PAPER 15

H_2S BIOGENIC CORROSION: WHY USING CALCIUM ALUMINATE CONCRETE AND MORTARS TO REHABILITATE CORRODED SEWER INFRASTRUCTURES

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ABSTRACT

H_2S biogenic corrosion is a growing problem for sewer owners around the world. In South Africa, the climatic conditions are especially favourable to the development of severe H_2S corrosion in municipal sewers and many municipalities have confirmed the pre-eminence of this issue. The most common and current rehabilitation method is to use polymer linings such as epoxy but the too high failure rates observed around the world, by many operators, is pushing them to search for a more reliable alternative solution.

Calcium aluminate cement (CAC) based mortar or concrete is one such alternative. This paper presents a short review of the H_2S biogenic corrosion process and the reasons explaining the exceptional durability of calcium aluminate cement to this deterioration process. In the absence of a standard test method, field track records remain the most reliable source of data to evaluate the biogenic corrosion resistance of repair materials, and such long term references are reviewed.

In South Africa, calcium aluminate cement has been utilized for decades to protect new concrete sewers pipes from H_2S biogenic corrosion, and Ciment Fondu® lined concrete pipes is a standard offer from concrete precast industry. The Virginia Experimental Sewer long term study, launched in 1989 and still on-going today, is a unique industry asset not only in South Africa, but also around the world. However, for the rehabilitation of corroded sewer infrastructures, the use of CAC based solutions is much less known. This paper aims to present how the municipalities can take advantage of the exceptional H_2S corrosion resistance of CAC mortar and concrete, through illustrationwith recent projects completed in South Africa.

INTRODUCTION

H_2S biogenic corrosion is a growing problem for sewer owners around the world. The Municipal Engineer in charge of sewer infrastructures – both the collection network and the sewage treatment plants - is often facing the premature decay of this essential asset. This paper proposes a general review of this important issue, explaining the reasons for the H_2S corrosion to happen, and moreover why the calcium aluminate solutions are a good choice for the Municipal Engineer to protect or rehabilitate the municipal asset.

The stakes are critical since a city cannot be "operational" if the sewer system is getting out-of-order. Because the sewer network is buried underground, most citizens do not realize the extent and the vital importance of this invisible grid transporting the septic waters away, up to the sewer treatment plant. One key challenge for the Municipal Engineer, and the Consulting Engineers working on his behalf, is to maintain this asset at a satisfactory level of serviceability, at a bearable cost. The goal is to ensure a long lasting performance, i.e. that a "sustainable" network is handed to future generations.

In South Africa, the warm and often dry climate is very favourable to the development of the H_2S corrosion conditions. Even within a well-designed sewer network, where the pipes diameter and slope are chosen to minimize the risk of H_2S formation, a rule of thumb in the industry suggests that at least 5% of the total length may/will suffer from biogenic corrosion. In fact, with the city expansion over time, it is not always possible to maintain ideal flow conditions of sewage. In these areas where the favourable conditions are reached, H_2Sbiogenic corrosion will deteriorate metal and concrete.

The South African engineers have acknowledged very early that the country climate and geography was prone to create H_2S corrosion conditions, and that a correct hydraulic design cannot be the only answer. This is why, as early as in the 1950s, the South African sewer industry implemented concrete pipes protected with a calcium aluminate cement (CAC) mortar lining. Such Ciment Fondu® lined concrete pipes are still a standard offer today. Moreover, the South African industry has been supporting, for almost 30 years, a unique "real-life H_2S corrosion study platform" at the Virginia Experimental Sewer (VES) which provides a unique body of well-documented results. The VES Project gave a very solid ground to define the corrosion control design approach proposed in the *Sewer Design Manual* published by the South African precast industry in 2008 (Goyns 2008).

The most recent chapter in South Africa for calcium aluminate cement products in sewer infrastructures has been its use for the rehabilitation of H_2S corroded structures. While the application of resin liner like epoxy is perceived as the industry reference for rehabilitation, the costs of this approach combined to the rate of failure observed in the field is a problem for sewer owners. One proven alternative solution is to utilize a calcium aluminate cement based mortar to repair H_2S corroded concrete structures. This solution has been applied for more than 25 years around the world with excellent track record, although it is still little known inthe industry. This paper provides more information about this additional tool for the Municipal Engineer to maintain the service level of city assets.

WHAT IS H_2S BIOGENIC CORROSION

The H_2S biogenic corrosion process in a septic sewer is the result of a two steps ecosystem that is summarized in Figure 1. The septic effluent by itself is not corrosive for concrete (in the absence of industrial effluent) with a typical pH around 7. However, it contains plenty of "food" that will feed bacteria, initiating the deterioration process.

The first step of H_2S biogenic corrosiontakes place in water, in locations where the effluent is deprived of oxygen because all the available dissolved oxygen has been consumed by bacteria for breathing or because of chemical oxidative reactions. Once the water is deprived of dissolved oxygen, some strains of anaerobic bacteria will literally "strip" the oxygen from the sulphates (from the organic matter, or from soil water or sea water intrusion) to continue breathing. One result of this metabolic action is the production of hydrogen sulphide (H_2S). When transition times are long (little slope, low volume of effluent, retention point), anaerobic bacteria will produce enough H_2S to saturate the water and H_2S gas will be released into the sewer aerial space above the effluent. Turbulent areas like at flow direction change in manholes, wet-wells, pumping stations or hydraulic jumps favour H_2S release. As H_2S gas is heavier than air, it tends to stay within the sewer system. The H_2S gas is remarkable for its "rotten egg" smell; it is also a deadly gas calling for stringent safety procedures for workers in sewers.

The second step of H_2S biogenic corrosion takes place in the aerial part of the sewer. On the wet walls and ceiling of sewers, other strains of aerobic bacteria are using the sulphur from H_2S as a source of energy by oxidizing it. The result of this oxidation is sulphuric acid (H_2SO_4). It is this bacteria borne sulphuric acid that is corroding away the concrete and the metal, and this is

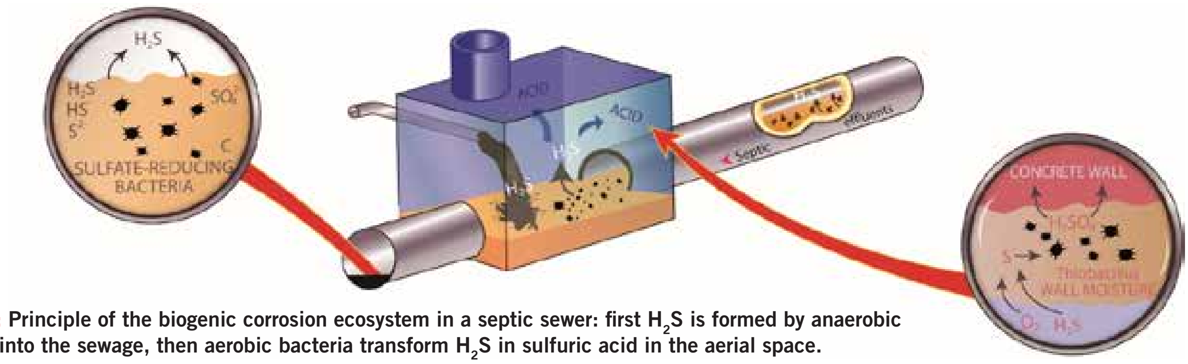

Figure 1: Principle of the biogenic corrosion ecosystem in a septic sewer: first H_2S is formed by anaerobic bacteria into the sewage, then aerobic bacteria transform H_2S in sulfuric acid in the aerial space.

why this process is named "biogenic" corrosion.

Figure 2 is showing the typical appearance of a concrete wall in a sewage treatment plant (STP) being severely damaged by H_2S biogenic corrosion.

Figure 2 – Typical appearance of severe H_2S biogenic corrosion damages in the entry channel of sewage treatment plant: around 50 to 70 mm of concrete has been lost with rebars totally corroded away in some parts.

HOW CALCIUM ALUMINATE RESISTS TO H_2S BIOGENIC CORROSION

Calcium aluminate cement (CAC) is a speciality cement with a different chemistry and a different mineralogy from Ordinary Portland Cement (OPC), the usual cement in the construction industry. CAC are made by fusing limestone (source of calcium) and bauxite (source of alumina) and the main component is "calcium aluminate" (CA), hence the name calcium aluminate cement. The first calcium aluminate cement was the "Ciment Fondu®", patented in 1908. In South Africa, there is a calcium aluminate cement plant in the KwaZulu-Natal province since 1975.

Mechanism of resistance to H_2S biogenic corrosion

Because of its different chemical nature, calcium aluminate cement has several properties that differ with those of OPC. One of these differences is the capacity to resist very well to the most severe H_2S biogenic corrosion condition, in places where OPC concrete rapidly deteriorates. The Figure 3 compares the appearance of small cylinders made of 100% CAC mortar and OPC mortar hung inside the screening chamber of a sewage treatment plant for 2 years. While the OPC specimen has been almost destroyed within 2 years, the CAC specimen appears almost intact. The mechanism explaining such a drastic difference of behaviour is well understood and explained here below.

Figure 3: **In situ specimens exposed for two years in the grit chamber of Monterey Wastewater Treatment Plant. Left: 100% CAC mortar. Right: OPC mortar**

When OPC concrete is exposed to the sulphuric acid produced by bacteria, the OPC hydrates (C_2S, C_3S) are dissolved and the calcium (Ca) from OPC reacts with sulphuric acid (H_2SO_4) to form gypsum ($CaSO_4{\cdot}2H_2O$). This wet gypsum appears as a soft whitish mud with no cohesion. Depending on the severity of the conditions in the sewer (moisture level, H_2S level, nutrients for bacteria, etc), the corrosion rate observed on OPC concrete can be as rapid as 10 mm per year.

In the case of CAC mortar or concrete, exposed to the very same H_2S environment, the behaviour is completely different and CAC appears resistant to H_2S biogenic corrosion. This is explained by the combination of 3 different mechanisms:

1. The first mechanism is the **larger neutralization capacity** of CAC vs. OPC; one gram of CAC can neutralize around 40% more acid than a gram of OPC. This means that for a given production of acid by the biofilm, a CAC concrete will last longer;
2. The second mechanism is due to the **precipitation of a layer of alumina gel** (AH_3 in cement chemistry notation). When the surface pH gets below 10, the aluminate precipitates as alumina gel. This AH_3 gel is a stable compound down to a pH of 4 and it will form an acid-resistant barrier as long as the surface pH is not lowered below 3-4 by the bacterial activity;
3. The third barrier is the **bacteriostatic effect** locally activated when the surface reaches a pH value less than 4. At this level, the alumina gel is no longer stable and will dissolve, liberating aluminium ions into the biofilm covering the walls. These aluminium ions will produce a "bacteriostatic effect" on bacterial metabolism, i.e. bacteria will stop being active. In other words, bacteria will stop oxidizing the sulphur from H_2S to produce acid, and the pH will stop decreasing. This third barrier – the

bacteriostatic effect - is the most important and it explains largely the calcium aluminate capacity to resist severe biogenic corrosion. Rather than trying to resist a continuous flow of acid – like an epoxy lining would do - the calcium aluminate surface stops the production of acid, putting the corrosion process on hold.

Academic research around the world and in South Africa

The H_2S corrosion resistance mechanism just described above is a synthesis of the global understanding developed over decades from various academic researches. While it is beyond the scope of this paper to do a detailed bibliographic review, few milestone contributions deserved to be mentioned here.

At Hamburg University, in the 1990s, the team of Professor Bock developed a biogenic simulation chamber where the sewer ecosystem was reproduced in order to test building material specimens in realistic but accelerated conditions. Operating such a simulation chamber was a quite delicate task as it necessitated microbiology skills to "cultivate" a representative and viable biomass. During the first few months of exposure, nothing visible happened because it took this time for the bacteria to colonize the concrete specimens and start lowering the pH enough to create damage. Within one year in the Hamburg Simulation Chamber, concrete specimens were showing damages equivalent to 24 years in a reference sewer located in Hamburg and described as highly deteriorated. Pr Bock worked for around 10 years on this topic and proposed the CAC resistance mechanism described above (Ehrich et al. 1999).

In South Africa, the "Virginia Experimental Sewer Project" was commissioned in 1989 under the sponsorship of the concrete industry. Nine different types of concrete – including CAC based concretes - were utilized to manufacture 900 mm diameter concrete pipes. Those pipes – 65 m length in total - were installed in a sewer known for its severe H_2S corrosion conditions. This section was doubled with a by-pass line allowing diversion of the water flow on demand, for regular inspection. Inspections and measurements were done after 5, 12 and 14 years. At the 14th year, some OPC concrete sections were so badly corroded that they had to be removed before they collapsed. The removed sections were replaced by a new set of specimens of shorter length – once again including CAC based concretes - allowing to explore new options for durable sewer construction. Over all those years, Alaster Goyns, a South African consultant specialized in sewers and storm water, has been managing this project and has been closely involved with the analysis and publication of the results.

Professor Mark Alexander, from Cape Town University, has been involved over the years in the Virginia Experimental Sewer by directing different M.Sc. and PhD studies. Using the data gathered from the VES Project, Goyns & Alexander 2008 proposed an improved version of the "Life Factor Method" (LFM) developed by Pomeroy and Pakhurst. While the original LFM only considered the alkalinity of concrete, the Virginia Experimental Sewer results gave a sound base to take into consideration the whole influence of the material through a "Material Factor" to be added in the LFM method.

The South African pipe manufacturing industry published these results, the improved LFM and the material factor proposed value in the Sewer Design Manual published in 2008. More recently, in 2016, Moses Kiliswa obtained his Ph.D. degree from Cape Town University for an in-depth study of concrete pipes exposed for 10 year to H_2S corrosion in the Virginia Experimental Sewer (Kiliswa 2016). Overall, the South African VES Project is a very unique contribution to a better understanding of H_2S corrosion resistance of concrete.

In France, the national research institute IFSTTAR launched in 2010 a program to improve the "doctrine" relative to concrete sewer infrastructure construction. One part of this program involved monitoring different type of concrete specimens - including some CAC based specimens - exposed to severe H_2S biogenic corrosion in a sewage treatment plant in Arcachon, in southern part of France. The results after 4 years of exposure were published by Herisson et al. 2017. The Figure 4 is showing the corrosion observed on OPC and CAC specimens after 6 years of exposure (not published yet).

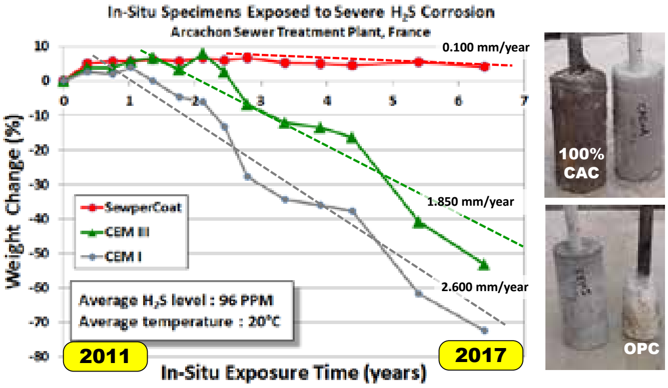

Figure 4: Mass loss and corrosion rates measured on specimens exposed in a STP in France

In parallel to the academic studies, the Fraunhofer UMSICHT Institute in Germany developed since 2009 a testing facility to permit the accelerated evaluation of building materials resistance to H_2S corrosion. The Fraunhofer testing protocol is following the same approach as the 1990 "Hamburg Simulation Chamber", but it is offered as a regular testing service to the industry (Wack & Gehrke 2018).

Various calcium aluminates mortar specimens have been tested with this protocol for a duration of 9 months. The results, published by Herisson *et al*. 2018, are showing good coherence with previous results like those obtained at the Virginia Experimental Sewer.

Figure 5 is showing the mass loss observed on 5 different mortar composition, the corrosion rate of CAC specimens being around 5 times slower than for OPC specimens.

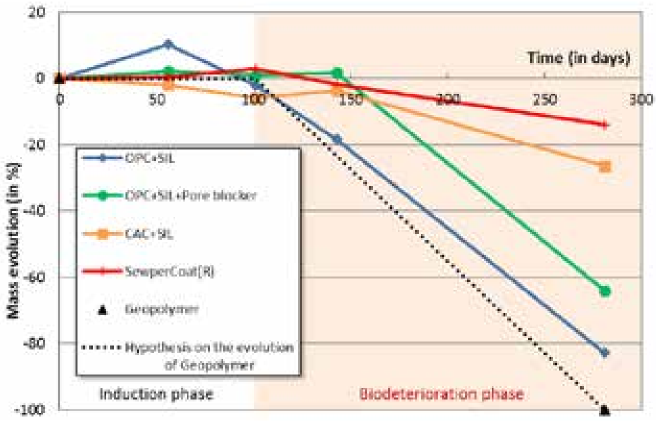

Figure 5: Mass loss of 5 different type of cementitious mortar exposed to accelerated H_2S biogenic corrosion using the Fraunhofer UMSICHT Protocol: SIL=siliceous aggregates; SewperCoat®=100% calcium aluminate mortar.

In all these various studies, it was put in evidence that calcium aluminates based mortars or concretes offer a much better resistance to H_2S biogenic corrosion. It has also been shown that the highest H_2S corrosion resistance was obtained with 100% CAC mortar, i.e. mortar made not only with calcium aluminate cement but also with calcium aluminate aggregates. With the whole surface of the mortar presenting the same chemistry, the bacteriostatic effect is active to all part of the material. Thus, when it comes to the rehabilitation of H_2S corroded structures, a mortar lining made of 100% CAC mortar will provide the longest service life possible.

Field evidence of CAC resistance to H_2S biogenic corrosion

The essential reason to consider CAC concrete mortar in sewers is the much longer service life it can deliver. Depending on the situation, CAC resistance is utilized in different ways around the world:

Sewer Element	Method of protection	CAC material
Precast Pipes	CAC internal mortar lining	CAC+natural aggregates
Precast Pipes	Whole thickness CAC Concrete	CAC+natural aggregates
New manhole wet well /Chambers / STP	As cast-in-place CAC concrete	CAC+natural aggregates
Critically exposed STP elements, like arrival channels	100% calcium aluminate concrete	CAC + calcium aluminate aggregates
Rehabilitation of corroded sewer and STP	100% calcium aluminate mortar	CAC + calcium aluminate aggregates

Field performance of real structures is showing the same CAC resistance to H2S corrosion as proven in academic studies. A first impressive result comes from eThekwini Municipality in South Africa. Around 1955, more than 60 years ago, several kilometres of sewer was built with 1.35 m diameter precast concrete pipes. As shown in Figure 6a, these pipes were made with an internal protection made of a "one inch" (2.54 mm) Ciment Fondu® mortar.

In 2018, some length of this sewer has reached the end of its service life and a new sewer is being built in the Point Road area to replace it. This gave the opportunity to dig-out some 60 years old pipes in April 2018 to perform a diagnosis. At time of writing this paper, the results are not yet available but Figure 6b is showing that the Ciment Fondu® lining is still in place after all those years. Further data will be made available in the near future.

Figure 6: Precast concrete pipes with an internal lining of Ciment Fondu® mortar installed at Durban Municipality around 1955: left, at time of manufacturing in 1955; right, segment extracted in April 2018 in Point Road area with the Ciment Fondu® mortar lining still present.

Another example of field performance is given by the very first rehabilitation made in USA with a 100% calcium aluminate mortar. In 1991, at the Hampton Roads Sanitation District in Virginia, in a split chamber was showing very severe H_2S biogenic corrosion: 75 mm of OPC concrete has been lost within only 7 years. Surface pH measurements as low as 1.5 were reported. The chamber was rehabilitated by rebuilding the lost concrete with a 100% calcium aluminate mortar by a dry guniting process. This repair was then monitored five times over a period of 11 years through visual inspection, hammer sounding, and surface pH measurement.

Pictures in Figure 7 were taken during these inspection. On the left picture, the inspector is hammering the 100% CA mortar surface, which was found to be hard and sound. Note that the manhole cast iron ring, which was originally protected with epoxy, is showing severe corrosion signs. The right pictures shows the pH measured after 11 years both on the cast iron manhole ring, and on the 100% CA mortar. On the epoxy surface, the pH is 1, showing that the biofilm has colonized the surface and is actively producing acid that has damaged the cast iron, despite the presence of an epoxy liner. On the 100% CA mortar, exposed to the same environment, the pH is at 4, the same value that was recorded after 3, 6 and 9 years. This real-life observation illustrates well that the bacteriostatic effect of calcium aluminate has impaired the bacteria to lower the pH below 4 for over 11 years. At the same time, only a few centimetres away, the biofilm without the CAC barrier was able to lower the pH to 1 and severely corroded cast iron. Note that the 100% CA mortar is not showing any sign of distress after 11 years in such a harsh environment.

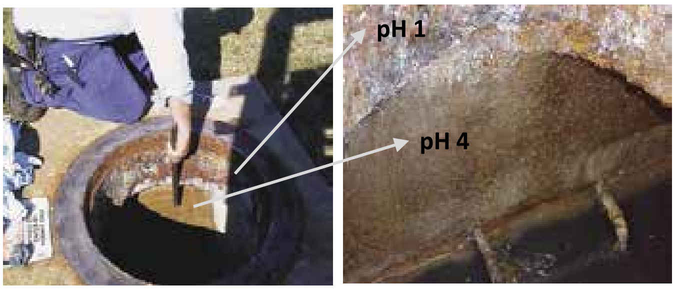

Figure 7: Manhole at Hampton Road Sanitation District rehabilitated with 100% CAC mortar. Left: Inspection of the rehabilitated surface. Right: pH surface measurements after 11 years in service

From the academic studies and real-life field track records synthesis, we are now seeing Municipal Owners stating that calcium aluminate mortar or concrete will provide them at least 50 years or service life, if not more.

THE SPECIFIC CHALLENGE OF REHABILITATION

At time of building a new sewer infrastructure that is expected to be exposed to H_2S biogenic corrosion, the design engineer will most probably specify a protection liner made polymer like epoxy, polyurethane or even plastic panels. When such products are carefully applied on newly cast structures, it may provide the expected service life.

However, when it comes to the specific challenge of rehabilitating in-service H_2S corroded sewers, the situation is very different. For the rehabilitation with a resin coating, the following issues need to be addressed:

Resin requires a dry substrate: Most resins systems require a dry substrate to be applied. For an existing sewer, buried underground, carrying effluent for years, the concrete is most probably moisture saturated. Drying the substrate is at least very difficult and costly to achieve. For one, this requires to by-pass the effluent, which means temporary pumps and conduits, and eventually the constraint of sending untreated effluent to nature. Drying the substrate may takes weeks before it is dry enough to receive a resin coating.

Resin requires a flat substrate: A thin resin coating cannot be applied on the very rough surface typically exposed by the H_2S corrosion process. It is thus needed to fill the voids and create an even surface with a mortar coating. This mortar coating needs to dry-out before a resin can be applied.

Costs of a long rehabilitation process: The long immobilization of a sewer infrastructures involves significant costs: costs of the by-pass system, typically for several weeks, costs of the drying units, costs of the manpower and products for a several layer system. Some owners will also consider the environmental cost of un-treated effluent rejection.

Risk of a premature failure: With a thin resin lining, any pin hole or bubble or flaws will compromise the expected protection because the sulfuric acid produced by bacteria will penetrate behind the liner and start corroding the concrete. Another risk comes from the sensibility of polymerization to condensation if the product is applied close to the dew point. Because a resin lining is typically quite thin, only few hundred microns, any protruding sand grains or flaws may create weaknesses. Another typical issues comes from the holes drilled after the resin application, for instance to bolt mechanical equipment or ladders, creating flaws in the resin barrier. According to the author experience, several sewer owners consider today that rehabilitation with a polymer lining is not a satisfactory solution because of too high a rate of failure observed in real life.

When sewer owners are looking for an alternative rehabilitation solution to polymer resins, they often find the 100% calcium aluminate mortar option. Considering all the constraint above, calcium aluminate provides a more affordable option for the following reasons:

CAC mortar requires moist substrate: Calcium aluminate cement is a hydraulic cement that reacts with water to harden. To achieve a good bonding, the substrate must be "saturated surface dry", which is often the actual state of the concrete for an in-service sewer. CAC mortar curing also requires a moist environment for the first few hours after installation, which is provided naturally by the running effluent.

Because CAC mortar requires a moist environment for successful installation, there is no need to by-pass the effluent in many cases. Because installing a by-pass is typically the most costly item in a rehabilitation project, saving this step is of considerable value.

CAC mortar requires rough surface: CAC mortar being based on a hydraulic cement will shrink like other cementitious mortars. This is why a sufficient roughness is recommended to permit a solid and durable interlocking allowing good bonding. With H_2S corroded concrete, the roughness exposed once the substrate has been correctly cleaned is generally more than sufficient. In other word, CAC mortar can be directly applied on the cleaned substrate, without the need for an intermediary filling mortar. In most case, one single layer of CAC mortar is enough to rehabilitate the concrete, leading to a "single step" application process.

Value of a short rehabilitation process: Without the need of substrate drying, without the need of a by-pass (in most cases), with a single layer system, with the need of a moist curing compatible with in-service sewer, the rehabilitation of a H_2S corroded sewer is much shorter than any resin based system.

SOUTH AFRICAN EXAMPLES OF REHABILITATION WITH 100% CAC MORTAR

Macassar Junction Chamber Rehabilitation

At the beginning of 2017, the Macassar Pumping Station, operated by the City of Cape Town, was stopped to rehabilitate the damages from H_2S corrosion. The rehabilitation was awarded to a polymer resin system. As the City of Cape Town became aware of the 100% calcium aluminate solution, they decided to make a first "test application" on a small junction chamber just aside the main building. The same applicator that was applying the resins was required to proceed with the rehabilitation of the junction chamber with SewperCoat®, the 100% calcium aluminate mortar from Kerneos. Figure 8 illustrates how this 80 m^2 was rehabilitated over 2 days. The first day, the corroded concrete was thoroughly cleaned to expose a solid and sound substrate. The second day, the 100% mortar was applied by low pressure wet spray method. The chamber was ready to put back in service the day after. About the installed costs per square meter, it was reported that SewperCoat® turned to be significantly cheaper than the multi-layer resin system installed just aside by the same applicator.

Figure 8: Macassar Junction Chamber rehabilitation in 2017: left, general view; center, close-up to show the extent of H_2S corrosion; right, on-going finishing of the 100% calcium aluminate mortar (notice the corrosion at the ceiling).

Lourens River Pumping Station

At the Lourens River Pumping Station, the City of Cape Town chose to rehabilitate the whole unit with the 100% calcium aluminate solution. Figure 9 gives an overview of the on-going rehabilitation over 850 m^2 of H_2S corroded concrete. This rehabilitation was completed in less than a 3 month period. An interesting benchmark was given by the rehabilitation of a similar pumping station, at Black Mack, that was rehabilitated just before the Lourens River Pump Station. With the classical resin system approach at Black Mack,the application of the was chemical protection was delayed significantly as the contractor battled to dry the concrete below the 3% moisture content target and costs were told to increase by at least 3 times the original budgeted cost.

Figure 9: Lourens River ongoing rehabilitation in 2017: Left, before rehabilitation; center, close-up showing concrete state of decay; right, back in service after rehabilitation with 100% calcium aluminate mortar.

Cape Flats Pumping Station

Figure 10 is showing the on-going rehabilitation at the Cape Flats Pumping Station. At that unit, H_2S corrosion had severely damaged 800 m^2 of concrete. One specific feature of this rehabilitation project is that it unit remained in operation during the whole rehabilitation process. The unit being equipped with 4 screw pumps, two were stopped during the rehabilitation while the other 2 remained in operation to keep the pumping station operational. In the same way, the arrival chamber walls were rehabilitated from a "raft" floating on the effluent, allowing to spray the 100% calcium aluminate mortar down to the lowest level of water reached in the very early morning. In fact, not only SewperCoat® requires a moist environment for proper curing, but it can be immersed under water within one hour of its application (with the proper surface curing agent). In the case of Cape Flats, the mortar started to be sprayed at 05:00, when the effluent levels were at their lowest, and then going up with the raising level of water flooding the just applied SewperCoat®. Such a rehabilitation would not have been possible with a resin calling for a dry substrate to apply.


Figure 10: Cape Flats ongoing rehabilitation in 2017, with a picture of the floating working platform

Chatty Sewer Line - Nelson Mandela Bay Metro

The Chatty Sewer Line gives an example of a different way to benefit from the calcium aluminate technology. For the project, the H_2S corrosion was so severe that some connection chambers were beyond reparability and had to be removed and rebuilt. But the Design Engineer had the goal of making a durable "repair" and decided to utilize the proved H_2S corrosion resistance of calcium aluminate to achieve this goal. A comparison was made between 2 options:

- To rebuild classical chambers made of usual OPC concrete and protect them, in a second step, by a spay applied 100% calcium aluminate mortar;
- To rebuild the chamber using "full-mass" calcium aluminate concrete (with natural aggregates) cast directly into the formwork, with no additional step required.

For that specific job site configuration, it was found not only faster but significantly cheaper to utilized "one step" full-mass CAC concrete to fill the formwork than applying a CAC protection after. In this case, the efficient approach to rehabilitation turned to be the complete replacement, but making sure to benefit of the CAC durability face to H_2S. Figure 11 is showing the on-going casting of a full-mass CAC concrete chamber.


Figure 11: Chatty Sewer Line chamber being rebuild in 2015 with full-mass CAC concrete: left, base level rebars, center, base level cast and upper level rebars; right, formwork installation before casting upper level.

CONCLUSION

Since the 1950', South Africa has been on the leading edge of durable sewer construction by adopting the use of calcium aluminate cement to manufacture H_2S resistant precast concrete pipes. Still today calcium aluminate precast concrete pipes are standard in South Africa, and utilized in location where H_2S corrosion is expected. Such pipes have been installed more than 60 years ago and are still in service today.

However, when it comes to the rehabilitation of H_2S corroded sewer infrastructures, the calcium aluminate technology started to be adopted only recently in South Africa. Polymer resins lining are still the usual approach, but the reported cases ofhigh rate of premature failure has fuelled dissatisfaction with resin solutions and have added recurring financial strain tometros and municipalities. It was explained why calcium aluminate cement is able to resist to the most severe H_2S biogenic corrosion conditions through the bacteriostatic effect. Key academic and field studies were summarized: they permitted to understand and quantify the H_2S corrosion resistance of calcium aluminate mortar and concrete. SouthAfrica's sewer industry has made a significant contribution with the "Virginia Experimental Sewer", which has delivered valuable results over the last 30 years.

Focusing on the rehabilitation specific challenge, it was shown that a 100% calcium aluminate mortar permits to achieve not only very durable rehabilitation, but in a shorter time and for a lower cost than the usual resin approach. The main reasons for this difference are: 1) no need to dry the substrate; 2) no need to by-pass the effluent in most cases; 3) a single layer application; 4) a rapid return to service, only few hours after application, and 5) an exceptional durability. The first application of 100% calcium aluminate mortar took place in 1991 in USA and the durability of this solution is now backed by more than 25 years of positive field return. Combined all together, these features makes the 100% calcium aluminate technology a very valuable option for the Municipal Engineer dealing with rehabilitation needs of his sewer infrastructures

South African examples of rehabilitation cases shown that this approach is both efficient and cost effective in this country. From the academic studies and real-life field track records synthesis, we are now seeing Municipal Engineers stating that 100% calcium aluminate mortar rehabilitation will provide them at least 50 years or service life, if not more.

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