STRUCTURAL REPAIR OF PIPES 900MM AND LARGER USING GEOPOLYMERS

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ABSTRACT

The care and maintenance of infrastructure has become a global issue. One of the most critical areas of concern is wastewater piping and related structures. It is well known that corrugated metal pipes used in storm-water structures are corroding and microbial-induced-corrosion of sanitary sewers of various materials results in structural concern. Geopolymers have long been known to provide enhanced physical performance to traditional cementitious binders with the added advantages of significantly reduced greenhouse emissions and superior chemical resistance. Geopolymers are ceramic polymer technology that creates a chemical material similar to natural stone that is superior to traditional Portland cement and shotcrete materials. However, they have not generally been contractor-friendly.

This paper reviews a geopolymer mortar system that has been used in the U.S. since 2011 is gaining use in additional global markets for trenchless pipe rehabilitation. The system is spray cast either by rotary nozzle or via traditional shotcrete delivery systems inside of existing structures to create whole new structures which do not depend on the existing structure, just using it as formwork. This paper discusses competitive advantages over other trenchless repair solutions such as spiral wound, slip-lining and CIPP through specific case studies including a corrugated metal storm drain rehabilitation in Hidalgo, Texas along with the repair of a concrete storm sewer in Hong Kong

1 INTRODUCTION

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 as 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 become larger (>1200mm), 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 120mm diameter sewer pipe were located in the center of town and a standard 750mm or 900mm manhole was the access point, in order to perform a CIPP (Cured-In-Place-Pipe) repair it would be necessary to excavate an access hole of at least the 1200mm diameter. While other techniques such as slip-lining would require even greater excavation for an access hole to install new liners. Additionally, with many of the standard so called 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 unpractical (Buczala,1990) (Osborn, 2010).

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 disruption. One such technological advance is the use of centrifugally cast geopolymer mortars to create a new pipe inside the existing old pipe (Henning, 2012). This techniques allows for a cementitious pipe to be created within the existing structure, using the existing pipe as a form, and can be designed such 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 equipment necessary can easily fit down standard manholes and all excavation can be avoided if there are access points at least every 250 meters.

The benefit of geopolymer mortars as compared to traditional Portland cement (OPC) materials is detailed in the following discussion. Additionally, case studies are included.

2 GEOPOLYMERS

Geopolymer is a term originally coined by French researcher Joseph Davidovits to describe a class of "cement" formed from aluminosilicates. While traditional Portland cement 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 (Bell, 2008) (Buchwald, 2006) but with the added advantages of significantly reduced greenhouse emissions, increased fire and chemical resistance, and reduced water utilization (Alonso, 2001). The use of geopolymers in modern industrial applications is becoming increasingly popular based on both their intrinsic environmental as well as performance benefits. 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 then known as "soil cements" (Davidovits, 2011). Figure 1 shows a typical aluminosilicate structure that is common among many geopolymer materials.

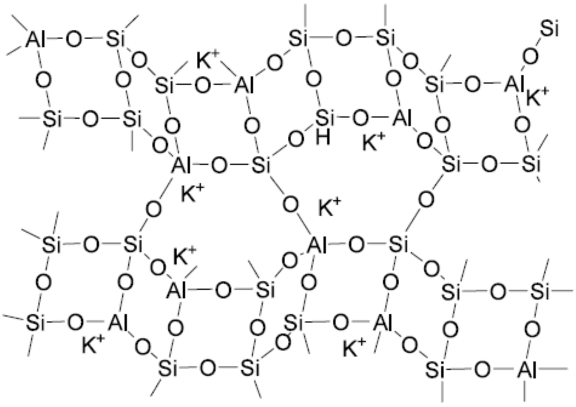


Figure 1: Example Aluminosilicate Molecular Geopolymer Structure

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 alumniosilicate back bone 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 make-up 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 rather associated. This is shown in a simplified structure in Figure 2. OPC itself is sufficiently complex that the structure shown in Figure 2 is only a basic representation of the molecules but no long chain covalently bonded backbone or network structure exists in standard cementitious materials.

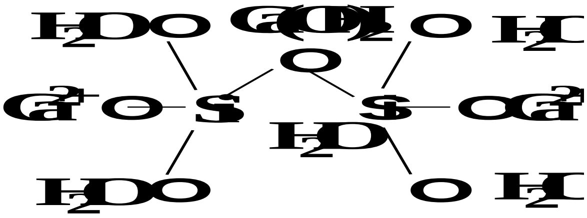
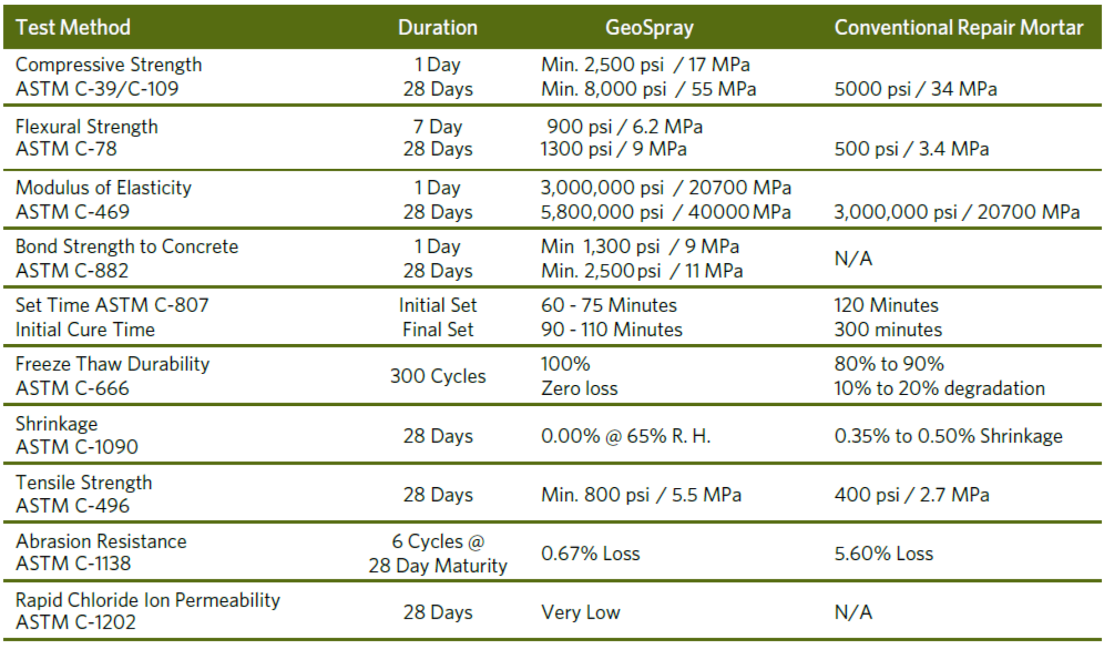


Figure 2: Simplified Example Molecular Structure of Hydrated Portland Cement (OPC)

3 GEOSPRAY GEOPOLYMER MORTAR

A specific example of a formulated geopolymer repair mortar is GeoSpray produced by Milliken Infrastructure Solutions, LLC. It is formulated to meet all the physical and chemical requirements for rehabilitating sewer and storm water structures. 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 are considered trade secrets, but generally speaking, geopolymers contains 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. Additional bio-based admixtures are included in the formulation in order 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 particular geopolymer system has been specifically developed to avoid the typical alkaline activation mechanisms and order of addition complexities of traditional geopolymers which have limited significantly the ability of most contractors and asset owners from using geopolymers commercially. A summary of the physical properties of GeoSpray as compared to conventional concrete pipe repair mortars is included in Table 1.

Table 1. Typical properties of GeoSpray compared to Conventional Cement Based Repair Mortars



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	900 psi / 6.2 MPa 1300 psi / 9 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 1,300 psi / 9 MPa Min. 2,500 psi / 11 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	6 Cycles @ 28 Day Maturity	0.67% Loss	5.60% Loss
Rapid Chloride Ion Permeability ASTM C-1202	28 Days	Very Low	N/A

With this type of repair mortar, the entire system is contained within the original powder formulation, allowing a single step addition. It is common for these materials to be pumped up to 150m 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.

4 GEOPOLYMER ADVANTAGES

4.1 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 include: 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 50mm by 100mm 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 45º angle in the lower portion of the cylinder (as shown in Figure 4). A second pour atop the

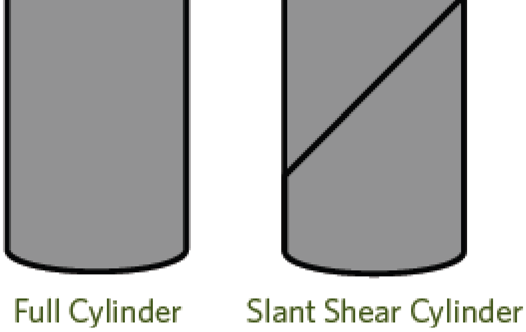


Figure 4: Schematic Illustration of Cold Joint Compression Experiment

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.

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 45º 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 of 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.

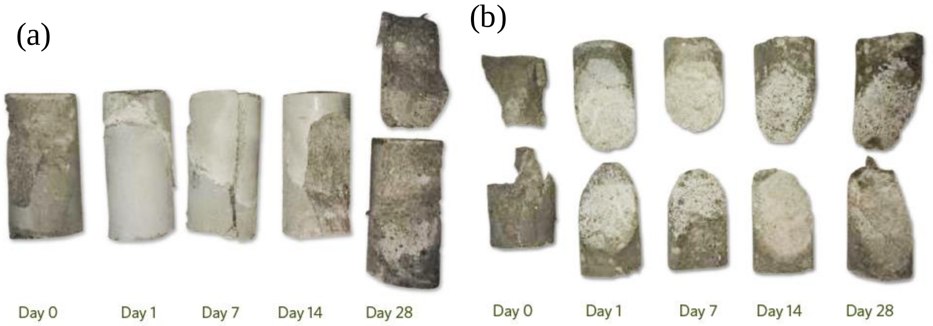


Figure 5: (a) Geopolymer samples showing compression failures located away from the joint (b) OPC samples with compression failure located at the joint.

4.2 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 or (MIC). The process of MIC involves a 3 step mechanism (shown schematically in Figure 6):

- First, hydrogen sulfide gas (H_2S), commonly referred to as sewer gas, is released by the reduction of sulfates in the sewer effluent from anaerobic bacteria – generally living in a "slime layer" below the water line.
- Secondly, sulfuric acid (H_2SO_4) is formed on exposed surfaces through the oxidation of H_2S by aerobic *Thiobacillus* bacteria.
- Finally, the sulfuric acid reacts most often with calcium hydroxide $Ca(OH)_2$ found in many cements to form gypsum $CaSO_4 \cdot 2H_2O$ which is water soluble and will wash away.

The chemical make-up of geopolymers makes them inherently more acid resistant to the MIC mechanism

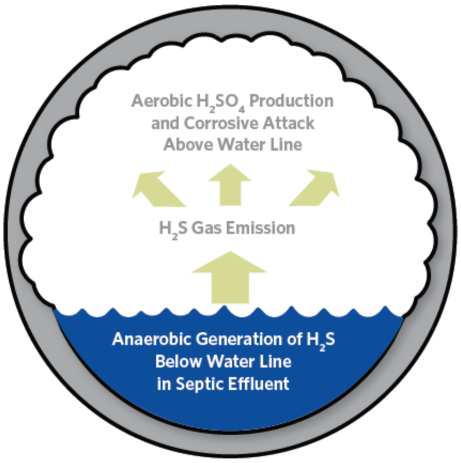


Figure 6: Schematic of the Chemical Processes associated with MIC Corrosion

found in many sewer environments. Geopolymers (dependent on the exact formulation) will contain greatly reduced concentrations of $Ca(OH)_2$ (calcium hydroxide) essentially preventing the acid corrosion mechanism found in many typical cements. Chemical resistant studies were performed following the procedures of ASTM-C267. Geopolymer sample cubes were cast and allowed to cure for 28 days before being soaked in both water and 7% sulfuric acid (pH 0.9). OPC cubes were also cast and soaked as representative samples for standard reinforced concrete pipes commonly found in sanitary sewer systems.

Samples were measured for weight and dimensional changes after soaking for 1, 7, 14, 28, 56 and 84 days. 3 samples of the materials were soaked and tested, and the solution volume relative to the cubes was held constant. The chemical solutions were refreshed on day 14, 28, and 56. Geopolymer samples showed only slight loss of mass and signs of surface corrosion through the 84 days exposure to 7% H_2SO_4 (sulfuric acid), while the Portland cement samples lost more than 50% of their weight over the same time period. Figure 7 shows samples cubes before and after 84 days of soaking exposure.

Figure 7: Image of cubes before and after soaking in 7% H_2SO_4

Figure 8 shows the effect of the 7% sulfuric acid on weight of the geopolymer and OPC cubes over the same time period. The results of weight are normalized to the percentage of weight change of samples soaked in water to account for the absorption of water. Through the 84 days exposure the geopolymer corrosion was approximately 1/5th of the standard OPC material.

When tested under the ASTM C-267 protocol against aggressively corrosive 7% sulfuric acid (pH 0.9), the geopolymer showed only approximately 5-7% (note: the samples are compared to water soaked materials and the below 0 starting point is due to gel formation of H_2SO_4 and not true weight loss) weight loss and slight surface corrosion compared to the >50% weight loss observed in OPC samples that reflect concrete sewers in use today. Where concrete pipes and structures exhibit the effects of microbial induced corrosion, geopolymers should result in significant resistance improvement over OPC.

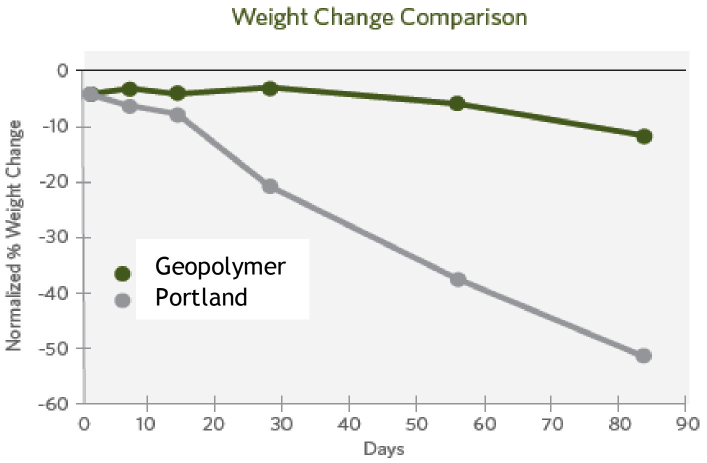


Figure 8: Comparative weight change over time for soaked cubes

5 CASE STUDIES

5.1 MCALLEN, TX. USA (2.9 METER CMP STORM DRAIN REHABILITATION)

In the rapidly growing Texas border town of McAllen, dealing with storm water runoff is a challenge. The weather fluctuates quite rapidly, and ensuring that storm water infrastructure is capable of dealing with large amounts of water quickly is of paramount concern. As the population of the community has nearly tripled over the past two decades, some of their storm water infrastructure has presented an ongoing challenge.

Such a problem was the Rado Storm Drain, located within one mile of the Rio Grande river. The storm drain consists of 2 side by side 2900mm (114 inch) corrugated metal pipes (CMP) each over 670 meters in length. The pipes had wear and structural issues since originally installed and have been repaired in various sections over the past decade with a non-structural shotcrete and a bitumen coating. These attempted repairs were completed over short segments of the pipe, but large scale separation of the joints along with water infiltration continued to be major concerns.

The local municipalities had experience with non-structural repairs in the past that had not been successful on this particular application. They investigated several repair options including Cured-in-Place-Pipe (CIPP), slip-lining, and geopolymers. Both the CIPP and slip-lining solutions were significantly higher cost with additional complications due to the large diameter. The community decided to specify a cementitious lining as their structural application. Inland Pipe Rehab, LLC using their Ecocast™ process installed GeoSpray as the repair solution for this project in the spring of 2014.

Because there were two side-by-side pipe sections, only one was repaired at a time and all of the flow was diverted to the other section. Each pipe section was cleaned and inspected for joint failure, cracking, and infiltration. Stopping water infiltration was the primary challenge of the project and required meticulous preparation. These issues were addressed with hand repair to ensure that all the infiltration of water was stopped and a continuous surface for the application of the geopolymer mortar was created. Once these issues were tackled, 50m to 100m sections were then sprayed with the final engineering designed thickness of 38mm of geopolymer. The ability to apply a 38mm thick layer in a single spray pass saved both time and cost for the asset owner. During most days of operation, the contractor was able to apply between 10,000 and 20,000kg of geopolymer in a single run within the pipe, creating a truly monolithic structure.

The use of geopolymer to create a new pipe within the existing CMP structure that existed was completed on time and under budget. The new pipe is ready to handle the unpredictable storms of southern Texas for years to come. Figure 9 shows a series of images from the job site, this includes upstream the entrance to the pipes, a view of the joint separation on the shotcrete repaired structure, the geopolymer application and the finished pipe.

Figure 9: Images from the jobsite for the Rado Storm Drain; McAllen, TX. USA

5.2 SHA TIN PASS, HONG KONG (1.4M STORM SEWER REHABILITATION)

As part of an evaluation of the geopolymer spin casting technology, the Drainage Services Department (DSD) of Hong Kong decided to rehabilitate a troublesome section of their storm sewer system. The DSD, and their engineering consultant Black & Veatch, discovered that a 110m section of concrete and stone sewer line was heavily deteriorated and in structural decline. CCTV records of the section showed almost no concrete lining, long sections of stone missing, and the invert almost completely washed away.

This specific project presented a host of unique challenges. First, the section of the pipe was on an almost 20^{o} slope on a heavily traveled and curved road. Second, the access to the pipe was in front of a hospital which limited the level of noise that was allowable. Due to the location, the work hours each day were limited such that minimizing disruption was a high priority. Finally, with a short window to complete the project after the Lunar New Year holiday, it was necessary to utilize a solution that could be flexible as well as quickly implemented.

In reviewing their options to address the deteriorated pipe, the DSD quickly realized that replacement was not a viable option because of the pipe's depth and location. When considering alternative trenchless methods a number of options were evaluated including Cured-In-Place –Pipe (CIPP) and Slip-lining. CIPP was a viable solution a viable solution, but due to the short hours in which to work each day, the fumes from the resin in close relation to local residents and hospital patients, and the steep slope of the road, this option was rejected. Slip-lining of the pipe was also a poor option for the same reasons, would have required digging several large access pits and result in an extremely expensive and disruptive project. In the end, the DSD chose to apply a geopolymer lining that would machine sprayed to create a new structure lining, repair the leaking, and return the pipe to its original shape.

Construction on the site began in March 2015. The first task was to bring the bottom/invert of the pipe back up to form. This was completed using ordinary Portland cement. The process of creating a virtual "pipe within a pipe" with a geopolymer liner means that uses the outer structure as the form and then establishes a monolithic structure within that form. Therefore, the contractor could use lower cost materials to create the form.

Second, it was necessary to clean the pipe with a high pressure wash and then to use a hand spray application of geopolymer to stop any leaking or water infiltration and to stabilize the existing block structure. One critical advantage of the technique of centrifugally spraying a geopolymer liner is that the equipment foot print can be limited to the size of approximately two 6 meter trucks and spraying can occur more than 150 meters from the actual mixing location. This allowed the crew to minimize any traffic disruption.

A mechanical sled system was used to apply the geopolymer liner and to arrive at the engineer's required thickness. While the geopolymer material can be placed up to 75mm in a single pass, it was decided to make three passes of 13mm to bring the total thickness to 38mm, which was the engineer's design requirement. This flexibility allowed the contractor to maximize application time each day, resulting in a more cost effective project. From start to finish the full project was completed in under 21 days, ahead of schedule and on budget. The flexibility of geopolymer mortars makes them an excellent choice for the toughest sewer repairs. Figure 10 shows a series of images from the job site.

6 CONCLUSIONS

Geopolymer mortar repair systems have been developed to be a cost effective alternative to other trenchless repair systems for large diameter pipes. Geopolymers have advantages over traditional OPC systems relating to the chemistry of the materials and how they are reacted that include (a) lower CO_2 footprints, (b) reduced tendency for cold joints and (c) enhanced chemical resistance. Multiple case studies have been shown where structural pipe repairs were designed and completed for both storm drain and sewer applications.

Figure 10: Images from the Sha Tin Pass, Hong Kong

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