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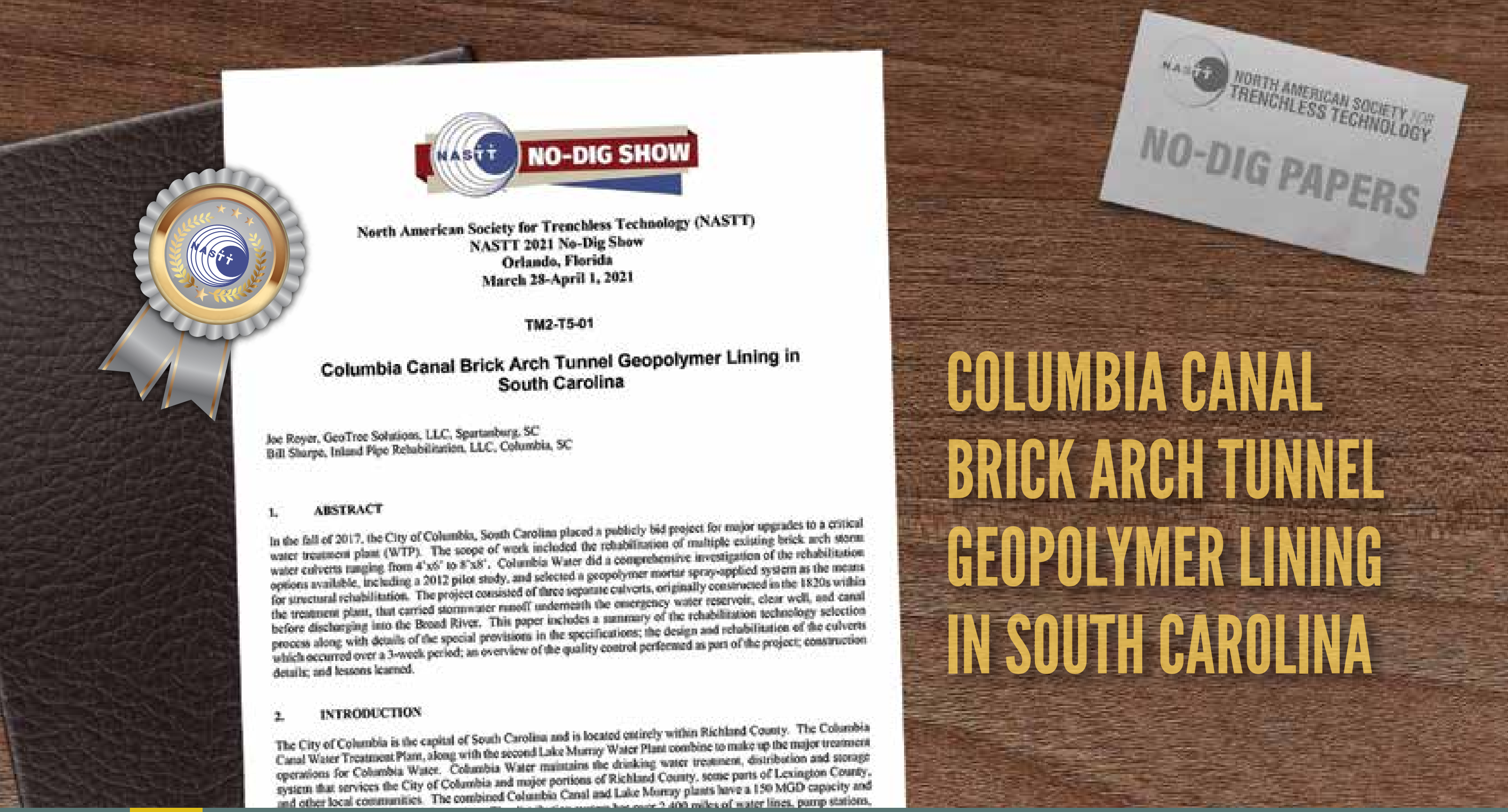

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Columbia Canal Brick Arch Tunnel Geopolymer Lining in South Carolina

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1. ABSTRACT

In the fall of 2017, the City of Columbia, South Carolina placed a publicly bid project for major upgrades to a critical water treatment plant (WTP). The scope of work included the rehabilitation of multiple existing brick arch storm water culverts ranging from 4'x6' to 8'x8'. Columbia Water did a comprehensive investigation of the rehabilitation options available, including a 2012 pilot study, and selected a geopolymer mortar spray-applied system as the means for structural rehabilitation. The project consisted of three separate culverts, originally constructed in the 1820s within the treatment plant, that carried stormwater runoff underneath the emergency water reservoir, clear well, and canal before discharging into the Broad River. This paper includes a summary of the rehabilitation technology selection process along with details of the special provisions in the specifications; the design and rehabilitation of the culverts which occurred over a 3-week period; an overview of the quality control performed as part of the project; construction details; and lessons learned.

2. INTRODUCTION

The City of Columbia is the capital of South Carolina and is located entirely within Richland County. The Columbia Canal Water Treatment Plant, along with the second Lake Murray Water Plant combine to make up the major treatment operations for Columbia Water. Columbia Water maintains the drinking water treatment, distribution and storage system that services the City of Columbia and major portions of Richland County, some parts of Lexington County, and other local communities. The combined Columbia Canal and Lake Murray plants have a 150 MGD capacity and ...

COLUMBIA CANAL BRICK ARCH TUNNEL GEOPOLYMER LINING IN SOUTH CAROLINA

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1. ABSTRACT

In the fall of 2017, the City of Columbia, South Carolina placed a publicly bid project for major upgrades to a critical water treatment plant (WTP). The scope of work included the rehabilitation of multiple existing brick arch storm water culverts ranging from 4 x 6 feet to 8 x 8 feet. Columbia Water did a comprehensive investigation of the rehabilitation options available, including a 2012 pilot study, and selected a geopolymer mortar spray-applied system as the means for structural rehabilitation. The project consisted of three separate culverts, originally constructed in the 1820s within the treatment plant, that carried stormwater runoff underneath the emergency water reservoir, clear well, and canal before discharging into the Broad River. This paper includes a summary of the rehabilitation technology selection process along with details of the special provisions in the specifications; the design and rehabilitation of the culverts which occurred over a 3-week period; an overview of the quality control performed as part of the project; construction details; and lessons learned.

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In 2017 the City of Columbia began a nearly $45 Million overhaul and renovation of its downtown Columbia Canal Water Treatment Plant. The upgrades of the WTP were in addition to the project to repair the adjacent Columbia Canal, which breached during the historic flooding of October 2015. This 100-year flood turned out to be 10 times worse than expected and caused the greatest crisis in the water department's history. The historic weekend deluge saw more than 24 inches of rain and flooded most of the metropolitan area, claiming nine lives in Richland County alone and causing more than $500 Million in damages. (LeBlanc, 2016). During the flooding the nearly 200-year-old Columbia Canal wall gave way, forcing the first ever system-wide, boil-water advisory. Costs of repair quickly grew to $100 Million. The levels of the Broad and Congaree rivers rose more than 12 feet above normal levels and water rushed into the Columbia Canal. Dating back to the 1820s, the canal once served as a shipping lane for cargo. A hydroelectric plant was added in the 1890s, which was still supplying power to the grid up to the time of the flood. The canal is also the source of water to the treatment plant's 60-million-gallon reservoir. While a temporary dam was installed by the National Guard to restore the City's water supply, a long-term rehabilitation solution was required to restore and service the needs of the community.

This paper reviews the history of the Columbia Canal, the adjacent water conveyance systems and the Water Treatment Plant, and the rehabilitation of critical sections of the water conveyance tunnel using a spray-applied geopolymer mortar. It includes a review of the design, preparation and rehabilitation of the conveyance tunnel, lessons learned and quality control for the project.

3. TUNNEL HISTORY & REHABILITATION OPTIONS

The City had known that the canal was a critical point of concern and had been working to understand and test rehabilitation options since the late 1990s. While sections of the canal are open channel, other sections included brick arch tunnels that range in size from 4 x 6 feet to 8 x 8 feet and are used to carry runoff under the emergency water reservoir prior to discharge into the Broad river. These sections fell under the operation of the water treatment plant specifically and were not part of the larger repair of the open channel canal.

The existing storm water conveyance tunnels were originally constructed of brick and granite arched pipes as shown in Figure 1. The City began to investigate the options for restoration and rehabilitation of the tunnel, many of which were quickly decided to either not be feasible or practical as a repair. CIPP was ruled out due to both the size and the shape of the tunnel, and it was determined slip-lining would restrict the area of flow too greatly due to the changing size and shape of the structure. They also decided against other custom-grouted liners due to cost, lead time, and construction duration.

In 2011, the City learned of a new technology, geopolymer mortar spray-applied rehabilitation, that was being marketed to the City by an existing contactor, Inland Pipe Rehabilitation (IPR). The technology offered a geopolymer mortar to structural repair and line large diameter structures. Based on the timing, constructability and cost consideration, the City decided to do a pilot project using the technology.

Figure 1. Internal view of the existing granite and brick tunnel prior to rehabilitation

Figure 2. Completed pilot project example after installation (left) and 5-year inspection (right)

4. 2012 PILOT PROJECT

In late summer of 2012, the City of Columbia under Pizzagalli Construction Company, the general contractor for the wastewater treatment plant rehabilitation, sub-contracted a 440 linear foot section of 72 x 60-inch concrete and stone tunnel to IPR. It was the City's first project with spray-applied geopolymers and offered the City a long-term look at the technology. Prior to specifying the remainder of the storm water conveyance tunnel running under the WTP, the City conducted a complete inspection of the pilot project and found the structure to be unchanged since its installation five years prior. Figure 2 shows a side by side comparison of the post-construction inspections completed in 2012 and a subsequent inspection conducted in 2018.

5. GEOPOLYMER ADVANTAGES AND DESIGN METHODOLOGIES

Geopolymer is a term originally coined by French researcher Joseph Davidovits to describe a class of "cement" formed from aluminosilicates. While portland cement (OPC) relies on the hydration of calcium silicates, geopolymers form by the 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 sodium, potassium and calcium have been shown to affect set-time, compressive strength, bond strength, shrinkage, and other desired properties. In various parts of the world, this type of material is also industrially known as "alkali-activated cement" or "inorganic polymer concrete." (Davidovits, 2011) 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. (Buchwals, 2006) Historically, trial applications of geopolymers were first used in some concrete applications by Glukhovsky and co-workers in the Soviet Union post-WWII; the geopolymer was at the time known as "soil cements." (Alonso, 2001) The use of geopolymers in modern industrial applications is becoming increasingly popular based on their intrinsic environmental and performance benefits.

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. While any specific geopolymer structure, such as the one represented in Figure 3, 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 is a hydrated complex of small molecules that are not covalently bonded but associated. This is shown in a simplified structure in Figure 4. OPC itself is sufficiently complex; the structure shown in Figure 4 is only a basic representation of the molecules. No long chain, covalently bonded backbone or network structure exists in standard cementitious materials.

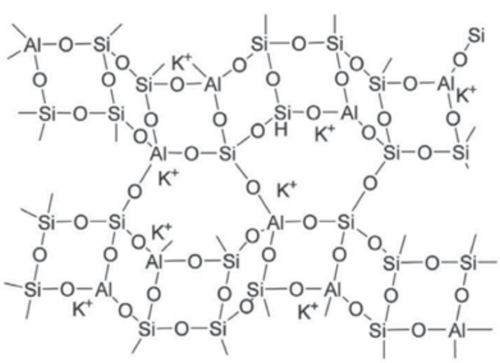

Figure 3. Example of aluminosilicate molecular geopolymer structure (Davidovits, 2011)

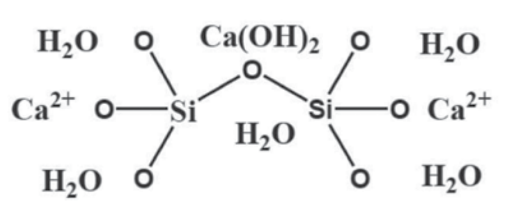

Figure 4. Simplified example of molecular structure of hydrated OPC

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

Columbia Canal Brick Arch Tunnel Geopolymer Lining in South Carolina

Test Method	Property	Duration	Typical Minimum Values
ASTM C39	Compression Strength	1 Day	2500 psi
		28 Day	8000 psi
ASTM C78	Flexural Strength	1 Day	600 psi
		28 Day	1200 psi
ASTM C496	Tensile Strength	28 Day	800 psi
ASTM C666	Freeze Thaw	300 Cycles	98%
ASTM C882	Bonding Strength	1 Day	900 psi
		28 Day	2500 psi
ASTM C1090	Shrinkage	28 Day	0.00%

Table 1. Example Geopolymer Mortar Physical Properties

to the geopolymer at the job site where the mix is then centrifugally, or hand sprayed inside a properly prepared existing structure. The exact formulation of most products is considered a trade secret, but 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. (Koo, 2015) 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 typical alkaline activation mechanisms and the 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.

While no international standard for design of spray-applied liners exists, significant scientific work has been presented and published on the topic specific to geopolymer liners. First and foremost, it is well accepted that geopolymer liners behave in either a semi-rigid or rigid method, and because the rigid models are more conservative, they are often preferred for use. Geopolymers do not behave as flexible pipes and therefore standards such as ASTM F1216 which are based on flexible pipe design methodologies, or other similar standards, that rely on buckling of the structure as a failure mechanism are not applicable. (Royer, 2018)

The most comprehensive work on design methodologies and actual testing of completed structures for spray-applied systems has been conducted on geopolymer materials. The critical concern for design is the generation of initial cracks inside the structure in a longitudinal direction, as this is the structural failure mode that is needed to be analyzed. (Garcia, 2015). Previously published work has shown that the critical design factors should be the ASTM C78 Flexural Strength value of the geopolymer. It is important to understand that while many in the industry are familiar with the design methods contained in ASTM F1216 which rely on a ASTM D790 measurement of the flexural elastic modulus this is not equivalent to the elastic modulus values that are typically testing for geopolymer or other cementitious materials under ASTM C469. The elastic modulus of rigid cementitious materials is measured in compression and are several orders of magnitude larger than the flexural elastic modulus of plastic materials. No standard exists to measure the flexural elastic modulus of geopolymer or other cementitious materials as it is typically not a controlling design parameter. It is critical to understand this variation in measurement and that elastic modulus values obtained by ASTM D790 for flexible plastic materials cannot be compared or substituted for elastic modulus values obtained by ASTM C469 for rigid cementitious or geopolymeric materials.

The design for the Columbia Canal Water Conveyance Tunnel project was based on previous research that showed a conservative design method for this type of structure could include an assumed flexural moment at the internal side of the arched crown. This methodology is based on a moment analysis of a partial ring where the maximum moment at the crown is 0.0062Pr2, where P is the pressure of the distributed beam load applied (Watkins, 2000). The flexural strength SF = Mc/I, where I = t3/12; where c is the distance from the inner surface to the neutral axis of the liner (lever arm). Typically, in a new pipe the neutral axis will be found at the center of the pipe wall. However, because the load transfer between the existing structure and the cement mortar liner is difficult to quantify, it has been assumed that c= t (i.e. the neutral axis is at the interface between the liner and the host pipe), which is a conservative assumption. Where N is the

$$t = \sqrt{\left(\frac{0.0744 q_t r^2}{S_F} \frac{N}{C}\right)}$$

(1)

safety factor, C is the ovality reduction factor presented in ASTM F1216 to account for ovality of the existing host pipe and qt is the total load on the structure. (Royer, 2019)

6. PROJECT BIDDING & SPECIFICATION

In order to expedite funding of the conveyance tunnel rehabilitation, the scope was included as part of a competitive low-bid project for a $45 million plant upgrade. Inland Pipe Rehabilitation (IPR) was selected by the low-bid general contractor, Adams-Robinson, based largely on three factors – prior experience with the pilot project on this conveyance tunnel, good standing relationship with the City, and proximity of their office to the jobsite to reduce mobilization costs.

Based on the applicable loads and physical properties of the geopolymer mortar the design thickness was determined to be 1.5 inches for the 54 x 66-inch pipe sections and 2.25 inches for the 96 x 96-inch sections. The design was prepared by a registered professional engineer in the State of South Carolina as required per the contract specifications. An example of the as- built drawings for the existing tunnel found in the bidding specification are shown in Figure 5.

7. PROJECT CONSTRUCTION & BY-PASS

Once the project was awarded to IPR, the project team mobilized to the job site in June of 2019. The contractor chose GeoSpray® geopolymer mortar produced by GeoTree Solutions as the lining product. The full project consisted of lining 120 linear feet of 54 x 72-inch arched brick pipe and 455 linear feet of 96 x 96-inch arched brick pipe. While the bidding specifications showed a brick structure, much of the existing material had granite blocks in the lower section of the pipe and brick in the arch. Many sections had severe deterioration. Examples of the existing pipe conditions can be seen in Figures 6 & 7. In order to apply a geopolymer liner, all active water flow must be stopped, including infiltration. The existing structure had in some cases nearly 24 inches of granite or brick, this material had either significant areas of missing mortar or areas where mortar was likely never present. To stop the active infiltration, injection grouting with hydrophobic grouts was performed in problem areas. Additionally, once grouted and cleaned, the entire structure was pressure washed and prepared for lining.

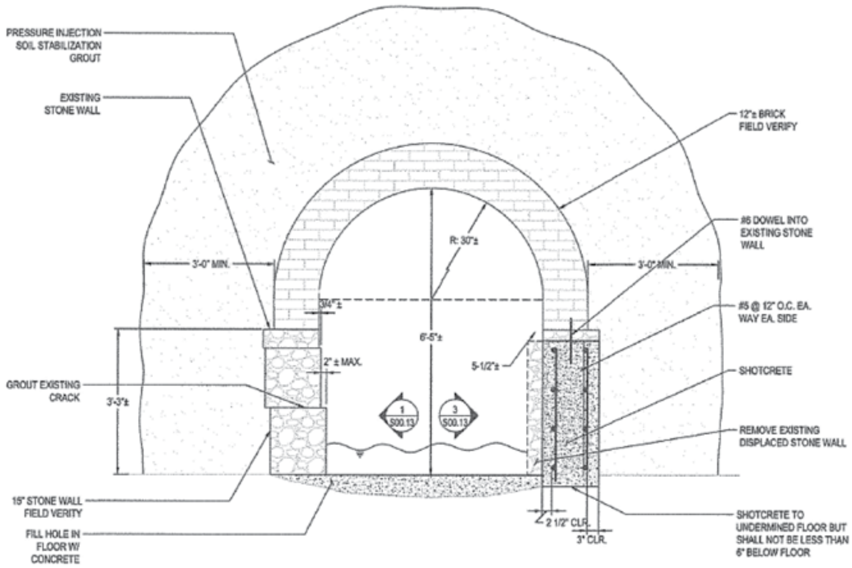

Figure 5. Example of specification drawings for Columbia Canal Tunnel Lining Project

Prior to any work starting a temporary by-pass was installed. At the North tunnel and East tunnel locations a retention pond was built with sandbags upstream of the tunnel. A two-inch electric submersible pump was dropped into the pond. The discharge of the pump was attached to a two-inch PVC pipe, which was attached to the brick wall of the tunnel for 70 feet discharging the water into the pipe downstream beyond the repair area. All voids in the floor were drained from upslope to down slope, then low strength flowable fill was poured into the voids to level the existing conveyance tunnel floor. Next the two-inch PVC pipe was dropped to the floor until the walls were hand sprayed with the geopolymer repair mortar then reattached to the tunnel wall while the floor was then hand sprayed with the geopolymer repair mortar.

At the South tunnel a retention pond was built with sandbags upstream of the manhole in the clear-well (our access point) and upstream of the tunnel repair area. A 6-inch Godwin HS 150mm hydraulic pump was installed at ground level at the access point with 40 feet of suction hose attached. Two-hundred feet of rubber discharge hose was attached to the pump head inside the manhole and discharged into the canal. All voids in the floor were drained from upslope to down slope then flowable fill was used to fill voids and level the tunnel invert. These pumps ran until the linear application was complete.

At the downstream discharge to the river a large sandbag dam was constructed in a ditch between the river and the tunnel to keep a possible rising river out of the tunnel. The contractor installed 3-inch and 4-inch pumps with 30 feet of suction hose in the ditch and 150 feet of suction hose

Columbia Canal Brick Arch Tunnel Geopolymer Lining in South Carolina

Figure 6. Existing conveyance tunnel invert with significant erosion of brick and granite

Figure 7. Example of large cracks in existing tunnel

was installed to carry water to the river with filter bags attached to the ends. All pumps were monitored and checked around the clock and ran until the lining was competed.

One of the more challenging aspects of this rehabilitation was the section that runs underneath the treatment plant that had significant infiltration. The original plan was to use a polyurethane injection grout to provide a protective sheet from the soil surrounding the tunnel. However, the recent flood waters left a portion of the tunnel with no surrounding soil, as it was washed off when the dike was breached. Consequently, the contractor elected to first spray the geopolymer lining, then apply an injection grout between the geopolymer lining and interior brick wall.

The project was divided into three sections. The first was approximately 455 linear feet and the other were each approximately 60 linear feet. The first step of the application was to pour a 2-foot thick floor to the structure with a low strength (3000 psi) compressive strength flowable fill concrete. This was necessary to smooth and level the full section of the tunnel floor, allowing improved hydraulics and facilitating hand-sprayed lining operations. Pouring the floor for the whole project length took two days. Preparation and grouting of each of the sections took approximately one to two days per segment. The finished invert pour is shown in Figure 8.

Once the floor was poured the conveyance tunnel was prepared to receive the lining. The contactor hand-sprayed the geopolymer mortar to create the required design thickness. The material was pumped up to 500 feet after being mixed on the surface, and the thickness was built up over several applications. Typically, for hand-spray applications, material will first be applied on the tunnel wall near the invert, then on the vertical wall and then on the crown. The final application being applied to the invert. One of the key advantages of this specific geopolymer mortar is that it bonds chemically to itself and doesn't allow for the formation of a cold-joint which may occur on multi-layer applications of other cementitious materials. (Royer, 2018) The 455 linear foot section took eight days to spray and the other two sections took

Figure 8. Completed 24-inch thick poured concrete floor to stabilize the flow and smooth the floor

Figure 9. Hand spray application of the geopolymer lining

Figure 10. Completed lining of the original 96 x 96-inch brick/granite arch tunnel

less than two days each. Figure 9 shows the hand spray application. The full project construction of the conveyance tunnel rehabilitation was completed in under three weeks. Pictures of the completed linings are shown in Figures 10 & 11. After the liner was completed a pressure grouting technique was used to grout behind the lining and stabilize the soil, this required cutting ports into the lining that were then repaired with the same geopolymer after the grouting was complete.

8. Quality Control and Quality Assurance

As with any project, planning, follow-up, inspection, and quality control/quality assurance are critical to getting the desired and specified product. With geopolymer linings there are typically three critical measures that are important to ensuring the lining is installed as design and specified: (A) thickness, (B) water content and (C) final geopolymer strength.

(A) Thickness:

To measure the thickness is it common for the contractor to tap the structure with depth screws or depth indicators that are placed about 1/8 inch below the desired thickness prior to lining. These gauges are placed at frequent spacing and various clock positions within the pipe to provide a visual guide that the proper thickness has been applied when all the gauges are covered in the final application. The thickness can also be gauged by the amount of material used. Contractors typically provide an estimated quantity of material that is needed to apply the desired thickness over the structure. The actual quantity used can be verified by the inspector to ensure that the full amount of material was utilized for the lining.

(B) Water Content:

Water content, or more specifically water to material ratio, is critical to ensuring that the proper material properties are developed. For the geopolymer product

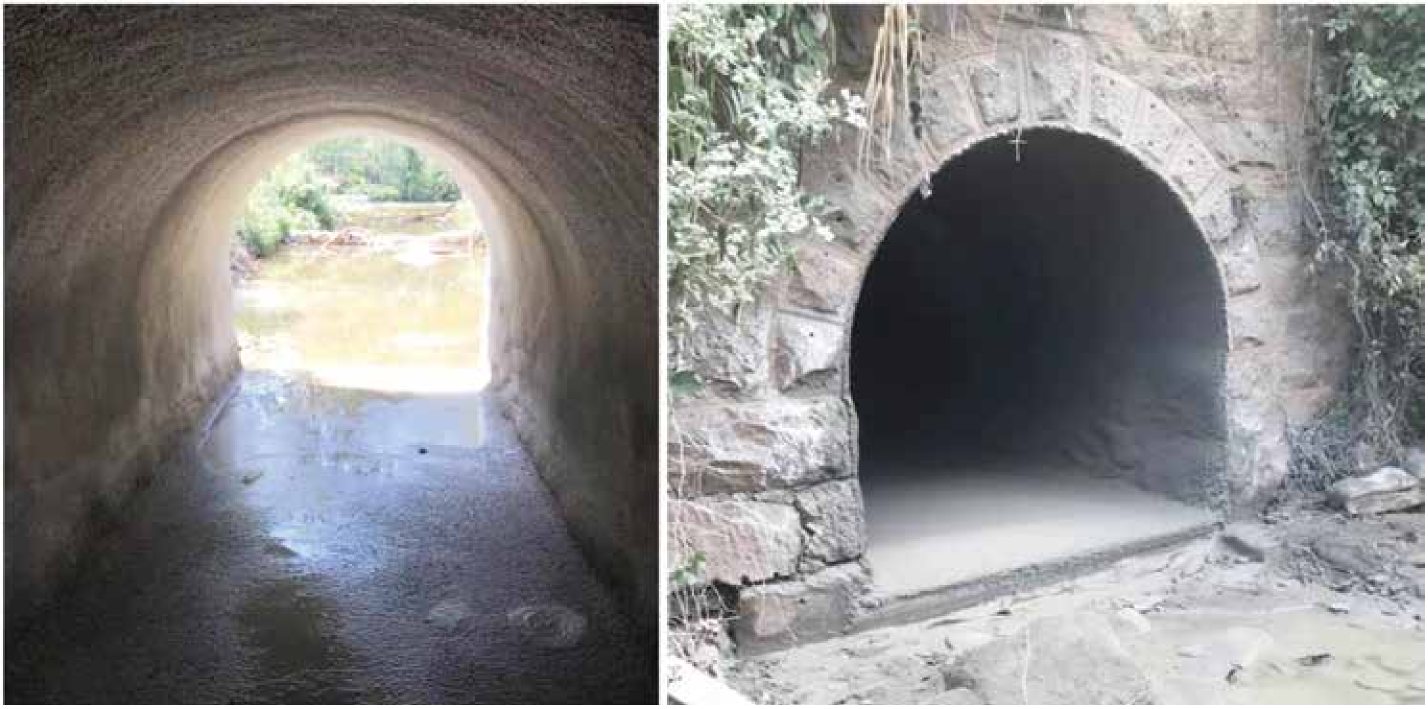

Figure 11. View of the completed lining at the outlet of the tunnel at the Broad River

used on this project, the maximum allowable ratio was 0.20 (i.e. 20 lbs of water per 100 lbs of geopolymer powder). A 3rd party inspector recorded the water settings on the mixing system prior to lining to ensure that excess water was not used.

(C) Final Geopolymer Strength:
The most critical part of quality control is the measure of fully cured physical properties. It is generally best to measure compressive strength of these samples after 7 and 28 days. The important value is typically 28 days and should meet the required minimums for material properties found in the specification. Materials suppliers should be able to provide the asset owner and engineers with a correlation of compressive strength which easily measured in the field to other physical properties not as easily measured such as flexural strength which is typically the critical design value. It is recommended that ASTM C39 cylinders be used, this measurement is more conservative than the ATSM C109 cube method for geometric reasons. During each day of spraying, six 4 x 8-inch cylinders were taken into the tunnel at the point of geopolymer application. The cylinders were produced by a certified 3rd party technician and tested by an independent laboratory. Two of the cylinders were tested at 7-days maturity to give an indication of early strength and to verify the testing method, then three of the samples were tested at 28 days. The 28-day samples each exceeded the specified value of 8,000 psi. (The American Concrete Institute – ACI, requires a minimum of three samples for a full test of this type at any maturity time frame.) A final cylinder was held in case of any discrepancies and could be tested at 56 days as necessary.

Figure 12. View of the completed lining at the outlet of the tunnel at the Broad River after 2 years of Service

8. 2020 Inspection
An inspection of the completed project was conducted in August of 2020 a full 2 years after the completion of the lining with the contractor and material manufacture. The lining was observed to be performing as designed with no visible cracks or structure concerns. A picture of the lining after 2 years in service is found in Figure 12 and can be compared to the original installation image in Figure 10.

9. CONCLUSIONS

The Columbia Canal owned and operated by the City of Columbia has construction dating to the 1820s. In October of 2015 a rain event in excess of the predicted 100-year storm levels damaged the canal and put significant stress on the water treatment plant and the City water supply. After emergency repairs were made by the National Guard to the open channel canal, an overhaul and upgrade of the WTP was undertaken beginning in 2017. One of the key aspects of the project was to rehabilitate and restore the structural strength of the existing brick/granite arched conveyance tunnel that was part of the canal system and diverted storm water away and under the treatment plant. A pilot project with geopolymers that was completed in 2012 supported use of the same technology for the full rehabilitation in 2018. The project included lining approximately 600 linear feet of arched pipe up to 8feet in size. The preparation and construction of the lining took approximately 24 days and was completed in the 3rd quarter of 2018.

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