, batch water temperature, dry mortar temperature and the feed rate of water to the mixing system for all applications. The log details are recorded periodically over the course of work shift. The slump of the mixed mortar are also measured at each application day at the start of spraying by an independent laboratory. The values of slump varies between 90 and 180 mm which is typical variation based on temperature and water content and length of pumping required.

In addition to the physical property testing the contractor installs reference tabs such as stainless steel screws on the inward corrugation crests (i.e. internal diameter of the pipe) at a depth of 100% of the design thickness to verify that minimum design thickness has been achieved. Once the application is completed the reference tabs will remain in place. Aside, the use of reference tabs, a wooden foldable ruler with 6" sliding extension is also used to spot check the spray liner thickness. Any punctures in the liner are repaired with addition of geopolymer material and hand troweling.

In cold weather, the curing environment shall be maintained above 3°C with frost heaters at either ends of pipe segments. This process allows for the temperature to be maintained above the threshold so optimal curing can occur in a moist and moderate environment. Where pipe sections terminated at open areas, such as outfall structures, winterization methods such as insulated poly tarp or equivalent are installed at the opening to prevent early age freezing for the first 6 hours post application of geopolymer.

8 CASE STUDY 1 HIGHWAY 406 DICK’S CREEK CULVERTS, ST CATHARINES, ONTARIO

Dick’s Creek culvert consists of two (2) CSP culverts with each cell having a diameter of approximately 4m, length of 94m and fill of 5.6m over the culverts. Prior to the rehabilitation, the culvert’s condition in general was in a fair to good condition. However, the first 10m of the inlets and outlets demonstrated severe corrosion due to de-icing salt from the roadside splash. Although the deterioration was at the ends, a feasible rehabilitation strategy was required to prolong the service life of the structures and to prevent a local failure of the culvert ends and the embankments. With the high fill over the culverts and the embankments having a different slope at each end, the replacement of the culverts ends through the open cut excavation was costly and not desirable. Other alternatives such as installation of CSP liner and concrete liners also imposed construction challenges, introduced traffic impacts on Highway 406 and impacted the hydraulic capacity. After assessment and evaluation of various alternatives, GeoSpray liner was selected as the feasible rehabilitation strategy. The thickness from the preliminary design is 50mm.

The construction scope included 4 x 10m end sections of the two CSP culverts to be sprayed to a minimum of 50mm thickness. Each end took one week to complete including pipe prep, cleaning and water ingress control, application, and QA/QC testing.

After few months of lining application, the Geo-spray lined section overall is in a good condition with few hairline efflorescence cracks.

Figure 7: Pipe Corrosion at Entrance

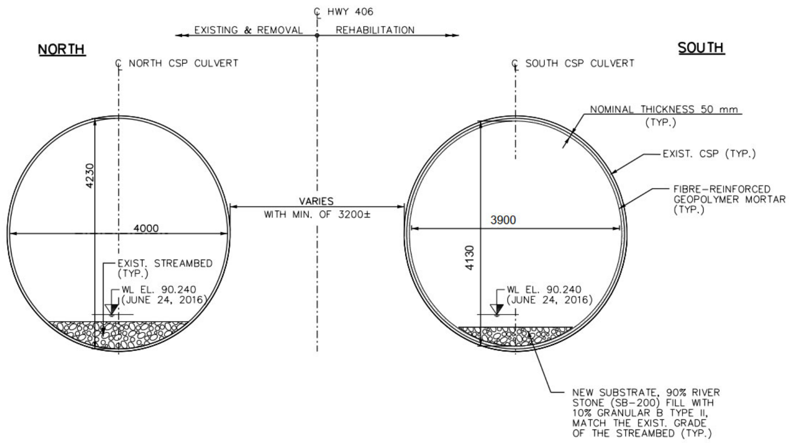

Figure 8: Rehabilitation Cross Section

Figure 9: Hand Spray

9 CASE STUDY 2 HIGHWAY 403 NEAR EGLINTON AVE, MISSISSAUGA, ONTARIO

Highway 403-Eglinton Avenue culvert is a single span ellipse corrugated steel pipe culvert with span of 3.02m, rise of 1.84m, total length of 287.5m long and fill height of 3m over the culvert.. Through the inspection, it was identified that approximately a 10m section of the culvert near the outlet over a traffic demonstrated a severe corrosion and deformation particularly at the lap splice connections at the crown. To prevent local failure of the CSP over the traffic, a feasible and cost-effective rehabilitation strategy was required to address the deformation and severe corrosion of the identified section to prolong the life of the asset. Various alternatives such as replacement of the CSP section through open cut excavation and CSP liner were further investigated but due to the restrictions involved such as requiring long-term closure of the traffic and introduction of user delays, high construction cost estimate and limiting the access point at the outlet for future rehabilitations, Geo-spray liner was selected as a feasible and cost-effective rehabilitation strategy. A finite element model was established to evaluate the geopolymer liner. It was assumed that the existing pipe will not support any loads and all loads will be supported by the new liner. The analysis results proved that the design methodology of distributed beam across a partial ring (Watkins, 2000) is conservative compared to the finite element model calculation and verified the thickness calculated by equation [1] is adequate. Therefore, the design thickness was established as 70mm.

The construction scope included spraying 10m section of the pipe to a minimum of 70mm thickness, which took 1 week to complete with 3 days of spraying and testing. The laydown area is immediately adjacent to the pipe mouth which affecting the wetland in the downstream of the pipe, and the highway 403 traffic was not impacted. The water bypass was set up by dam and gravity bypass pipes through work area with secondary pumping to capture any overflow.

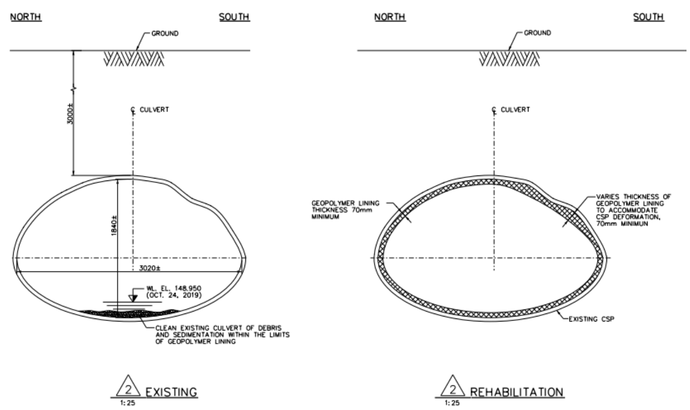

Figure 9: Rehabilitation Cross Section

Figure 10: Pipe after first pass

The culvert's condition after a year of Geo-spray liner application at the local section of the outlet revealed that repaired section overall is in a good condition. The Geo-spray lined section demonstrated no signs of deformation or progression of the deformation from the host pipe. However light corrosion in few areas and local leakage through the Geo-Spray lined section as shown in Figure 11 was identified in areas where previously severe corrosion was noted in the host pipe prior to the rehabilitation. The leakage and local light corrosion may attribute to the extent of surface preparation prior to the lining, challenges involved during the construction with the use of hand-spray application in a small CSP, and possibly minor leaks. Although pressure washing was completed prior to the Geo-spray lining application, further local wire brushing at areas with severe corrosion in conjunction with introduction of wall lining material on the culvert's surface particularly at splice location maybe necessary prior to Geo-spray application to prevent leakage and corrosion deposits penetrating from the host pipes through the cracks on the Geo-sprayed lined section to the surface. In addition, the CSP ceiling was too low for hand spray application. The distance from the nose to CSP ceiling was too close where the pressurized material caused a great impact onto the adjacent just-sprayed material, where it caused it to deform and hence created more porosity and rough surface.

Figure 11: Culvert's Condition a Year After Liner Installation

10 LESSONS LEARNED

- when CSP is below water table, making the CSP totally waterproofing with urethan injection is very costly, suggest to install a valve and let water flow into the pipe when spraying, close it after Geospray is cured
- Compression testing. Contact surfaces need to be perfect flat, and 48 hours drying is required
  a. Grinding the surfaces can be very much depending on the worker and the flatness varies a lot, dedicated worker is required.
  b. When testing crew forgets to take the water out of water 48 hours prior to testing, the results can be lower.
  c. Suggest using sulfur cap instead of neoprene cap, which does not bond to wet surface and force the lab to take the samples from water. Sulfur cap is stronger than mortar,
- Rough surface of 403/Eglinton. The roughness does not affect the strength, as consolidated thicknesses are exceeded. The crown of CSP (3.3m x 1.8) is low for handspray, the distance from nose to CSP surface is too close, the pressurized material cause a great impact onto the adjacent just-sprayed material, and cause it to deform hence the rough surface. If smooth appearance is preferred, hand-trowel immediately after the spray can smooth the surface.

References

Royer, J. & Matthews, J. 2019. Laboratory Testing and Analysis of Geopolymer Pipe-Lining Technology for the Rehabilitation of Sewer and Storm Water Conduits, *Transportation Research Board*, TRB Annual Meeting, Washington DC.

Watkins, R. & Anderson, L.; (2000) "Mechanics of Buried Pipes", *CRC Press*.