

Microbially-induced Concrete Corrosion- A worldwide problem

Grengg, C.¹, Kiliswa, M.², Mittermayr, F.³, Alexander, M.²

¹Institute of Applied Geosciences, Graz University of Technology, Rechbauerstraße 12, 8010, Graz, Austria

²Department of Civil Engineering, University of Cape Town, Private Bag X3, 7701 Rondebosch, South Africa

³ Institute of Technology and Testing of Building Materials, Graz University of Technology, Inffeldgasse 24, 8010, Graz, Austria

ABSTRACT

Concrete degradation due to microbially-induced acid attack in sewer systems is a frequently observed issue worldwide. Remediation and repair of sewer systems subjected to microbially-induced concrete corrosion (MICC) is complex and of high economic relevance. Numerous field campaigns and in-situ experiments are continuously being conducted in such aggressive environments in order to understand the underlying reaction mechanisms, environmental controls and material related aspects, with the view of reducing concrete corrosion rates in such systems. This study aims to summarize existing literature on field observations and in-situ tests, in order to compare and discuss MICC initiation and propagation regarding different material and environmental settings. Therefore, decisive parameters measured in various field and laboratory campaigns including (i) temperature, (ii) concentrations of gaseous H₂S, CH₄ and CO₂, (iii) chemical and mineralogical composition of solids, (iv) pH, alkalinity, chemical composition of the solutions, and (v) microbiological analyses, are compared. Additionally, certain aspects steering MICC, such as environmental parameters, material aspects and microbiology involved were reviewed in line with findings from both field observations and in-situ tests. Speciation of standard regulations, related to material guidelines, and their control on concrete durabilities in MICC environments are discussed, together with engineering aspects and sewer designs. Conflating all those aspects contribute towards a deeper understanding regarding the process mechanisms and corrosion propagation, promoting advances in concrete durabilities and service life predictions of affected sewer systems.

KEYWORDS: *microbially-induced concrete corrosion, concrete durability, H₂S, sewer, bacteria*

1. Introduction

Modern society requires a high density network of sewage transport systems within congested urban areas. Construction and maintenance of latter systems is of high social and economic relevance. Microbial induced concrete corrosion (MICC) is recognized as the main process responsible for deterioration of concrete based sewage systems worldwide. In severe cases the service life of sewer systems and pumping stations were reduced from originally 100 down to less than 10 years [1–3]. Remediation and repair of corroded systems, drawn to MICC, are challenging and costly. Annual rehabilitation costs were estimated to reach values of €100 million in Germany [4] and £84.8 million in the UK, while the US need to spent around \$390 billion within the next 20 years, in order to keep the existing wastewater infrastructure on life support [5]. Additionally, the production of hazardous and odorous gases, associated with MICC, represents a significant health risk for community workers, as well as for private residents of affected communities. This paper aims to compile knowledge obtained from various field studies and in situ tests in order to link the influence of different environmental parameters, engineering aspects and sewer designs with corrosion initiation and progression. Consequential, these insights will contribute towards advances in efficient mitigation strategies and system rehabilitations.

2. General process description

Microbial induced concrete corrosion can be seen as a sequence of biogenic sulfate reduction and re-oxidation. Initial sulfide production occurs within the sludge and sediment layers, deposited along the pipe walls of slow flowing sewage transport systems and power mains with long retention times, favoring corners and turns. There, sulfate reducing bacteria (SRB), mainly of the type *Desulfovibrio* and *Desulfomaculum*, adopt those substrates and sulfate respiration proceeds. Accordingly, sulfides are formed as a side product of anaerobic oxidation of organic carbon, whereas sulfate and other oxidized sulfur compounds are used as electron acceptors in the absence of oxygen and nitrate [3,6]. The most important factors controlling sulfate reduction in such environments are temperature, pH, presence of oxidized sulfur compounds, wastewater flow rates, retention times and the biodegradability of organic matter present [1,7]. Subsequently, gaseous hydrogen sulfide (H₂S) together with carbon dioxide (CO₂) and other volatiles organic compounds (VOCs) degasses into the sewer atmosphere. The liberation of those volatile components is governed by changes in the surrounding gas pressure, pH,

temperature and wastewater turbulences, favoring transition chutes after power mains and gravity sewer sections with turns and hydraulic drops [2]. Via gaseous diffusion H_2S and CO_2 accumulate in the pore space of the concrete and subsequently, dissolution occurs under moist conditions, initiating acid-base reactions [8]. Since concrete is a strongly alkaline, porous and multiphase material, with an initial interstitial solution of around pH 12.5 [9], abiotic pH reduction due to carbonation proceeds. Additionally, chemical oxidation of H_2S produces thiosulfuric and polythionic acids [10]. Both processes are supporting pH reduction. Once a pH of 9 is reached, strains of neutrophilic sulfur oxidizing bacteria (SOB) adopt the moist pore volume and biotic acid production is initiated [11–14]. Okabe et al. (2007) revealed a succession of at least 6 phylotypes of SOB with decreasing pH [15].

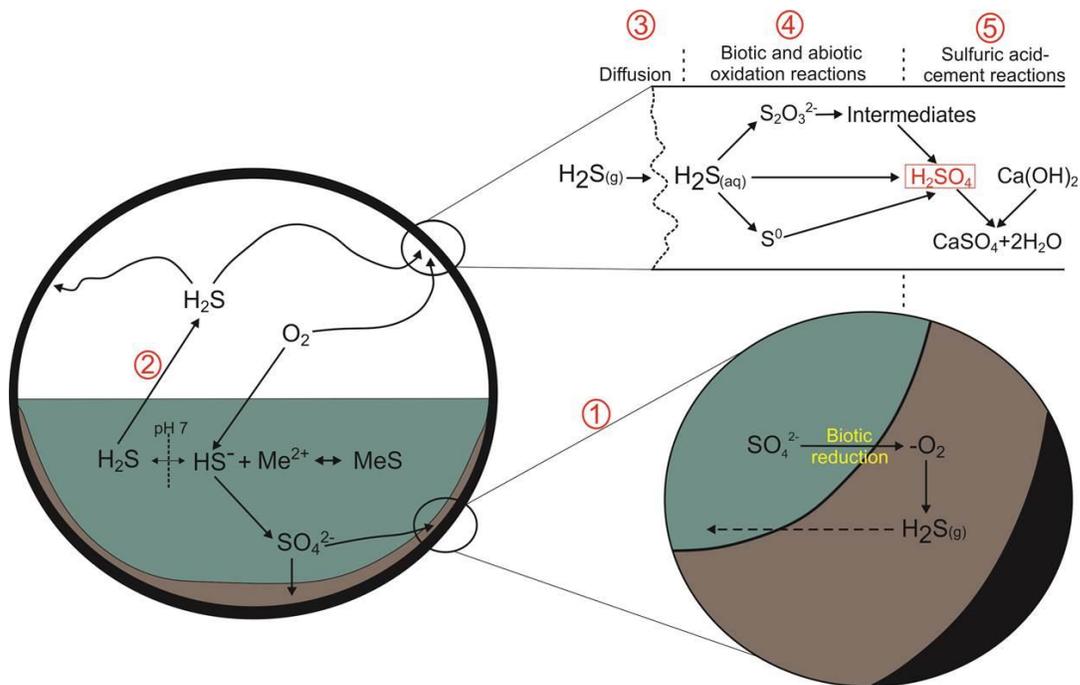


Figure 1: Schematic description of one MICC sequence, including initial sulfate reduction (1), subsequent degassing of H_2S into the sewer atmosphere (2), followed by its diffusion into the pore space of the concrete (3). Accordingly abiotic and biotic re-oxidation proceeds associated with H_2SO_4 production (4), triggering dissolution and mineral neo-formation (5).

Continues bacterial activity, associated with sulfuric acid production and corresponding decreasing pH is causing dissolution of the cementitious matrix and, if present, carbonatic aggregates, together with neo-formation of sulfate salts. Once a pH of 4 is reached acidophil bacteria are starting to dominate the biofilm, with *Acidithiobacillus thiooxidans* being the most

common one [12,15]. This last stage of MICC is associated with massive losses of material, which can be seen in reported corrosion rates of up to 10 mm/y [2]. The general process mechanisms of MICC are presented in Figure 1.

3. Engineering aspects and sewer design
 - a. Sewer alignment considerations
 - i. Flow velocity

Sewers are generally gravity pipelines that flow partly full and follow natural watercourses. These watercourses often have alignments that are not ideal for sewers such as relatively flat gradients, interspersed with short steep sections and bends. Therefore, sewers are designed to cope with both vertical and horizontal changes in alignment (and the energy losses that occur due to these changes) to ensure effective performance, for example, by maintaining recommended flow velocities.

As will be discussed later, silt deposition in sewers due to inadequate flow velocities is one of the contributors towards the inception of biogenic corrosion. The maintenance of minimum flow velocities (generally between 0.6 and 0.8 m/s) so that silt does not accumulate at invert levels in sewers is an accepted principle in sewer design [16,17]. One of the widely used equations for determining flow velocity in sewers, the Manning's equation, is given below (Equation 1):

$$v = \frac{1}{n} R^{2/3} S^{1/2} \quad (1)$$

where v = velocity (m/s)

n = Manning's roughness coefficient ($s/m^{1/3}$; 0.013, for centrifugally spun concrete)

R = hydraulic radius (m)

S = gradient of conduit (m/m)

Equation 1 shows that the flow velocity is proportional to both the diameter and gradient, so smaller diameter sewers are often at gradients that are insufficient to ensure self-cleansing velocities while larger diameter sewers often experience flow disruptions in the form of, for example, super-critical flows. These different types of flows (subcritical, critical, and super-critical) are discussed in the following section.

b. Specific energy and critical flow

The flow in sewers is similar to that in open channels. Therefore for a uniform flow section between any two points (such as point 1 and 2, see Figure 2), the specific energy, E is defined as the sum of the depth of flow and the velocity head (Equation 2).

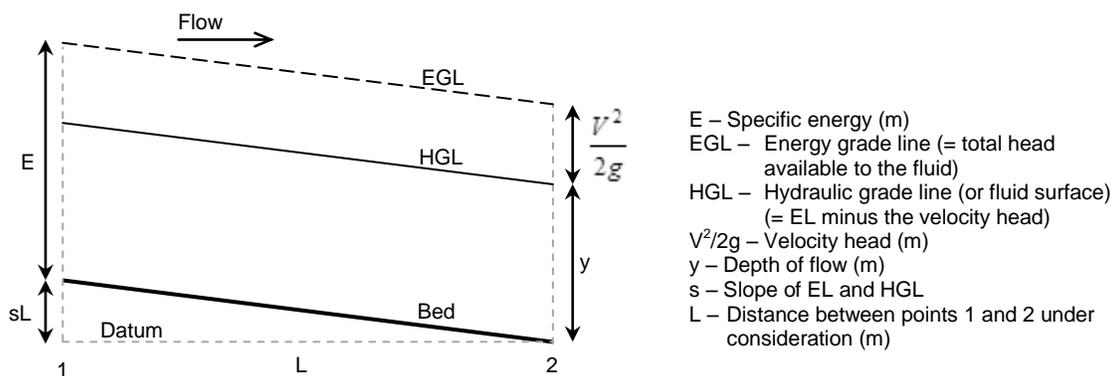


Figure 2: Specific energy diagram for uniform flow [18].

$$E = y + \frac{V^2}{2g} \quad (2)$$

where y = depth of flow (m)

V = mean velocity (m/s)

g = gravitational acceleration (m/s²)

Assuming an infinitely short section (essentially no friction losses and no change in elevation) of an open channel, the general energy equation (Equation 2) can be re-written as an equality of specific energies (Equation 3).

$$E_1 = y_1 + \frac{V_1^2}{2g} = y_2 + \frac{V_2^2}{2g} = E_2 \quad (3)$$

According to Equation 1, flow velocity is directly related to the area of flow (by the hydraulic radius), and the area of flow is a function of channel depth. Therefore the flow velocity can be related to a discharge rate per unit width, q (Equation 4), and Equation 3 can be re-written as Equation 5.

$$q = \frac{Q}{b}; v = \frac{q}{y} \quad (4)$$

$$E = y + \frac{q^2}{2gy^2} \quad (5)$$

For a given flow (discharge), the specific energy at each point is solely a function of channel depth, so we may have the same specific energy for various depths. This can be illustrated by the specific energy diagram (Figure 3).

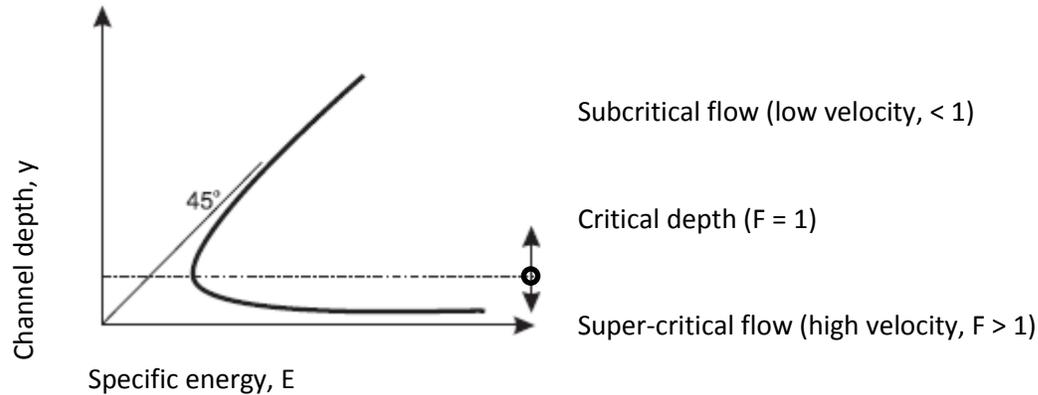


Figure 3: Relationship between specific energy and depth of flow. The relationship given in Figure 2 is described by a dimensionless number known as the Froude number, F (Equation 6).

$$F = \frac{V}{\sqrt{gD}} \quad (6)$$

where D = hydraulic mean depth (= flow area/top width of flow) (m)

V = mean velocity (m/s)

g = gravitational acceleration (m/s^2)

A depth (depth of flow or channel depth) at which the specific energy is at a minimum is known as the critical depth ($F = 1$). Sections where the depth of flow is less than the critical depth (or velocity is higher than the critical velocity) experience super-critical flows ($F > 1$). Sections where the depth of flow is more than the critical depth (or velocity is less than the critical velocity) experience subcritical flows ($F < 1$).

The Froude number is one of the significant parameters (others are sediment volumetric concentration and relative size of particles) that influence the design criteria for self-cleansing velocities in sewers [19].

c. Laminar and turbulent flow

Laminar flow occurs with low velocities and/or high viscosity. It is characterized by smooth, predictable streamlines. Turbulent flow, on the other hand, occurs with high velocities and/or low viscosity. It is characterized by the formation of eddies within a certain flow, resulting in erratic and unpredictable streamlines [20]. In sewers, the flow of sewage is characterized by low-velocity flow near the sewer walls (due to effects of friction and drag) and higher-velocity flow towards the center, and so they experience a continuous mixing of flow resulting in turbulence. Therefore flows in sewers are, in principal, turbulent, and the velocity at any given point within a turbulent section will be closer to the mean velocity of the entire section than with laminar flow conditions. It is also important to mention that (i) turbulent flows are typical in sewer sections located downstream of pump stations due to the pumping cycles of the sewage, and (ii) turbulent flows occur where there is an abrupt change in the direction of flow in a sewer section.

In order to classify flow as either laminar or turbulent, a dimensionless number, known as the Reynolds number, Re is used (Equation 7).

$$Re = \frac{4VR}{\nu} \quad (7)$$

where V = mean velocity (m/s)

R = hydraulic radius (m)

ν = kinematic viscosity (m^2/s)

In sewers, laminar flow occurs when $Re < 500$, and turbulent flow occurs when $Re > 2000$. For $500 > Re < 2000$, the flow is known as transitional.

The hydraulic principles reviewed above have a significant impact on biogenic corrosion since the flow velocity and turbulence will determine whether air is entrained or released from the sewage, and whether there is solid deposition on the sewer invert. The minimum and maximum flow velocities and energy losses could vary along a particular sewer section due to changes in both vertical and horizontal alignments. This means that sulfides could be generated in one section of the sewer and due to factors such as turbulence, be released at another section. At low flow velocities, solids are deposited on the sewer's invert in form of sludge and silt to form additional habitat for the microorganisms. In contrast, at high flow velocities, air is entrained in the sewage and most solids are carried in suspension throughout the sewer. Air entrainment will in turn determine whether the effluent will be aerobic or anaerobic. Under anaerobic

conditions, there is insufficient oxygen in the sewage to support microbial activities within the biofilm. Therefore, SRB will obtain oxygen by reducing SO_4^{2-} to S^{2-} . Thus, sewer hydraulics are one of the central parameters influencing systems susceptibility to MICC.

4. Field case studies and in situ tests

Although MICC is a well-known problem, most of the studies so far focused on laboratory tests and in situ experiments, rather than on field studies. Examples of typical damage pattern from field observations are displayed in Figure 4. This chapter aims to describe the variation of distinct constructional, operational and environmental aspects within sewer systems drawn to MICC, on the extent of damage and corrosion propagation observed in field analyses and in situ test's, from coupled engineering, hydro geochemical and material sciences perspectives.



Figure 4: Examples of strongly deteriorated concrete manholes drawn to MICC.

a. Engineering and operational aspects

As described above, sewer design and operation conditions can have an important influence on the initiation and propagation of MICC. From a constructional point of view, up to date insufficient flow rates and long retention times are seen as the main cause for biofilm

development and correlated sulfate reduction. Grengg et al. (2015) described a system in which wastewater retention times within the power mains of up to 6 h produced strong reducing conditions (EH down to -320 mV), initiating almost complete sulfate reduction, high H₂S concentrations of up to 370 ppm within the first transition chutes and associated high corrosion rates of up to 10 mm/y. Interestingly, also within the Virginia Experimental Sewer (VES) in South Africa high concentrations of H₂S are measured, though being designed with a sewage flow velocity of 2.5 m/s, which should not allow sulfide build-up within this section [21]. However, the average daytime H₂S concentrations reach 86 ppm in summer and 20 ppm in winter. The VES is a 63 m experimental sewer line, connected to the urban sewer network, which is run since 1989.

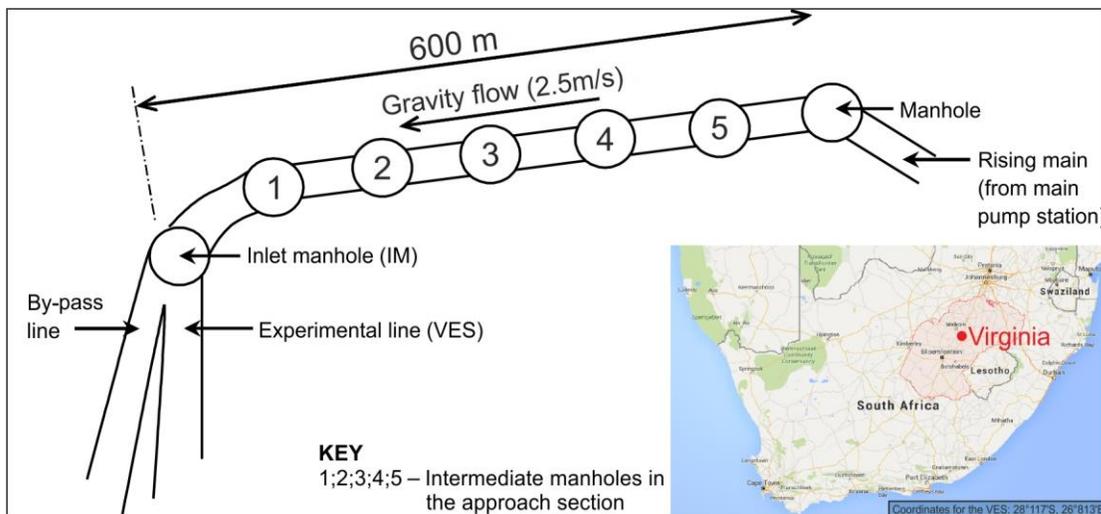


Figure 5: Geographical location of the Virginia Experimental Sewer (VES), Free State Province, together with a schematic outline of a section of the Virginia urban sewer network, showing a gravity sewer feeding into the VES, 600 m downstream of the rising main [22].

b. Environmental parameters

Measuring temperature (T), relative humidity (RH), pH of the wastewater and the concentrations of toxic and odorous gases, mainly H₂S and CO₂, are central in order to determine ambient environmental conditions together with the distinct influence of each parameter on concrete corrosion initiation and propagation. Significant seasonal variations of temperatures are reported within different field observation sites, controlling process kinetics, bacterial activities and consequential production and diffusion rates of H₂S and CO₂. For instance, the Virginia Experimental Sewer (VES) experiences a wide range of temperature and RH gradients. In summer the monthly average-high ambient temperatures reach 30 °C, while the

monthly average-low ambient temperatures are -1 °C in winter. Likewise, H₂S concentrations within the sewer atmosphere decrease from an average of 50 ppm in summer, down to around 10 ppm in winter (Figure 6).

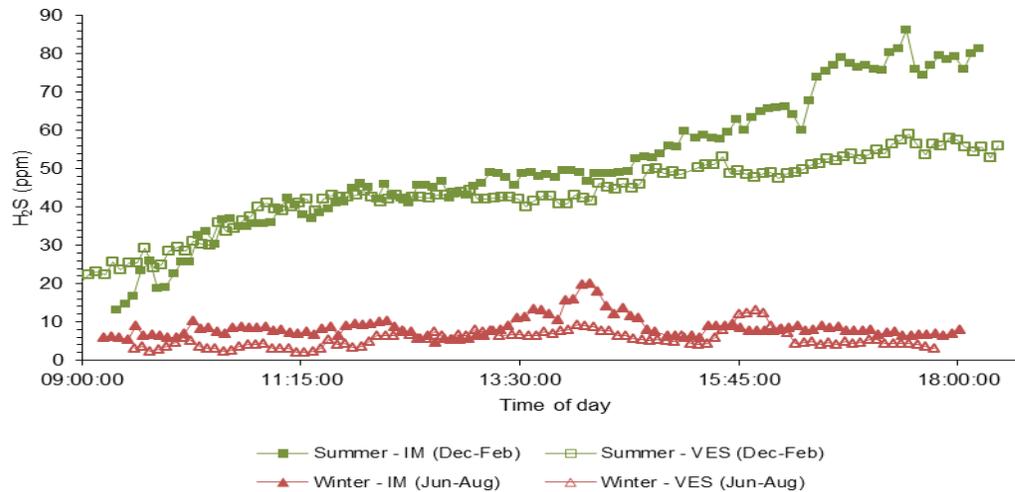


Figure 6: Typical H₂S profiles in Virginia Experimental Sewer during summer and winter months (data from ongoing Moses Kiliswa’s PhD study (2013-2016)).

Alternatively, H₂S concentrations within systems containing sequences of coupled power mains and gravity sewer sections correlate with pump rates. H₂S peak concentrations correspond to pump events, while low average concentrations are typical during intervening periods. In general, sewers containing average H₂S concentration of between 2 and 6 ppm are known to be capable of forming biogenic H₂SO₄ with a concentration of 6% v/v (pH <1) on the sewer’s non-submerged moist walls, if temperature is in the order of 18 °C [23]. Differences in RH levels are influencing the diffusion rates of H₂S and CO₂ and are therefore central within the initial stage of corrosion during abiotic pH reduction. Carbonation proceeds best in environments with RH between 50-70% where the pH is lowered down to 9 [10,24]. Ambient relative humidity (RH) within VES varies between 45% and 70%, thus creating suitable conditions for gaseous diffusion. Also, wastewater pH plays a central role for hydrogen sulfide emission, since its controlling the distribution of produced sulfide speciation. Nielsen et al (2006) demonstrated the correlation between pH and sulfide distribution, by monitoring H₂S concentration during pH fluctuations of the wastewater. A pH reduction from 7.9 to 7.2 resulted in decreasing volumes of dissolved sulfide species from 44% to 12% within the wastewater. Correspondingly, H₂S concentrations increased from 0 to 11 ppm within the atmosphere of the gravity sewer [25].

c. Microbiology observed

Understanding the growth, succession and interaction of different microorganisms involved in biogenic concrete corrosion is central for understanding the processes mechanisms of MICC. Current field observations propose a vital interaction of autotrophic SOB with various heterotrophic genera and fungi [14,15,26]. During the early stage of biofilm colonization, starting from pH 9, biogenic community structures consist of a succession of neutrophilic SOB, e.g. *Halothiobacillus spp.*, together with larger abundances of heterotrophs, such as *Pseudomonas* or *Serratia* [27]. These heterotrophs are believed to support corrosion by metabolizing microbial by-products, which would inhibit the growth of autotrophic SOB, to organic acids that additionally contribute to acidification [27]. Biodiversity significantly decreases when community structures shift to acidophil SOB at pH around 2 and below, with *Acidithiobacillus spp.* as the most dominant genera [12,15,27] (Figure 7).

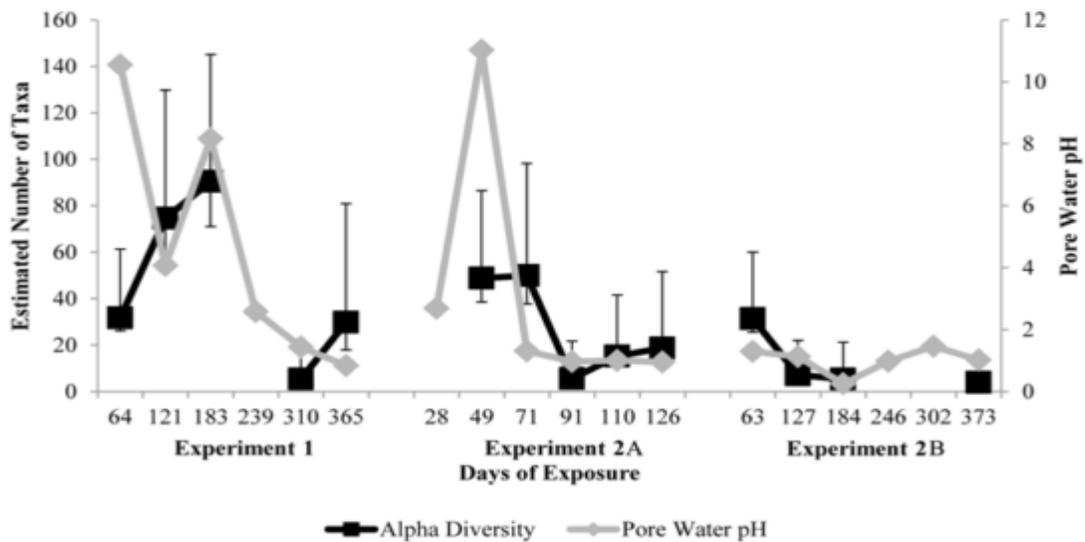


Figure 7: Estimated bacterial community diversity in corrosion products, together with estimated pore water pH by Ling et al. 2015 [27].

Most studies reported the gram negative sulfur oxidizing bacteria *Acidithiobacillus thiooxidans* to dominate the biofilm during late stages of MICC. Nevertheless, recent studies emphasize also the role of *Acidithiobacillus ferrooxidans*, concerning biogenic acid production [2,28,29].

d. Material and mineralogical aspects

Material characteristics, such as concrete chemistry, water/cement (w/c) ratio, porosity, surface properties and curing have a large impact on mechanisms for concrete deterioration

propagation, such as diffusion rates of gaseous H₂S and CO₂ and acid buffer capacity. These factors mainly control the bioreceptivity of concrete, which ultimately steers the biogenic sulfide oxidation and acid production. Differences in surface roughness, porosity, mineralogical and chemical composition, e.g. aluminum and iron content, could be directly correlated with biological activity [2,30,31]. In general it can be stated that, so far no commercially produced concrete can completely withstand a constant biogenic acid attack over its operating life. Therefore it has to be stated that standard regulations, such as EN-206-1 within the European Union, are not sufficient in inhibiting MICC initiation and propagation. For instance, high corrosion rates have been observed in systems in which high performance concrete was used for constructions, according to prevailing standard regulations (Figure 8).

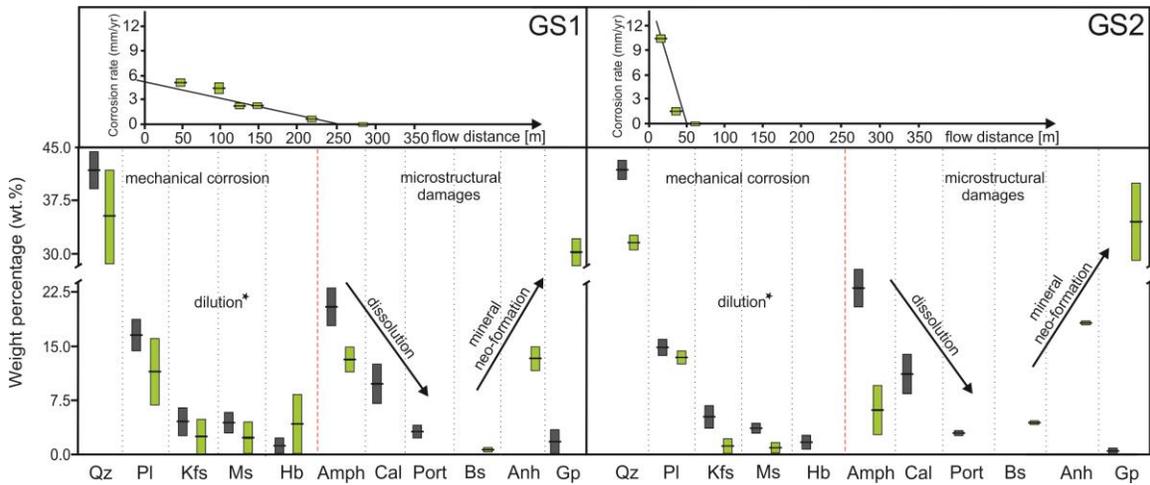


Figure 8: Change in the quantitative, mineralogical composition of unaltered (grey) versus heavily damaged concrete (green), related to MICC. The concrete corrosion rate with flow distance within two gravity sewer sections (GS1 and GS2) is reported on top of the figure. *Ongoing dissolution of the supporting cementitious matrix is causing dilution of siliceous compounds such as quartz (Qz), plagioclase (PI), K-feldspar (Kfs), muscovite (Ms) and hornblende (Hb). Decrease of carbonatic and cementitious phases like calcite (Cal) and portlandite (Port) can be attributed to dissolution and subsequent mineral neo-formation of gypsum (Gp), anhydrite (Anh) and bassanite (Bs) formation, which causes intense microstructural damage of the concrete. X-ray amorphous phases (Amph), mainly represent the CSH phases of the cement. Results reported from Grengg et al. (2015).

Nevertheless, various in situ testing and field studies have shown that significant durability improvements can be achieved due to the application of suitable construction material. Figure 9 displays a typical long term in situ test, conducted within the VES in South Africa, where different concrete admixtures are tested regarding their performance within MICC environments.



(a) Pipe sections (samples) of different concrete mixtures



(b) Typical 'lid' samples removed for inspection and core samples suspended in the sewer

Figure 9 (a) and (b): Typical setup of in situ studies of various concrete mixtures at the VES in South Africa.

For instance, calcium aluminates cements (CAC), either with carbonatic (CAC/DOL) or silicate (CAC/SIL) aggregates, have shown significant higher durabilities compared to ordinary portlandite concrete (PC) within numerous in situ tests [31–34] (Figure 10). The reasons given are the higher acid buffer capacity of CAC compared to PC and the formation of an aluminum hydroxide gel under humid conditions, which decreases concrete pore volumes and corresponding diffusion rates [33]. Additionally, higher aluminum contents might promote bacteriostatic effects on neutrophilic SOB, thereby lowering biogenic acid production.

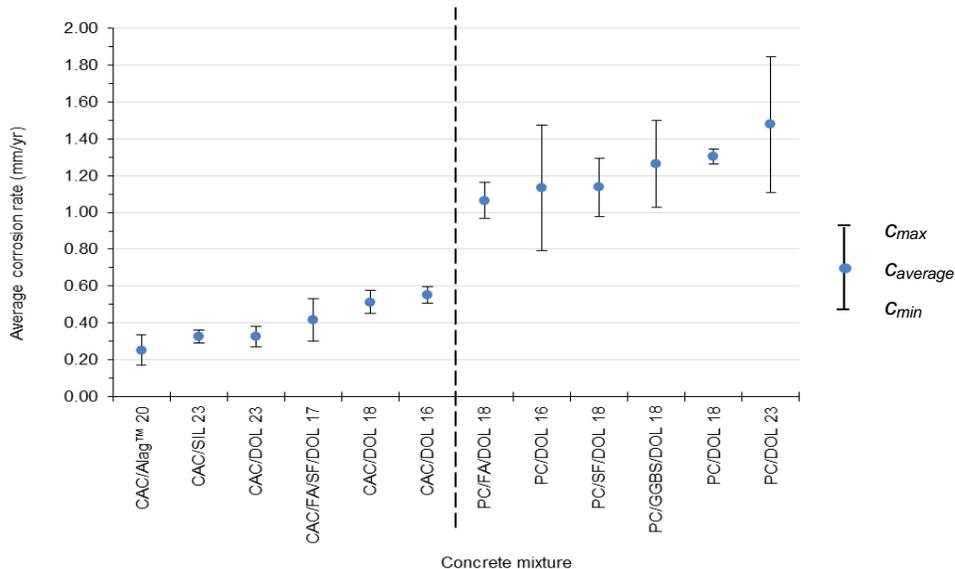


Figure 10: Average corrosion rates of PC- and CAC-based concrete mixtures subjected to biogenic H_2SO_4 for 127 months in a 'live' sewer. Notice the low corrosion rates for binder systems, containing high aluminium content (left side), such as mixtures like CAC/DOL, CAC/SIL, compared to PC based (right side) mixtures (data from ongoing Moses Kiliswa's PhD study (2013-2016)).

5. Mitigation strategies

a. Chemical dosing

Chemical dosing, such as the injection of oxygen, nitrates, iron chlorides and hydrogen peroxide, are to date the most frequent applied methods for corrosion and odor prevention. In general two different mitigation approaches can be subcategorized. The first method targets the inhibition of primary sulfate reduction and subsequent H₂S formation, whereas the second approach aims to control the sulfide species produced [35].

Inhibition of sulfide production

Anaerobic conditions are crucial for sulfate reduction and corresponding sulfide production. Accordingly, air injection is a commonly applied method for odor prevention in power mains and wet wells. Oxygen can be added as air or pure oxygen, although it must be reconsidered when injecting air that only around 20 % of its volume consist of oxygen and great amounts of inert N₂ gas must be anticipated, which may accumulate somewhere in the system [1]. Injecting pure oxygen resolves this problem, although it has to be taken into account that its technical utilization is more complex.

The inhibitory effect of nitrate on sulfate reduction has been reported [36]. The addition of nitrate is causing increasing redox potentials together with rising anoxic conditions. Moreover, the bacteriostatic effects of nitrate on different strains of sulfate reducing bacteria possibly limit sulfate respiration [37]. Nitrates can be added in the form of various salts e.g. Ca(NO₃)₂. Quantity controls are necessary in order to avoid nitrate inflow into purification plant, located downstream.

Sulfide control – metal precipitation

This approach aims to control and obviate the damaging effects caused by degassing of H₂S. Thereby, no alteration within the prevailing anaerobic and strongly reducing conditions within the systems can be achieved. Several metal salts can be used for sulfide precipitation within wastewater systems, with ferrous iron, Fe(II), and ferric iron, Fe(III), bond within iron-chlorines or iron-sulfates being the most common ones. Thereby, iron sulfide (FeS) is formed according to the stoichiometry of the following equations [7]:





Under anaerobic conditions FeS exists as a metastable precipitate, which potentially re-oxidizes once aerobic conditions establish with flow direction, covering a half-life period of 11.7 h [38]. Due to different reaction times of Fe(II) and Fe(III), the retention time of the wastewater has to be taken into account when choosing the proper mixture. In general a combination of ferric and ferrous chloride is reported to work most efficiently, whereas ferric iron is initially reduced to ferrous iron by the oxidation of dissolved sulfide species (Equation 1). Consequently, ferrous iron produced is precipitated as iron sulfide (Equation 2). However, decreasing sulfide elimination rates are reported within wastewaters with pH levels lower 8. Therefore, a combined application of iron-chlorides/sulfates together with alkaline substances like calcium hydroxide (Ca(OH)₂) or sodium hydroxide (NaOH) is advised [7].

Alternatively, chlorine (Cl₂) can be added to the wastewater, either directly in its gaseous form or as hypochlorite (OCl⁻) or sodium hypochlorite (NaOCl). Chlorine species are known to oxidize sulfide to elemental sulfur (S⁰) or sulfate, following the reaction:



Caution is needed when working with OCl⁻ due to its toxicity. Furthermore, Cl₂ might inhibit the biological processes occurring voluntarily within the purification plant if the apportioning is too high. One of the major advantages of chlorine addition is that it works efficiently at pH 7 to 8, conditions present in most communal wastewaters.

Another possible additive is hydrogen peroxide (H₂O₂) which oxidizes sulfides into S⁰ or SO₄²⁻. In addition, it potentially partly degrades sulfate-reducing bacteria within the biofilm [7].

b. Coatings

The study on MICC has been going on for over 25 years in South Africa. During this period, results have shown that calcium aluminate cement (CAC) based systems undergo less MICC than Portland cement (PC) based systems. Although a CAC concrete was more effective than a PC concrete in controlling corrosion it was also more costly. This being the case it was only on the small diameter pipes (600 mm and less) that the use of this type of concrete would be more economical than a pipe with a cast-in HDPE lining. However the South African pipe industry uses spinning processes during pipe manufacture and the integral casting of an inert lining into such pipes proved to be both difficult and ineffective. Ways were therefore investigated of extending

the application of CAC concrete to larger diameter pipes. The problem was how to cost effectively produce a concrete pipe using this material. The most effective avenue investigated was the concept of a host pipe with a lining that was integrally cast into it. The host pipe acted as the structure, manufactured from the most economic concrete locally available and the lining acted as a corrosion control layer, manufactured from a concrete that was effective at controlling corrosion. In this regard, a South African concrete pipe manufacturer successfully developed a technique for a wet on wet application of this corrosion control lining to a concrete host pipe using the roller suspension process.

6. Conclusion

Various field studies and in situ tests, presented in this paper have shown the global relevance of microbial induced concrete corrosion. Under favorable conditions MICC is capable to cause whole systems to fail after only 10 or less years of service, thus being of huge economic relevance. It can be concluded that not only well known environmental parameters, such as H_2S concentrations, RH, temperature, retention times and flow rates, but also material related aspects are central for corrosion initiation and progression. Reconsidering critical sewer alignments, such as sewer hydraulics and materials, can contribute towards higher service lives. When system remediation is conducted not only material aspects but also odor relevant aspects have to be considered and restored. Various long term in situ studies have shown improved performances of CAC based concretes within MICC environments due to aluminum related acid buffer capacity, the development of an aluminum gel when reacting with H_2SO_4 , together with reported bacteriostatic effects. Various mitigation strategies, including chemical dosing can alleviate corrosion propagation and odor production, nevertheless, many are cost intensive and require a constant maintenance.

7. References

- [1] T. Hvitved-Jacobsen, J. Vollertsen, C. Yongsiri, A.H. Nielsen, Sewer microbial processes, emissions and impacts, in: Sewer Process. Networks, Paris, 2002: p. 13.
- [2] C. Grengg, F. Mittermayr, a. Baldermann, M.E. Böttcher, a. Leis, G. Koraimann, et al., Microbiologically induced concrete corrosion: A case study from a combined sewer network, Cem. Concr. Res. 77 (2015) 16–25. doi:10.1016/j.cemconres.2015.06.011.

- [3] H.S. Jensen, PhD thesis; Hydrogen sulfide induced concrete corrosion of sewer networks, Aalborg University, 2009.
- [4] W. Kaempfer, M. Berndt, Polymer modified mortar with high resistance to acid corrosion by biogenic sulphuric acid., in: Proc. IX ICPIE Congr., Bologna, 1998: pp. 681–687.
- [5] M.G.D. Gutiérrez-Padilla, A. Bielefeldt, S. Ovtchinnikov, M. Hernandez, J. Silverstein, Biogenic sulfuric acid attack on different types of commercially produced concrete sewer pipes, *Cem. Concr. Res.* 40 (2010) 293–301. doi:10.1016/j.cemconres.2009.10.002.
- [6] H.S. Jensen, P.N.L. Lens, J.L. Nielsen, K. Bester, A.H. Nielsen, T. Hvitved-Jacobsen, et al., Growth kinetics of hydrogen sulfide oxidizing bacteria in corroded concrete from sewers., *J. Hazard. Mater.* 189 (2011) 685–91. doi:10.1016/j.jhazmat.2011.03.005.
- [7] T. Hvitved-Jacobsen, J. Vollertsen, A.H. Nielsen, *Sewer Processes - Microbial and Chemical Process Engineering of Sewer Networks*, Second Edi, CRC Press, London, 2013.
- [8] H. Yuan, P. Dangla, P. Chatellier, T. Chaussadent, Degradation modeling of concrete submitted to biogenic acid attack, *Cem. Concr. Res.* 70 (2015) 29–38. doi:10.1016/j.cemconres.2015.01.002.
- [9] M. Alexander, A. Bertron, N. De Belie, *Performance of Cement-Based Materials in Aggressive Aqueous Environments*, 1st ed., Springer, Ghent, 2013. doi:10.1007/978-94-007-5413-3.
- [10] D.J. Roberts, D. Nica, G. Zuo, J.. Davis, Quantifying microbially induced deterioration of concrete: initial studies, *Int. Biodeterior. Biodegradation.* 49 (2002) 227–234. doi:10.1016/S0964-8305(02)00049-5.
- [11] A.P. Joseph, J. Keller, H. Bustamante, P.L. Bond, Surface neutralization and H₂S oxidation at early stages of sewer corrosion: influence of temperature, relative humidity and H₂S concentration., *Water Res.* 46 (2012) 4235–45. doi:10.1016/j.watres.2012.05.011.
- [12] H. Satoh, M. Odagiri, T. Ito, S. Okabe, Microbial community structures and in situ sulfate-reducing and sulfur-oxidizing activities in biofilms developed on mortar specimens in a corroded sewer system., *Water Res.* 43 (2009) 4729–39. doi:10.1016/j.watres.2009.07.035.
- [13] E. Vincke, S. Verstichel, J. Monteny, W. Verstraete, A new test procedure for biogenic sulfuric acid corrosion of concrete, (2000) 421–428.
- [14] B.R.L. Islander, J.S. Deviny, A. Member, F. Mansfeld, A. Postyn, H. Shih, Microbial ecology of crown corrosion in sewers, *J. Environ. Eng.* 117 (1991) 751–770.

- [15] S. Okabe, M. Odagiri, T. Ito, H. Satoh, Succession of sulfur-oxidizing bacteria in the microbial community on corroding concrete in sewer systems, *Appl. Environ. Microbiol.* 73 (2007) 971–980. doi:10.1128/AEM.02054-06.
- [16] E.P. Agency, *Design manual: Odor and corrosion control in sanitary sewage systems and treatment plants.*, Chincinnati, 1985.
- [17] P. Bizier, *Outfall sanitary sewer design and construction*, 2nd ed., American Society of Civil Engineers, 2007.
- [18] R.L. Daugherty, J.B. Franzini, *Fluid mechanics with engineering applications.*, 6th ed., McGraw-Hill, New York, 1965.
- [19] I. Ebtehaj, H. Bonakdari, A. Sharifi, Design criteria for sediment transport in sewers based on self-cleansing concept, *J. Zhejiang Univ. Sci. A.* 15 (2014) 914–924. doi:10.1631/jzus.A1300135.
- [20] H.H. Bengtson, *Uniform Open Channel Flow and the Manning Equation*, Morrisville, 2011.
- [21] Council for Scientific and Industrial Research, *Consolidated report on phase 1 of sewer corrosion research: The Virginia sewer experiment and related research.*, Pretoria, 1996.
- [22] M. Alexander, A. Goyns, C. Fourie, Experiences with a full-scale experimental sewer made with CAC and other cementitious binders in Virginia, South Africa., in: *Proc. Centen. Conf. Calcium Aluminate Cem.*, IHS, Avignon, 2008: pp. 279–292.
- [23] H. Schremmer, Report of the ATV working party concerning parameters of the ATV Code of Practice A115., *Wastewater Corresp.* 33 (1972) 729.
- [24] J. Stark, B. Wicht, *Dauerhaftigkeit von Beton*, 2nd ed., Springer, 2013. doi:10.1007/978-3-642-35278-2.
- [25] A.H. Nielsen, J. Vollertsen, H.S. Jensen, H.I. Madsen, T. Hvitved-Jacobsen, Aerobic and Anaerobic Transformations of Sulfide in a Sewer System – Field Study and Model Simulations, *Proc. Water Environ. Fed.* 2006 (2006) 3654–3670. doi:10.2175/193864706783751447.
- [26] K.-S. Cho, T. Mori, A newly isolated fungus participates in the corrosion of concrete sewer pipes, *Water Sci. Technol.* 31 (1995) 263–271. doi:doi:10.1016/0273-1223(95)00343-L.
- [27] A.L. Ling, C.E. Robertson, J.K. Harris, D.N. Frank, C. V Kotter, M.J. Stevens, et al., High-resolution microbial community succession of microbially induced concrete corrosion in working sanitary manholes, *PLoS One.* 10 (2015). doi:10.1371/journal.pone.0116400.

- [28] M. Hernandez, E.A. Marchand, D. Roberts, J. Peccia, In situ assessment of active *Thiobacillus* species in corroding concrete sewers using uorescent RNA probes, 49 (2002) 271–276.
- [29] T. Maeda, A. Negishi, H. Komot, Y. Oshima, K. Kamimura, T. Sugi, Isolation of Iron-Oxidizing Bacteria from Corroded Concretes of Sewage Treatment Plants, *Biosci. Bioeng.* 04 (1999) 300–305.
- [30] L. Mei, H.J. Busscher, H.C. van der Mei, Y. Ren, Influence of surface roughness on streptococcal adhesion forces to composite resins, *Dent. Mater.* 27 (2011) 770–778. doi:10.1016/j.dental.2011.03.017.
- [31] J. Herisson, M. Guéguen-Minerbe, E.D. van Hullebusch, T. Chaussadent, Behaviour of different cementitious material formulations in sewer networks., *Water Sci. Technol.* 69 (2014) 1502–8. doi:10.2166/wst.2014.009.
- [32] J. Herisson, E.D. van Hullebusch, M. Moletta-Denat, P. Taquet, T. Chaussadent, Toward an accelerated biodeterioration test to understand the behavior of Portland and calcium aluminate cementitious materials in sewer networks, *Int. Biodeterior. Biodegradation.* 84 (2013) 236–243. doi:10.1016/j.ibiod.2012.03.007.
- [33] A.M. Goyns, M. Alexander, Performance of various concretes in the Virginia experimental sewer over 20 years., in: *Calcium Aluminates*, Balkema, 2014: pp. 573–84.
- [34] J. Herisson, M. Gueguen-Minerbe, E.D. Van Hullebusch, T. Chaussadent, Biogenic corrosion mechanism: Study of parameters explaining calcium aluminate cement durability., in: *Calcium Aluminates*, Balkema, 2014: pp. 645–58.
- [35] L. Zhang, P. De Schryver, B. De Gusseme, W. De Muynck, N. Boon, W. Verstraete, Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: a review., *Water Res.* 42 (2008) 1–12. doi:10.1016/j.watres.2007.07.013.
- [36] W. Yang, J. Vollertsen, T. Hvitved-Jacobsen, Anoxic sulfide oxidation in wastewater of sewer networks, *Water, Sci. Technol.* 52 (2005) 191–199.
- [37] S. Abdul-Talib, T. Hvitved-Jacobsen, J. Vollertsen, Z. Ujang, Anoxic transformations of wastewater organic matter in sewers – process kinetics, model concept and wastewater treatment potential, 45 (2002) 53–60.
- [38] A. Haaning Nielsen, P. Lens, J. Vollertsen, T. Hvitved-Jacobsen, Sulfide-iron interactions in domestic wastewater from a gravity sewer., *Water Res.* 39 (2005) 2747–55. doi:10.1016/j.watres.2005.04.048.