Microbiologically Induced Deterioration and Protection of Concrete in Municipal Sewerage System: Technical Review

Vinayak Kaushal, Ph.D., A.M.ASCE[1]; Mohammad Najafi, Ph.D., P.E., F.ASCE[2]; Johnny Love, M.ASCE[3]; and Syed R. Qasim, Ph.D., P.E., F.ASCE[4]

Abstract: Microbiologically induced deterioration (MID) of concrete sewers is a common problem that requires a considerable amount of rehabilitation investment every year. MID is the result of dilute sulfuric acid dissolving the cement matrix. The acid is produced by a complex series of chemical and biochemical reactions. Hydrogen sulfide (H_2S) is produced by sulfur reducing bacteria (SRB) in the liquid phase, and then in time, this gas is converted by sulfur oxidizing bacteria (SOB) into sulfuric acid (H_2SO_4). The last conversion occurs above the liquid level under aerobic condition. The objective of this study is to present a literature review and authors' experience on progress acquired over years in understanding causes and effects of MID of concrete in municipal sewerage systems, methods to prevent and control MID from happening, and rehabilitation of already damaged pipes and structures. Published papers were identified that directly or indirectly reported MID of concrete in sewer structures over a period from 1980–2018. The literature review and authors' data suggest that deterioration of concrete is a complex process that involves varied surface interactions. Many empirical inputs that vary with installation and repair of various structures have been identified. The addition of liquid antimicrobial additive per standard procedure shows resistance of concrete to MID. Additionally, results show that resistance of concrete to MID increases with increase in the mixing time of the admixture. Further research is needed to study the concrete–microorganism interactions to have a better understanding of the microbiologically induced culture that leads to concrete deterioration in the sanitary sewerage systems. Additionally, there is a need to identify and develop more effective coatings, and safe antibacterial agents that can be used during construction of sewers to inhibit colonization of SOB over the exposed portion of the sewers. **DOI:** 10.1061/(ASCE)PS.1949-1204.0000424.

Author keywords: Microbiologically induced deterioration; Municipal sewerage systems; Sanitary sewers; Pipelines; Concrete deterioration; Hydrogen sulfide; Sulfuric acid; Sulfur reducing bacteria.

Introduction

Concrete remains one of the fundamental materials of choice in sanitary sewerage collection and treatment systems (Taylor 1997). From the large tanks needed at treatment plants to maintenance and conveyance structures such as sanitary sewers, manholes, junction boxes, pump stations, inverted syphons, and tunnels, it is the most cost effective, durable, and adaptable construction material. However, concrete's intrinsic lack of chemical resistance to dilute acids results in its deterioration and destruction. Because of deterioration, concrete structures have a persistent, costly, unpredictable, and disruptive maintenance history often calling for expensive and difficult repairs, or complete replacement (Gutierrez-Padilla et al. 2010).

Microbiologically induced deterioration (MID) of concrete is recognized as one of the main processes for degradation of concrete-based wastewater networks worldwide. It has been increasingly triggering high economic expenses, and severe health and environmental concerns (Islander et al. 1991; USEPA 1991; Qasim 1999; Najafi and Gokhale 2005; Apgar and Witherspoon 2008; O'Connell et al. 2010; Jiang et al. 2016a; Herisson et al. 2017; Qasim and Zhu 2018). In the United States, it is estimated that the cost to replace the deteriorated sewers is $14 billion per year (Brongers et al. 2002). There is a need to spend about $390 billion within the next 20 years to keep the existing wastewater infrastructure operational in the US (Gutierrez-Padilla et al. 2010). Costs to renew deteriorated municipal sewer structures can be extremely high (Wu et al. 2018).

The MID is caused by dilute sulfuric acid continuously being generated by bacteria from hydrogen sulfide (H_2S). Sulfur reducing bacteria (SRB) present under the waterline inside the sanitary sewers produces this foul-smelling gas. The problem of MID is not limited to certain climates or geography. It occurs in all municipal sewer systems to some degree. Fig. 1 shows concrete structures typically deteriorated due to MID.

The objective of this study is to present a literature review on progress acquired over years in understanding MID of concrete in municipal sewerage systems, methods to present MID from happening, and rehabilitation of already damaged structures.

[1]Post-Doctorate Research Associate and Fellow, Center for Underground Infrastructure Research and Education, Dept. of Civil Engineering, Univ. of Texas at Arlington, P.O. Box 19308, 428 Nedderman Hall, Arlington, TX 76019 (corresponding author). ORCID: https://orcid.org/0000-0001-7922-2746. Email: vinayak.kaushal@mavs.uta.edu

[2]Professor and Director, Center for Underground Infrastructure Research and Education, Dept. of Civil Engineering, Univ. of Texas at Arlington, P.O. Box 19308, 428 Nedderman Hall, Arlington, TX 76019. Email: najafi@uta.edu

[3]National Product Manager, ConShield Technologies, Inc., 541 10th St. NW #233, Atlanta, GA 30318. Email: jlove@conshield.com

[4]Professor Emeritus, Dept. of Civil Engineering, Univ. of Texas at Arlington, P.O. Box 19308, 428 Nedderman Hall, Arlington, TX 76019. Email: qasim@uta.edu

Note. This manuscript was published online on October 17, 2019. Discussion period open until March 17, 2020; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Pipeline Systems Engineering and Practice*, © ASCE, ISSN 1949-1190.

(a) (b)

Fig. 1. (a and b) Concrete structures typically deteriorated due to MID. (Images by Johnny Love.)

Published papers were identified that directly or indirectly reported MID of concrete in sewer structures over a period from 1980 to 2018. Published papers were identified from many databases such as ProQuest, Engineering Village, ASCE and Google Scholar that reported MID of concrete in sanitary sewer structures during 1980–2018. This paper provides MID processes and stages in concrete deterioration due to attack by sulfuric acid and attempts to fortify concrete along with methods to reduce deterioration.

Microbiologically Induced Deterioration

In municipal sewerage systems, progress of MID often determines the service life of concrete structure (Jiang et al. 2016b; Wu et al. 2018). During MID process, aqueous H_2S is first produced from reduction of sulfate by microbiological activity in the slime layer. The gaseous H_2S is released from sewage to the crown of the sewer (Wu et al. 2018). The gaseous H_2S then dissolves in the moisture film formed above the liquid level. Finally, the dissolved H_2S is converted to sulfuric acid (H_2SO_4) under the action of sulfur oxidizing bacteria (SOB) (primarily *Thiobacillus*) (Alexander and Fourie 2011; Wu et al. 2018). The H_2SO_4 is the *end-product* that lowers the pH of the liquid in contact with the concrete surface to about 1–2 (House 2013; Wu et al. 2018).

In acidic environments like that, cement hydration products are easily decomposed. The hydration products such as portlandite, calcium aluminate hydrate, ettringite, and calcium silica hydrate dissolve sequentially as the pH of the solution gradually lowers from 12.5 to below 8.8 (Reardon 1990; Wu et al. 2018). Below a pH of 6, portland cement is readily decomposed, and below a pH of 4 practically all calcium-based binders are rapidly dissolved. In addition, MID is an active deterioration process because bacteria continue to produce sulfuric acid to sustain these reactions (House 2013; Wu et al. 2018). As a result, the MID rate can be as high as 12 mm/year in many sewer systems (Wells and Melchers 2014; Wu et al. 2018) and even 14 mm/year in laboratory setups (Æsøy et al. 2002). Wells and Melchers (2014) and Wu et al. (2018) reported that the deterioration rates in many concrete structures in the US and abroad at times exceeded 25 mm per year. The following section provides more details regarding the MID process. Fig. 2 shows a schematic of the MID process in municipal sewers.

MID Processes

As shown in Fig. 2, MID process involves various reactions that take place both below and above the liquid surface. Generally, five separate processes take place to complete a MID cycle: (1) initial buffering of the exposed highly alkaline concrete surfaces, (2) H_2S generation in the sewage, (3) liberation of H_2S (gas) and subsequent buildup at the crown, (4) sulfuric acid generation, and (5) the concrete deterioration reaction (Wu et al. 2018). Each process is discussed below.

Initial Buffering of the Fresh Exposed Surfaces of Concrete

The initial buffering of fresh exposed concrete surfaces is an essential process. The sulfur oxidizing bacteria cannot colonize on fresh

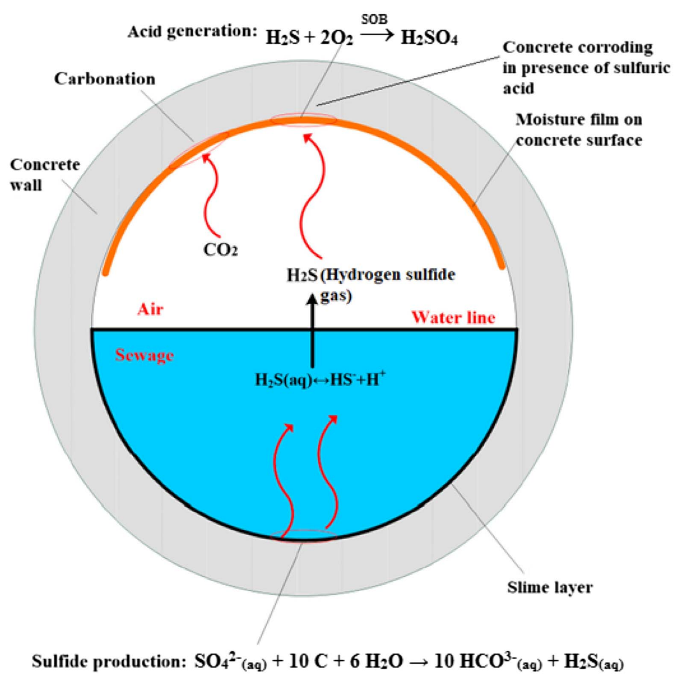

Fig. 2. Schematic of the microbiologically induced deterioration (MID) process in a sanitary sewer. (Modified from Wu et al. 2018.)

J. Pipeline Syst. Eng. Pract., 2020, 11(1): 03119002

high alkaline surfaces. The lowering of surface pH is a complex process. The major factors are carbonation, humidity, temperature, time, and air currents. The generated H_2S gas also directly reduces the surface pH.

The exposure time to high humidity usually found in most sewers will buffer the surfaces. As most cements age, they continue to react and bind minerals that cause the high alkaline condition. Like most reactions, higher temperatures speed the process.

Taylor (1997) reported that carbonation is the process where carbon dioxide (CO_2) dissolves in the pore water solution of the hardened cement paste. This pore water contains calcium hydroxide ($Ca(OH)_2$) which is partially disassociated in two ions, Ca^{2+} and OH^- [Eq. (1)]. CO_2 then dissolves in water resulting in carbonate ion and water [Eq. (2)]. The carbonate and plentiful calcium ions readily combine to form insoluble calcium carbonate [Eq. (3)]. Fully carbonated concrete has a pH of about 8. The carbonated layer impedes ingress of additional carbon dioxide; this layer can be 1 mm or less in thickness (Richardson 2002)

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^- \tag{1}$$

$$CO_2^{2+} + 2OH^- \rightarrow CO_3^{2-} + H_2O \tag{2}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \tag{3}$$

The calcium carbonate immediately reacts with dilute sulfuric acid produced from H_2S, which is a product of MID process.

Hydrogen Sulfide Generation in the Sewage

A major misunderstanding is the formation of H_2S (aq). It is produced from sulfates in the wastewater stream by anaerobic SRB located in the slime layer (Wu et al. 2018). Sulfates may be present in residential wastewater and discharge from various industrial processes. The slime layer is a layer containing bacteria and inert solids at the interface between the concrete wall and the liquid waste (Okun et al. 2010; Wu et al. 2018). The slime layer is usually between 0.3 and 1.0 mm thick, and depends on the flow velocity and solids abrasion in the municipal sewage (Bowker and Smith 1985; Wu et al. 2018). This process is complex because there is a competition between various other microorganisms attempting to break down phosphates and nitrates.

The formation of hydrogen sulfide is believed to initiate MID processes in sewer systems. It is considered one of the essential components of the complex process. Sulfate ions are the primary sulfur source in sewers. SRB under anaerobic conditions in the submerged part of sewers facilitate the reduction of sulfate ions and the production of H_2S (gas) (Taylor 1997). House and Weiss (2014) reported that H_2S (aq) is released into the gas phase with or without the aid of turbulence (turbulence increases the gas release).

Table 1. Factors affecting sulfide content in wastewater collection networks

Factor	Effect
DO	Low DO encourages activity of SRB and conversion of sulfates to sulfides
Sulfate content	Sulfates must be present for the biological conversion to sulfide
Temperature	High temperatures encourage bacterial activity and lower oxygen solubility
BOD	BOD represents nutrients available for bacteria that deplete DO
Turbulence	Encourages reaeration resulting in growth of sulfur-oxidizing microorganisms (SOM) and chemical oxidation resulting in lowered potential for sulfide buildup

Source: Data from House and Weiss (2014).

The SRB are *Sulfovibrio desulfuricans* and *Desulfovibrio desulfuricans* (Bowker and Smith 1985). Eqs. (4) and (5) describe the formation of hydrogen sulfide from reduction of sulfates by SRB, in which sodium sulfate is the sulfur source:

$$CH_3COOH + Na_2SO_4Na_2CO_3 + H_2O + CO_2 + H_2S \tag{4}$$

$$2CH_3CHOHCOONa + Na_2SO_42CH_3COONa + 2NaHCO_3 + H_2S \tag{5}$$

In the above equations, acetic acid and sodium lactate are the essential chemicals to allow the process to proceed. The process involves complex biochemical reactions.

Recent molecular surveys of biofilm communities in sewers have revealed the presence of several species of SRB present in municipal wastewater; however, *Desulfovibrio desulfuricans* is commonly the primary contributor to the sulfate reduction in the collection system of municipal wastewater (Santo Domingo et al. 2011).

Desulfovibrio desulfuricans is an obligate anaerobe that relies on the availability of organic substances for food supply (electron donor) and utilizes sulfate as an oxygen source (House and Weiss 2014). Table 1 shows the factors affecting sulfide content in wastewater collection networks.

Liberation of Hydrogen Sulfide (Gas) and Subsequent Buildup at the Crown

The H_2S dissolves in the municipal wastewater after diffusing through the slime layer. The dissolved H_2S exists both as aqueous H_2S and HS^- ions in wastewater. The relative proportion depends upon the pH of the wastewater value (Wu et al. 2018). The solubility of H_2S gas in water is reasonably high at almost several thousand ppm but at the same time, it is easily released into the atmosphere. The reaction equilibrium [Eq. (6)] determines the amount of aqueous H_2S in sanitary wastewater (Wu et al. 2018). At a pH equal to 6, about 100% of the sulfur exists as aqueous H_2S in wastewater. On the other hand, when the pH rises to about 9, H_2S content decreases in a significant manner, and about 100% of the sulfur exists as HS^- (Bowker and Smith 1985; Wu et al. 2018). The typical pH of sanitary wastewater is in the range of 6–8 (Firer et al. 2008; Wu et al. 2018).

In most cases, a large proportion of hydrogen sulfide exists in the form of aqueous solution. The H_2S is then released as gas from the wastewater and disperses all over the sewer atmosphere above the liquid surface. This gaseous H_2S becomes a significant issue because it serves as a source of food for the sulfur oxidizing bacteria that produce the sulfuric acid. The dilute sulfuric acid at the crown causes the deterioration of concrete during the final phase of the MID process. Additionally, H_2S gas results in an odor source when released from the sewerage system (Wu et al. 2018)

$$H_2S\,(aq) \rightleftharpoons HS^- + H^+ \tag{6}$$

After the release of H_2S gas into the sanitary sewer atmosphere, it sulfide builds up in the crown of pipe and other structures (Wu et al. 2018). One theory (at least in pipe) is that near the flowing liquid level there may be air currents that help to diffuse the gas, whereas at the crown the air is more stagnant. This H_2S buildup plays an important role in the MID process. A higher gaseous H_2S concentration at the crown may cause a higher level of concrete deterioration. This relationship, however, has not been fully confirmed (Wells et al. 2009; Vollertsen et al. 2008; Wu et al. 2018). Sun (2015) concluded that a wide range of H_2S concentration ranging from 2 ppm to several hundred ppm can trigger severe acid deterioration (Sun 2015). Æsøy et al. (2002) and Wu et al. (2018) reported that a severe deterioration of concrete was found at a H_2S concentration of 4 ppm.

Sulfuric Acid Generation or Sulfide Oxidation

In the sulfuric acid generation process, the H_2S is oxidized into dilute sulfuric acid ($H_2SO_4 + H_20$) through various biological activities. First, the moisture in the crown atmosphere condenses on the concrete wall that forms a moisture film (Wu et al. 2018). Then, due to various factors discussed above, the pH of the moisture layer of the concrete rises, and the SOB start colonizing on the crown of the pipe, and other underground structure (Sun 2015; Wu et al. 2018). Atmospheric temperature is critical for the reaction rate of the microorganisms. There is an increase in microbial activity due to the increase in atmospheric temperature (Huseyin et al. 1987; Joseph et al. 2012), thereby increasing the reaction rate of the MID. For example, the sulfide oxidation rate at the temperature of 25°C was found 15% higher than that at 20°C (Sun 2015; Wu et al. 2018). Temperature lower than 15.6°C inhibits the activity of sulfide-oxidizing organisms (Sublette et al. 1998). Relative humidity (RH) is another important factor influencing sulfuric acid formation (Wu et al. 2018).

A minimum value of 87% RH is required for bacteria to be active (Rootsey et al. 2012). Generally, high humidity increases the rate of sulfuric acid formation (Islander et al. 1991; Wu et al. 2018). For example, the pH of the concrete surface was reduced significantly, when the RH was from 95% to 100% as compared with when the RH was between 85% and 95% (Wells et al. 2012). Thus, more sulfuric acid forms when the RH is between 95% and 100%. Generally, in sewers, RH is high, and moderate temperatures persist year around.

Final Concrete Deterioration Reaction by Sulfuric Acid

Because of the alkaline nature, concrete deteriorates easily after sulfuric acid forms. In this process, aggressive ions in the sulfuric acid (i.e., H^+ and SO_4^{2-}) react with conventional hydration products such as calcium silica hydrate gel and $Ca(OH)_2$ (Wu et al. 2018). The generalized chemical formula of calcium silica hydrate gel is $x\text{CaO–}y\text{SiO}_2\text{–}z\text{2H}_2\text{O}$. The coefficients x may range from 1 to 2, y from 1 to 1.3, and z from 2 to 4. [see unbalanced Eqs. (7) and (8)]. One immediate byproduct is $CaSO_4 \cdot 2H_20$ that is expansive with a volume increase of 124% (Idriss et al. 2001; Parande et al. 2006; IUPUI 2009; Wu et al. 2018), and produces the punky mushy appearance of the destroyed concrete.

The MID is a pure surface attack where the acid dissolves various calcium containing minerals and produces a punky mush of water, various salts and complex minerals like ettringite. These after-products are of little interest. This punky mush is not a barrier to various gases and bacteria. The acid continues to be produced, and it continues to attack the underlying hardened concrete, thus, affecting its structural stability (IUPUI 2009).

$$\text{H}_2\text{SO}_4 + x\text{CaO–}y\text{SiO}_2\text{–}z\text{2H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{Si(OH)}_2 \tag{7}$$

$$\text{H}_2\text{SO}_4 + \text{Ca(OH)}_2 \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} \tag{8}$$

The typical concrete binders are calcium rich, and they will dissolve by most acids. The reactions are driven by the hydrogen ions. The type of acid only affects the type of byproducts produced and does nothing to stop the bacteria growth and acid production, which continue to weaken the structure. Internal deterioration caused by slow forming ettringite needs to be well understood and not to be confused with external surface attack caused by sulfuric acid. Table 2 shows various chemical reactions that can cause concrete degradation.

Stages in the Aerobic Process

A significant amount of research has been conducted on the complex mechanisms involved with MID (Islander et al. 1991; Yamanaka et al. 2002; Zhang et al. 2008; Jensen et al. 2009; Kaushal et al. 2017; Najafi and Kaushal 2017; Kaushal et al. 2018). Based on the typical biological and physical-chemical reactions and their resulting byproducts, MID is broken down in three stages.

First Stage: Colonization of Neutrophilic Sulfur Oxidizing Bacteria

The beginning of the colonization is marked by the presence of various strains of neutrophilic sulfur oxidizing bacteria (NSOB) which adopt to the moist concrete surface and pore structure at pH of 9–9.5 (Islander et al. 1991; Joseph et al. 2012; Satoh et al. 2009; Vincke et al. 2000). NSOB possess the ability to utilize different sulfur compounds to form sulfuric acid (H_2SO_4) under moist conditions (Gomez-Alvarez et al. 2012; Okabe et al. 2007).

Second Stage: Attack of Acidithiobacillus Bacteria

The next deterioration stage begins once as pH of 4 approaches. The acidophil bacteria start to dominate the biofilm, with Acidithiobacillus thiooxidans being the most common one (Jiang et al. 2016b; Okabe et al. 2007; Satoh et al. 2009). Whereas the central role of *A. thiooxidans* is well described in the literature, little information exists regarding the contribution of other bacterial species, especially, the impact of *Acidithiobacillus ferrooxidans*, a chemoautotrophic ASOB. These organism are well known from acid mine drainage environments (Osorio et al. 2013; Valdes et al. 2008). They cause deterioration of strongly deteriorated systems (Maeda et al. 1999; Yamanaka et al. 2002). Okabe et al. (2007), from their sampling campaign, reported low abundances of these organisms and consequently their low impact on deterioration processes. However, other studies emphasized their possible impact under suitable conditions (Grengg et al. 2017, 2015; Jiang et al. 2016b).

Table 2. Reactions of concretes with acids

Type of acid	Lime + acid	Result	Salt + water
Hydrochloric	$Ca(OH)_2 + 2HCl$ (aq)	→	$CaCl_2$ (aq) $+ 2H_2O$
Phosphoric	$3Ca(OH)_2 + 2H_3PO_4$ (aq)	→	$Ca_3(PO_4)_2$ (s) $+ 6H_2O$
Sulfuric	$Ca(OH)_2 + H_2SO_4$ (aq)	→	$CaSO_4 + 2H_2O$ (gypsum)

Third Stage: Loss of Material

The third and last stage of MID of concrete is associated with massive loss of material. Grengg et al. (2015) and Mori et al. (1992) reported deterioration rates greater than 10 mm/year. During the biotic cycle of MID, the appearance and dominance of SOB (both NSOB and ASOB) are controlled by pH, trophic properties, and the ability to utilize different sulfur compounds such as H_2S, S_0, and S_2O_3 (Islander et al. 1991). Besides SOB, heterotrophic bacteria and fungi have also been found in biofilms observed in various deteriorated wastewater systems (Cho and Mori 1995; Davis et al. 1998; Peyre Lavigne et al. 2015a, b; Nica et al. 2000; Vincke et al. 2001; Okabe et al. 2007). The importance of fungi, algae, and lichens in colonization of stone and concrete buildings especially under extreme environmental conditions is well documented. These organisms are important in biofilm formation and stabilization of the MID process (Cheng 2014; Flemming et al. 2016). Associated gaps in knowledge have to be bridged by complementary research activities to develop sustainable materials and efficient mitigation strategies for MID environments (Gomez-Alvarez et al. 2012; Okabe et al. 2007; Satoh et al. 2009).

MID Control

There are three classical means that have been attempted to control deterioration and improve concrete durability, but they offer limited success where acid generation is concerned. These classical means are discussed below:

Reducing Calcium Compounds

The use of pozzolans such as fly ash and colloidal silica in concretes offers excellent mechanical properties and low permeability. This helps to control deterioration of concrete. Pozzolans work in two ways to improve the basic mechanical properties (Gruyaert et al. 2012; Hossain et al. 2016).

First, as pozzolans are rich in amorphous silica, they will react over time with the calcium hydroxide hydration byproducts to form additional calcium silicate hydrates. These additional hydrates are strong, dense, and offer less mobility to ions versus the watery pore space and calcium hydroxide (Roy et al. 2001; Sabir et al. 2001; Duan et al. 2013). This action helps to control and prolong concrete deterioration.

Second, use of pozzolans improves the workability of concrete allowing for reduced water content when used in conjunction with high-range water reducing admixtures. Many studies over the years have demonstrated that simple cement substitutions with pozzolans produced modest improvements in deterioration of concrete (Monteny et al. 2003; House and Weiss 2014; Senhadji et al. 2014). Whereas the use of pozzolans improved concrete durability in many ways, this does little to improve the concrete's ability to resist the corrosive actions of strong acids.

Reducing Permeability of Concrete

Permeability can be reduced by a combination of two means: cement modifiers and crystalline forming water proofing admixtures (Valix et al. 2012; Sun et al. 2016). These permeability reducing means are described below:

Cement Modifiers

There has been a significant amount of work done in the area of reducing permeability with additives. This includes the combination of water reducing admixtures, cement substitutions with pozzolanic materials as mentioned above, and cement modifiers such as latex and acrylic emulsions. These concepts have their applications especially where the attack is due to penetration of the hydrate structure by a mobile ion (Morrison et al. 2013; Hossain et al. 2016). MID is a surface attack caused by powerful acid, not internal deterioration caused by ion penetration.

Crystalline Forming Water Proofing Admixtures

These admixtures are based on certain minerals that contain combinations of rare earth metal oxides. They promote a complex growth of solid crystals within the watery pore space of hardened Portland cement paste. They have two important functions: (1) they dramatically reduce the permeability of even mediocre concretes, and (2) the crystalline growth can continue while there is moisture, space, and reactive mineral complexes available within the cement gel structure. This last point is most important for healing cracks, which inevitably form in dams, tunnels, tank structures, and thin linings. Careful aggregate grading is essential to reduce the paste volume requirement and, therefore, keep the mix economical (Dinakar et al. 2008; Ekolu et al. 2016).

Buffering the Concrete with Limestone Aggregates

This concept is to use the coarse fraction of the aggregates that consumes some of the acid and protects the lime-rich cement paste. This requires a firm understanding of factors like age, material, length of sewer, flow rates, retention times, seasons, rain water count, ventilation, BOD, COD, type of sulfides produced, and sewer temperature (Ana et al. 2009). These factors are often difficult to obtain in new construction. From these factors, an appropriate loss rate can be calculated, and then the wall thickness of the structure is increased to compensate for the loss of concrete. In many instances, the wall thickness is not increased, and the life span is incorrectly determined from 100% of the base wall thickness.

In a typical concrete, the limestone-based aggregates may also contain dolomites (Shetti and Das 2015; Chindaprasirt et al. 2004). This concept may work for some limited industrial cases where limited acid production takes place, and acid concentration is well understood. This is not the case in most of the sanitary sewers because the production of acid is neither limited nor generally very well understood. For these reasons, MID readily destroys most sanitary structures made of these concretes unless additional protection is provided.

Action of Antimicrobial Admixtures

A completely different approach to protect concrete from MID is to render it uninhabitable by the bacteria that convert the H_2S into sulfuric acid. The breakthrough research in the 1990s was to utilize the antimicrobial chemicals in an aqueous solution. The properties of this chemical are discussed later. The chemical is readily dispersible in a high-pH wet concrete mix. The key is to protect the fresh highly alkaline concrete before it hardens. It remains active and effective in the hardened concrete over a long term. As a thin liquid, the additive readily disperses throughout the concrete mix and ultimately bonds molecularly with all the concrete's ingredients (IUPUI 2009; Kaushal et al. 2018).

Antimicrobial admixtures prevent the colonization of acid-producing aerobic bacteria on the exposed surfaces of the concrete over the life of the concrete. It is environmentally friendly and cannot leach out nor affect the chemistry of the wastewater. It is safe, easy to apply, and requires no special handling or safety precautions. In the hardened concrete, the additive is nontoxic to humans and animals, but permanently inhibits the growth of single-celled organisms such as *Thiobacillus* (Bell et al. 1999).

The active ingredient in antimicrobial admixtures is generally categorized as a complex quaternary ammonium silane (QAS). The admixtures have been modified to function within cementitious materials like concrete and repair mortars. The QAS type molecule has a head group containing the silane functional group and cationic ammonium moiety); and a tail group containing hydrophobic water-shedding carbon chain. By virtue of these chemically distinct groups, a bifunctional molecule is produced. The head group provides a mechanism for covalent bonding and cross linking. The cationic and the tail groups drive the molecular interaction with microbial membranes leading to the antimicrobial performance (Franke and Sisomphon 2004).

Cement-Based Rehabilitation Methods

In addition to MID control methods, there are several cement-based renewal methods like shotcrete, cast-in-place concrete, and spin-cast that can be used to increase the life span of deteriorated concrete structures. Table 3 illustrates the advantages and limitations of each of these methods (Najafi and Gokhale 2005; Wu et al. 2018). A brief discussion of these cement-based renewal methods is given below:

Shotcrete

Shotcrete is the method of pneumatically spraying fresh cement-based mixtures on a deteriorated surface of pipe or any other structures through a hose at a very high velocity. There are two types of processes: dry-mix and wet-mix. In the dry-mix process, water is added at the nozzle, whereas, in the wet-mix process, all ingredients are mixed with water before being introduced to the delivery hose and the nozzle (Morrison et al. 2013; ACI 2016; Wu et al. 2018).

Cast-in-Place Concrete Method

Another effective renewal technique for various sewer shapes is the cast-in-place concrete method. In this type of pipe rehabilitation method, the designed steel mesh is affixed to the existing pipe in the form of reinforcement. The gap between the formwork and the pipe wall is the annular space that is filled later. A venting or overflow hole is required at the highest point of the formwork that not only provides a path for air to escape when fresh concrete is injected but also intimates the worker to stop grouti/ng when it overflows (WEF 2009). After the formwork, a grouting pipe is laid in the crown of the deteriorated sewer pipe. Thereafter, concrete ingredients are introduced and mixed in the grout plant on the ground. The readily mixed fresh mixture is then pumped to the grouting location through the pipe laid onto the formwork's crown. When the venting hole overflows, the grout operation is stopped, followed by sealing of the venting hole with a plug (McAlpine and Anderson 2005; Wu et al. 2018).

Spin-Cast Method

In addition to shotcrete and cast-in-place concrete, spin cast is another automated process that uses centrifugal force to spin cementitious materials onto the deteriorated pipe surface. It is an effective rehabilitation method for circular or almost-circular sewers. At first, a pumping plant is set up on the ground. Similar to the cast-in-place method, all ingredients are introduced and mixed in here (Norman 2016). However, no coarse aggregates are introduced. Thereafter, the readily mixed paste is transported to a spincaster that is located in the pipe. During the renewal process, the spincaster rotates and sprays cementitious materials onto the old, deteriorated pipe structure (Wu et al. 2018).

Authors' Experience

Kaushal et al. (2018) conducted a laboratory test as per ASTM D4783 (ASTM 2013) procedure to determine the resistance of treated concrete materials to microbial attack by challenging the test specimen with a bacterial culture.

Test Methodology

Inoculated specimens were stored at 30°C for 24 h. If the inoculated specimen showed microbial growth on the streak plate or test surface after 72 h, the test was discontinued, and the sample specimen

Table 3. Review of advantages and limitations for cement-based renewal methods in the municipal sewerage system

Cement-based renewal method	Advantages	Limitations
Shotcrete	• Fiber-reinforced shotcrete shows excellent mechanical properties • Improved compaction resulting in enhanced chemical resistance • Applicable in almost all sewer shapes	• Limited acid resistance • Flow bypass required • High level of cleaning required • Removal of inflow and infiltration (I & I) required • Decreased cross-sectional area • Pumping length < 500 m • Rebound impact
Cast-in-place concrete	• Effective for a variety of sewer shapes	• Limited acid resistance • Flow bypass required • High level of cleaning required • Removal of I & I required • Decreased cross-sectional area • Formwork or assembly system required
Spin-cast	• Cost-effective • Can be done without confined space entry • Can be used in small diameter sewer pipes	• Limited acid resistance • Flow bypass required • High level of cleaning required • Removal of I & I required • Decreased cross-sectional area

Source: Adapted from Najafi and Gokhale (2005) and Wu et al. (2018).

was reported as not resistant to attack. Whereas, if the culture showed no growth, it was reported as resistant to attack and positive for the presence of the antimicrobial agent. After 24 h of bacterial preparation, Serratia Marcescens was grown on nutrient agar at 30°C. The plates were incubated for 48 h at 3°C. The result was positive when there was no growth of Serratia Marcescens on the agar plates within a 48-h period and a negative result was shown by the growth of red colonies of Serratia Marcescens on the agar plates which demonstrated that the antimicrobial agent was not present in the sample in sufficient concentration to kill the indicator microorganism in 48 h.

Testing

Three concrete samples designated as C1, C2, and C3 were analyzed per ASTM D4783 (ASTM 2013). Antimicrobial chemical was added and mixed to the second and third samples for 90 s and 7 min, respectively, and absent in the first one. The concrete samples were washed with isopropyl alcohol, dried, and then placed in a carbon dioxide chamber overnight. Additionally, the pH of the samples was taken after they were removed from the carbon dioxide chamber. A cell suspension of Serratia marcescens was prepared using distilled water, estimated at 1×10^7 cfu/mL. Approximately, 0.2–0.3 mL of the cell suspension was placed on the sample surface and allowed to dry. The samples were then placed in a closed container with moist paper towels and incubated for 24 h at 30 ± 1°C.

For cell recovery, 0.2–0.3 mL of sterile water was washed over the outside surface of the core, not the cut surface, stirred with a pipette, then removed and plated on nutrient agar. Additionally, a sterile cotton swab was brushed over the surface of the sample and then used to streak another nutrient agar plate. Both plates were incubated for 48 h at 30 ± 1°C.

Results

Once removed from the carbon dioxide chamber, the pH of samples 1–3 were 6, 7, and 6, respectively. After 48 h of incubation, samples 1 and 2 contained red colonies indicating the absence of antimicrobial additive, whereas sample 3 had no growth, indicating that the additive was present. Figs. 3–5 show samples and nutrient agar plates.

The above results show resistance of concrete samples to the microbial growth by the use of antimicrobial. Additionally, this resistance increases with an increase in the mixing time of antimicrobial admixture.

Discussion and Conclusions

Based on a comprehensive literature review and the authors' work, it is concluded that the biological activity in the sewerage systems is complex and produces corrosive sulfuric acid irrespective of location, climate, or geography. The addition of liquid antimicrobial additive as per ASTM D4783 (ASTM 2013) procedure shows resistance of concrete to MID. Additionally, results show an increase in the resistance of concrete to MID with an increase in the mixing time of the admixture. The formation of H_2S in the wastewater systems during MID process is misapprehended. It is produced from sulfates in the wastewater stream by anaerobic SRB located in the slime layer. The thickness of the slime layer ranges between 0.3 and 1.0 mm and depends on the flow velocity and solids abrasion in the municipal sewage. This process is complex because there is a competition between various other microorganisms attempting to break down phosphates and nitrates.

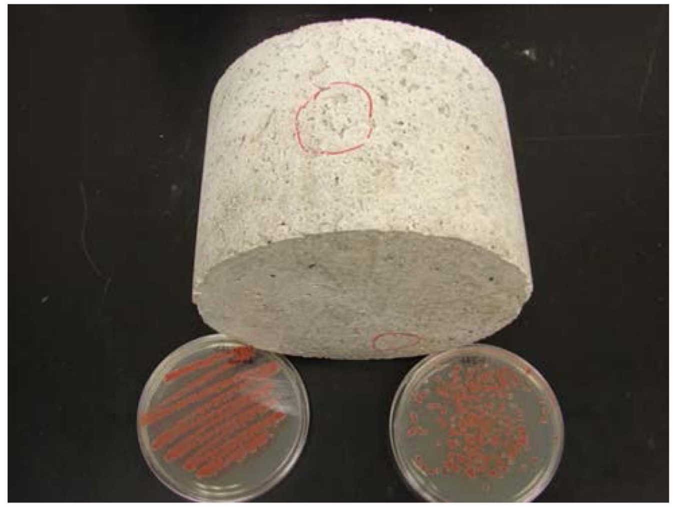

Fig. 3. Sample 1.

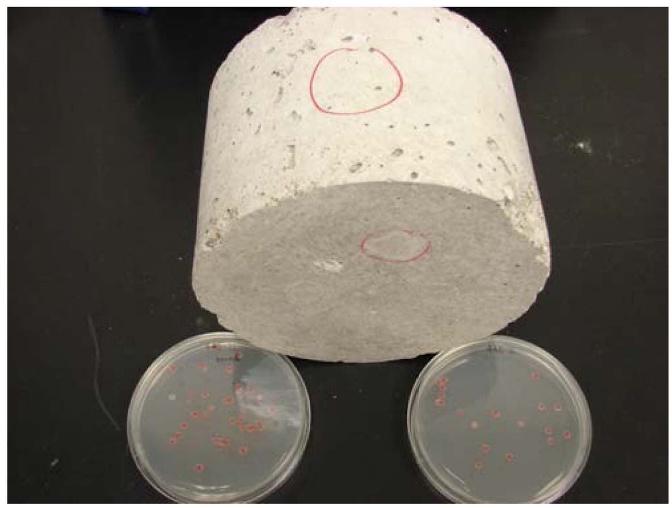

Fig. 4. Sample 2.

Fig. 5. Sample 3.

SRB under anaerobic conditions in the submerged part of the sewers facilitates reduction of sulfate ions and produces various forms of sulfides. The formation of H_2S occurs as soon as it escapes from the liquid sewage and becomes the essential feedstock for the MID processes in the sewer systems. Aerobic bacteria colonize on all surfaces above the water line and convert H_2S gas into dilute sulfuric acid by means of many complex biochemical processes.

Due to the presence of calcium-based minerals in the binder phase, typical concretes cannot tolerate the effects of corrosive sulfuric acid. The acids produced during MID cause an immediate disassociation of the calcium and associated hydroxide radicals, resulting in nonstructural calcium sulfate hydrate complexes and water as the byproducts. In addition to this, the deterioration byproducts are not stable, provide zero structural value, and do not slow down the attack or block further production of acid. Therefore, the immediate surface destruction outpaces penetration of the acid and hence, giving rise to MID. Low-cost resins like asphalt, coat tars, linseed oil, sulfur, and ure-formaldehyde may increase the deterioration resistance and strength and reduce the permeability of concrete used in the sewerage system [ACI 515.2R (ACI 2013)].

Recommendations for Future Research

The MID of concrete in municipal sewerage system is of great concern. There is a need to study the concrete–microorganism interactions to have a better understanding of the microbiologically induced culture that leads to concrete deterioration in the sanitary sewerage systems. It is also necessary to identify and develop more effective coatings, and safe antibacterial agents that can be used during construction of sewers to inhibit colonization of SOB over the exposed portion of the sewers. Different classes of antimicrobial admixtures should be identified and investigated that specifically inhibit acid producing organisms as deterioration starts and these acid-forming chemicals are released from the concrete.

There is an evidence that acid is generated upstream in various pipes and structures, and an acid-rich atmosphere is produced that could migrate downstream and attack concrete prone to classical MID. Therefore, there is a need to model H_2S production and accumulation in the aerobic environment and deterioration rate of the sewers. Because the deterioration of concrete is a complex process that involves varied surface interactions, there is a need to better understand various empirical inputs that vary with every installation. Detailed examination of the specific points where the deterioration began and the migration of the microbial community along the concrete surface are needed. Physical and chemical concrete parameters must be characterized in detail regarding their impact on microbiological growth.

Acknowledgments

The authors acknowledge the support of the Center for Underground Infrastructure Research and Education (CUIRE) and Con-Shield Technologies, Inc., for funding this study.

Notation

The following symbols are used in this paper:

aq = aqueous;
C3A = tricalcium aluminate;
$Ca(OH)_2$ = calcium hydroxide;
$Ca_3(PO_4)_2$ = calcium phosphate;
$CaCl_2$ = calcium chloride;
$CaCO_3$ = calcium carbonate;
$CaSO_4$ = calcium sulfate;
$CH_3CHOHCOONa$ = sodium lactate;
CH_3COOH = acetic acid;
CH_3COONa = sodium acetate;
H_2CO_3 = carbonic acid;
H_2S = hydrogen sulfide;
H_2SO_4 = sulfuric acid;
H_3PO_4 = phosphoric acid;
HCl = hydrochloric acid;
HS^- = bisulfide;
Na_2CO_3 = sodium carbonate;
Na_2SO_4 = sodium sulfate;
$NaHCO_3$ = sodium bicarbonate;
NSOB = neutrophilic sulfur oxidizing bacteria;
pH = potential of hydrogen;
$Si(OH)_2$ = silicon hydroxide;
SO_3 = sulfide or $\overline{\overline{S}}$;
SO_4^{2-} = sulfate;
xCaO–ySiO$_2$–zH$_2$O = amorphous calcium silicate hydrate; and
$3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$ = ettringite.

References

ACI (American Concrete Institute). 2013. *Guide to the use of waterproofing, damping, protective, and decorative barrier systems for concrete*. ACI 515.2R. Farmington Hills, MI: ACI.

ACI (American Concrete Institute). 2016. *Guide to shotcrete*. ACI 506. Farmington Hills, MI: ACI.

Æsøy, A., S. W. Østerhus, and G. Bentzen. 2002. "Controlled treatment with nitrate in sewers to prevent concrete corrosion." *Water Sci. Technol. Water Supply* 2 (4): 137–144. https://doi.org/10.2166/ws.2002.0131.

Alexander, M., and C. Fourie. 2011. "Performance of sewer pipe concrete mixtures with portland and calcium aluminate cements subject to mineral and biogenic acid attack." *Mater. Struct.* 44 (1): 313–330. https://doi.org/10.1617/s11527-010-9629-1.

Ana, E., W. Bauwens, M. Pessemier, C. Thoeye, S. Smolders, I. Boonen, and G. De Gueldre. 2009. "Investigation of the factors influencing sewer structural deterioration." *Urban Water J.* 6 (4): 303–312. https://doi.org/10.1080/15730620902810902.

Apgar, D., and J. Witherspoon. 2008. *Minimization of odors and corrosion in collection systems*. Alexandria, VA: Water Environment Research Foundation.

ASTM. 2013. *Standard test methods for resistance of adhesive preparations in container to attack by bacteria, yeast, and fungi*. ASTM D4783. West Conshohocken, PA: ASTM.

Bell, L. W., W. E. Shook, and T. Norris. 1999. "Mitigating the corrosion of concrete pipe and manholes." In *Concrete pipe for the new millennium: ASTM STP1368*, edited by J. I. Enyart and I. I. Kaspar. West Conshohocken, PA: ASTM.

Bowker, R. P., and J. M. Smith. 1985. *Odor and corrosion control in sanitary sewerage systems and treatment plants: Design manual*. Washington, DC: USEPA.

Brongers, M., P. Virmani, and J. Payer. 2002. *Drinking water and sewer systems in corrosion costs and preventative strategies in the United States*. Washington, DC: US Dept. of Transportation.

Cheng, L. 2014. "Microbial biofilm development on and degradation of concrete surfaces." Ph.D. dissertation, Dept. of Civil and Environment Engineering, Purdue Univ.

Chindaprasirt, P., S. Homwuttiwong, and V. Sirivivatnanon. 2004. "Influence of fly ash fineness on strength, drying shrinkage and sulfate resistance of blended cement mortar." *Cem. Concr. Res.* 34 (7): 1087–1092. https://doi.org/10.1016/j.cemconres.2003.11.021.

Cho, K. S., and T. Mori. 1995. "Newly isolated fungus participates in the corrosion of concrete sewer pipes." *Water Sci. Technol.* 31 (7): 263–271. https://doi.org/10.2166/wst.1995.0242.

Davis, J. L., D. Nica, K. Shields, and D. J. Roberts. 1998. "Analysis of concrete from corroded sewer pipe." *Int. Biodeterior. Biodegrad.* 42 (1): 75–84. https://doi.org/10.1016/S0964-8305(98)00049-3.

Dinakar, P., K. G. Babu, and M. Santhanam. 2008. "Durability properties of high volume fly ash self compacting concretes." *Cem. Concr. Compos.* 30 (10): 880–886. https://doi.org/10.1016/j.cemconcomp.2008.06.011.

Duan, P., Z. Shui, W. Chen, and C. Shen. 2013. "Effects of metakaolin, silica fume and slag on pore structure, interfacial transition zone and compressive strength of concrete." *Constr. Build. Mater.* 44 (Jul): 1–6. https://doi.org/10.1016/j.conbuildmat.2013.02.075.

Ekolu, S. O., S. Diop, F. Azene, and N. Mkhize. 2016. "Disintegration of concrete construction induced by acid mine drainage attack." *J. South Afr. Inst. Civ. Eng.* 58 (1): 34–42. https://doi.org/10.17159/2309-8775/2016/v58n1a4.

Firer, D., E. Friedler, and O. Lahav. 2008. "Control of sulfide in sewer systems by dosage of iron salts: Comparison between theoretical and experimental results, and practical implications." *Sci. Total Environ.* 392 (1): 145–156. https://doi.org/10.1016/j.scitotenv.2007.11.008.

Flemming, H., J. Wingender, U. Szewzyk, P. Steinberg, and S. A. Rice. 2016. "Biofilms: An emergent form of bacterial life." *Nat. Rev. Microbiol.* 14 (9): 563–575. https://doi.org/10.1038/nrmicro.2016.94.

Franke, L., and K. Sisomphon. 2004. "New chemical method for analyzing free calcium hydroxide content in cementing material." *Cem. Conc. Res.* 34 (7): 1161–1165. https://doi.org/10.1016/j.cemconres.2003.12.003.

Gomez-Alvarez, V., R. P. Revetta, and J. W. Domingo. 2012. "Metagenome analyses of corroded concrete wastewater pipe biofilms reveal a complex microbial system." *BMC Microbiol.* 12 (1): 122. https://doi.org/10.1186/1471-2180-12-122.

Grengg, C., F. Mittermayr, A. Baldermann, M. E. B€ottcher, A. Leis, G. Koraimann, P. Grunert, and M. Dietzel. 2015. "Microbiologically induced concrete corrosion: A case study from a combined sewer network." *Cem. Concr. Res.* 77 (Nov): 16–25. https://doi.org/10.1016/j.cemconres.2015.06.011.

Grengg, C., F. Mittermayr, G. Koraimann, F. Konrad, M. Szabo, A. Demeny, and M. Dietzel. 2017. "Decisive role of acidophilic bacteria in concrete sewer networks: A new model for fast progressing microbial concrete corrosion." *Cem. Concr. Res.* 101 (Nov): 93–101. https://doi.org/10.1016/j.cemconres.2017.08.020.

Gruyaert, E., P. Van den Heede, M. Maes, and N. De Belie. 2012. "Investigation of the influence of blast-furnace slag on the resistance of concrete against organic acid or sulphate attack by means of accelerated degradation tests." *Cem. Concr. Res.* 42 (1): 173–185. https://doi.org/10.1016/j.cemconres.2011.09.009.

Gutierrez-Padilla, M. G. D., A. Bielefeldt, S. Ovtchinnikov, M. Hernandez, and J. Silverstein. 2010. "Biogenic sulfuric acid attack on different types of commercially produced concrete sewer pipes." *Cem. Concr. Res.* 40 (2): 293–301. https://doi.org/10.1016/j.cemconres.2009.10.002.

Herisson, J., M. Gueguen-Minerbe, E. D. van Hullebusch, and T. Chaussadent. 2017. "Influence of the binder on the behaviour of mortars exposed to H_2S in sewer networks: A long-term durability study." *Mater. Struct.* 50 (1): 8. https://doi.org/10.1617/s11527-016-0919-0.

Hossain, M. M., M. R. Karim, M. Hasan, M. K. Hossain, and M. F. M. Zain. 2016. "Durability of mortar and concrete made up of pozzolans as a partial replacement of cement: A review." *Constr. Build. Mater.* 116 (Jul): 128–140. https://doi.org/10.1016/j.conbuildmat.2016.04.147.

House, M. W. 2013. "Using biological and physico-chemical test methods to assess the role of concrete mixture design in resistance to microbially induced corrosion." Ph.D. dissertation, Dept. of Civil and Environment Engineering, Purdue Univ.

House, M. W., and W. J. Weiss. 2014. "Review of microbially induced corrosion and comments on needs related to testing procedures." In *Proc., 4th Int. Conf. on the Durability of Concrete Structures*. West Lafayette, IN: Purdue Univ.

Huseyin, S., M. Mohammed, S. Mohammed, and A. Ibrabimm. 1987. "Case study of deterioration of concrete in sewage environment in an Arabian Gulf country." *Durability Build. Mater.* 5 (2): 145–154.

Idriss, A., S. Negi, J. Jofriet, and G. Hayward. 2001. "Effect of hydrogen sulphide emissions on cement mortar specimens." *Can. Biosyst. Eng.* 43: 523–528.

Islander, R. L., J. S. Devinny, F. Mansfeld, A. Postyn, and S. Hong. 1991. "Microbial ecology of crown corrosion in sewers." *J. Environ. Eng.* 117 (6): 751–770. https://doi.org/10.1061/(ASCE)0733-9372(1991)117:6(751).

IUPUI (Indiana University–Purdue University Indianapolis). 2009. *Indianapolis Department of Public Works (INDY-DPW) and Indiana University–Purdue University Indianapolis (IUPUI)-Purdue School of Engineering and Technology (IUPUI) INDY-DPW/IUPUI NRP (New Product Review) Process Report on ConmicShield®, IN.* Indianapolis, IN: IUPUI.

Jensen, H. S., A. H. Nielsen, T. Hvitved-Jacobsen, and J. Vollertsen. 2009. "Modeling of hydrogen sulfide oxidation in concrete corrosion products from sewer pipes." *Water Environ. Res.* 81 (4): 365–373. https://doi.org/10.2175/106143008X357110.

Jiang, G., J. Keller, P. L. Bond, and Z. Yuan. 2016a. "Predicting concrete corrosion of sewers using artificial neural network." *Water Res.* 92 (Apr): 52–60. https://doi.org/10.1016/j.watres.2016.01.029.

Jiang, G., M. Zhou, T. H. Chiu, X. Sun, J. Keller, and P. L. Bond. 2016b. "Wastewater enhanced microbial corrosion of concrete sewers." *Environ. Sci. Technol.* 50 (15): 8084–8092. https://doi.org/10.1021/acs.est.6b02093.

Joseph, A. P., J. Keller, H. Bustamante, and P. L. Bond. 2012. "Surface neutralization and H_2S oxidation at early stages of sewer corrosion: Influence of temperature, relative humidity and H_2S concentration." *Water Res.* 46 (13): 4235–4245. https://doi.org/10.1016/j.watres.2012.05.011.

Kaushal, V., M. Najafi, and J. Love. 2018. "Qualitative investigation of microbially induced corrosion of concrete in sanitary sewer pipe and manholes." In *Proc., ASCE Pipelines 2018*, 768–775. Reston, VA: ASCE.

Kaushal, V., M. Najafi, and V. Young. 2017. "Microbiologically induced concrete corrosion in sanitary sewer systems." In *Proc., Trenchless Technology and Pipe Conf.*, Arlington, TX: Univ. of Texas at Arlington.

Maeda, T., A. Negishi, H. Komot, Y. Oshima, K. Kamimura, and T. Sugi. 1999. "Isolation of iron-oxidizing bacteria from corroded concretes of sewage treatment plants." *J. Biosci. Bioeng.* 88 (3): 300–305. https://doi.org/10.1016/S1389-1723(00)80013-4.

McAlpine, G., and B. Anderson. 2005. "Structural rehabilitation of cast-in-place concrete sewers." In *Proc., Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy*, 510–522. Reston, VA: ASCE.

Monteny, J., N. De Belie, and L. Taerwe. 2003. "Resistance of different types of concrete mixtures to sulfuric acid." *Mater. Struct.* 36 (4): 242–249. https://doi.org/10.1007/BF02479618.

Mori, T., T. Nonaka, K. Tazaki, M. Koga, Y. Hikosaka, and S. Noda. 1992. "Interactions of nutrients, moisture and pH on microbial corrosion of concrete sewer pipes." *Water Res.* 26 (1): 29–37. https://doi.org/10.1016/0043-1354(92)90107-F.

Morrison, R., T. Sangster, D. Downey, J. Matthews, W. Condit, S. Sinha, S. Maniar, and R. Sterling. 2013. *State of technology for rehabilitation of water distribution systems: EPA/600/R-13/036 2013*. Washington, DC: USEPA.

Najafi, M., and S. B. Gokhale. 2005. *Trenchless technology: Pipeline and utility design, construction, and renewal*. New York: McGraw-Hill.

Najafi, M., and V. Kaushal. 2017. *Investigating and reporting solutions for microbiologically induced corrosion of concrete in sanitary sewer pipe and manholes*. Final Report. Arlington, TX: Center for Underground Infrastructure Research & Education.

Nica, D., J. K. Davis, L. Kirby, G. Zuo, and D. J. Roberts. 2000. "Isolation and characterization of microorganisms involved in the biodeterioration of concrete in sewers." *Int. Biodeterior. Biodegrad.* 46 (1): 61–68. https://doi.org/10.1016/S0964-8305(00)00064-0.

Norman, E. 2016. "Manhole rehabilitation: Delivering on the design with proper installation practices and related quality assurance testing." In *Proc., NASTT's 2016 No-Dig Show*, 9. Arlington, TX: North American Society for Trenchless Technology.

O'Connell, M., C. McNally, and M. G. Richardson. 2010. "Biochemical attack on concrete in wastewater applications: A state of the art review." *Cem. Concr. Compos.* 32 (7): 479–485. https://doi.org/10.1016/j.cemconcomp.2010.05.001.

Okabe, S., M. Odagiri, T. Ito, and H. Satoh. 2007. "Succession of sulfur-oxidizing bacteria in the microbial community on corroding concrete in sewer systems." *Appl. Environ. Microbiol.* 73 (3): 971–980. https://doi.org/10.1128/AEM.02054-06.

Okun, D. A., L. K. Wang, and N. K. Shammas. 2010. *Water supply and distribution and wastewater collection*. Hoboken, NJ: Wiley.

Osorio, H., S. Mangold, Y. Denis, I. Ancucheo, M. Esparza, D. B. Johnson, V. Bonnefoy, M. Dopson, and D. S. Holmesa. 2013. "Anaerobic sulfur metabolism coupled to dissimilatory iron reduction in the extremophile acidithiobacillus ferrooxidans." *Appl. Environ. Microbiol.* 79 (7): 2172–2181. https://doi.org/10.1128/AEM.03057-12.

Parande, A., P. Ramsamy, S. Ethirajan, C. Rao, and N. Palanisamy. 2006. "Deterioration of reinforced concrete in sewer environments." *Proc. Inst. Civ. Eng.* 159 (1): 11–20. https://doi.org/10.1680/muen.2006.159.1.11.

Peyre Lavigne, M., A. Bertron, L. Auer, G. Hernandez-Raquet, J.-N. Foussard, G. Escadeillas, A. Cockx, and E. Paul. 2015a. "Innovative approach to reproduce the biodeterioration of industrial cementitious products in a sewer environment. Part I: Test design." *Cem. Concr. Res.* 73 (Jul): 246–256. https://doi.org/10.1016/j.cemconres.2014.10.025.

Peyre Lavigne, M., A. Bertron, C. Botanch, L. Auer, G. Hernandez-Raquet, A. Cockx, J.-N. Foussard, G. Escadeillas, and E. Paul. 2015b. "Innovative approach to simulating the biodeterioration of industrial cementitious products in sewer environment. Part II: Validation on CAC and BFSC linings." *Cem. Concr. Res.* 79 (Jan): 409–418. https://doi.org/10.1016/j.cemconres.2015.10.002.

Qasim, S. R. 1999. *Wastewater treatment plants: Planning, design, and operation*. 2nd ed. Boca Raton, FL: CRC Press.

Qasim, S. R., and G. Zhu. 2018. *Wastewater treatment and reuse: Theory and design examples*. Boca Raton, FL: CRC Press.

Reardon, E. J. 1990. "Ion interaction model for the determination of chemical equilibria in cement/water systems." *Cem. Concr. Res.* 20 (2): 175–192. https://doi.org/10.1016/0008-8846(90)90070-E.

Richardson, M. G. 2002. *Fundamentals of durable reinforced concrete*. London: Spon Press.

Rootsey, R., R. Melchers, R. Stuetz, J. Keller, and Z. Yuan. 2012. "Taking control of odours and corrosion in sewers." In *Proc., Australia's National Water Conf. and Exhibition (OzWater 2012)*, 8–10. Sydney, Australia: Australian Water Association.

Roy, D. M., P. Arjunan, and M. R. Silsbee. 2001. "Effect of silica fume, metakaolin, and low-calcium fly ash on chemical resistance of concrete." *Cem. Concr. Res.* 31 (12): 1809–1813. https://doi.org/10.1016/S0008-8846(01)00548-8.

Sabir, B. B., S. Wild, and J. Bai. 2001. "Metakaolin and calcined clays as pozzolans for concrete: A review." *Cem. Concr. Compos.* 23 (6): 441–454. https://doi.org/10.1016/S0958-9465(00)00092-5.

Santo Domingo, J. W., R. P. Revetta, B. Iker, V. Gomez-Alvarez, J. Garcia, J. Sullivan, and J. Weast. 2011. "Molecular survey of concrete sewer biofilm microbial communities." *Biofouling* 27 (9): 993–1001. https://doi.org/10.1080/08927014.2011.618637.

Satoh, H., M. Odagiri, T. Ito, and S. Okabe. 2009. "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 (18): 4729–4739. https://doi.org/10.1016/j.watres.2009.07.035.

Senhadji, Y., G. Escadeillas, M. Mouli, and H. Khelafi. 2014. "Influence of natural pozzolan, silica fume and limestone fine on strength, acid resistance and microstructure of mortar." *Powder Technol.* 254 (Mar): 314–323. https://doi.org/10.1016/j.powtec.2014.01.046.

Shetti, A. P., and B. B. Das. 2015. "Acid, alkali and chloride resistance of early age cured silica fume concrete." In Vol. 3 of *Advances in structural engineering*, 1849–1862. New Delhi, India: Springer.

Sublette, K. L., R. Kolhatkar, and K. Raterman. 1998. "Technological aspects of the microbial treatment of sulfide-rich wastewaters: A case study." *Biodegradation* 9 (3–4): 259–271. https://doi.org/10.1023/A:1008262522493.

Sun, X. 2015. "Improving the understanding of concrete sewer corrosion through investigations of the gaseous hydrogen sulfide uptake and transformation processes in the corrosion layer." Ph.D. thesis, Dept. of Civil Engineering, Univ. of Queensland, Brisbane, Queensland.

Sun, X., G. Jiang, T. H. Chiu, M. Zhou, J. Keller, and P. L. Bond. 2016. "Effects of surface washing on the mitigation of concrete corrosion under sewer conditions." *Cem. Concr. Compos.* 68 (Apr): 88–95. https://doi.org/10.1016/j.cemconcomp.2016.02.013.

Taylor, H. F. 1997. *Cement chemistry*. 2nd ed. London: Thomas Telford.

USEPA. 1991. *Hydrogen sulfide corrosion in wastewater collection and treatment systems*, 59. Washington, DC: USEPA.

Valdes, J., I. Pedroso, R. Quatrini, R. J. Dodson, H. Tettelin, R. Blake, J. A Eisen, and D. S. Holmes. 2008. "Acidithiobacillus ferrooxidans metabolism: From genome sequence to industrial applications." *BMC Genom.* 9 (1): 597. https://doi.org/10.1186/1471-2164-9-597.

Valix, M., D. Zamri, H. Mineyama, W. H. Cheung, J. Shi, and H. Bustamante. 2012. "Microbiologically Induced corrosion of concrete and protective coatings in gravity sewers." *Chin. J. Chem. Eng.* 20 (3): 433–438. https://doi.org/10.1016/S1004-9541(11)60150-X.

Vincke, E., N. Boon, and W. Verstraete. 2001. "Analysis of the microbial communities on corroded concrete sewer pipes—A case study." *Appl. Microbiol. Biotechnol.* 57 (5–6): 776–785. https://doi.org/10.1007/s002530100826.

Vincke, E., S. Verstichel, J. Monteny, and W. Verstraete. 2000. "New test procedure for biogenic sulfuric acid corrosion of concrete." *Biodegradation* 10 (6): 421–428. https://doi.org/10.1023/A:1008309320957.

Vollertsen, J., A. H. Nielsen, H. S. Jensen, T. Wium-Andersen, and T. Hvitved-Jacobsen. 2008. "Corrosion of concrete sewers—The kinetics of hydrogen sulfide oxidation." *Sci. Total Environ.* 394 (1): 162–170. https://doi.org/10.1016/j.scitotenv.2008.01.028.

WEF (Water Environment Federation). 2009. *Existing sewer evaluation and rehabilitation: WEF manual of practice*. 3rd ed. Alexandria, VA: WEF Press.

Wells, T., R. Melchers, A. Joseph, P. Bond, D. Vitanage, H. Bustamante, J. De Grazia, T. Kuen, J. Nazimek, and T. Evans. 2012. *Collaborative Investigation of the microbial corrosion of concrete sewer pipe in Australia*. St. Leonards, Australia: Australian Water Association.

Wells, T., and R. E. Melchers. 2014. "An observation-based model for corrosion of concrete sewers under aggressive conditions." *Cem. Concr. Res.* 61–62 (Jul–Aug): 1–10. https://doi.org/10.1016/j.cemconres.2014.03.013.

Wells, T., R. E. Melchers, and P. Bond. 2009. "Factors involved in the long-term corrosion of concrete sewers." In *Proc., Corrosion and Prevention on Australasian Corrosion Association*. Coffs Harbour, Australia: Australian Water Association.

Wu, L., C. Hu, and W. V. Liu. 2018. "Sustainability of concrete in sewer tunnel—A narrative review of acid corrosion in the City of Edmonton, Canada." *Sustainability* 10 (2): 517. https://doi.org/10.3390/su10020517.

Yamanaka, T., I. Aso, S. Togashi, M. Tanigawa, K. Shoji, T. Watanabe, N. Watanabe, K. Maki, and H. Suzuki. 2002. "Corrosion by bacteria of concrete in sewerage systems and inhibitory effects of formates on their growth." *Water Res.* 36 (10): 2636–2642. https://doi.org/10.1016/S0043-1354(01)00473-0.

Zhang, L., P. De Schryver, B. De Gusseme, W. De Muynck, N. Boon, and W. Verstraete. 2008. "Chemical and biological technologies for hydrogen sulfide emission control in sewer systems: A review." *Water Res.* 42 (1–2): 1–12. https://doi.org/10.1016/j.watres.2007.07.013.