

Microbially Induced Corrosion of Concrete

Members of ACI Committee 201 Task Group 5 explain the science of biogenic acidification in sewer system structures

by Samuel J. Lines, David A. Rothstein, Brent Rollins, and Charles (Chuck) Alt

Despite being one of the most durable construction materials, concrete can exhibit deterioration resulting from contact with chemicals, minerals, or environmental conditions. Common mechanisms of deterioration include damage from freezing and thawing, salt attack, and carbonation. A lesser-known cause of deterioration is microbially induced corrosion of concrete (MICC).

The root cause of MICC has been well documented; after World War II, C.D. Parker discovered that a sulfur-oxidizing bacterium, *Acidithiobacillus thiooxidans*, was involved in converting hydrogen sulfide (H_2S) gas into sulfuric acid (H_2SO_4).¹ Parker originally called these bacteria *Thiobacillus concretivorus* because they eat concrete. The acid attacks the concrete, causing the surface to erode or “corrode,” as it is termed in the sewer infrastructure literature (not to be confused with reinforcing steel corrosion). Since the initial identification of *Acidithiobacillus thiooxidans*, others have confirmed that it is the primary bacteria that causes MICC of concrete pipes in sewer systems.² These bacteria live at a very low pH, perhaps 2 to 4, whereas concrete has a pH of about 13 after manufacture. The high initial pH of new concrete provides a period of immunity to most bacterial growth. As the surface pH of the concrete is lowered by carbonation and sewer gases, however, it becomes more hospitable to hosting bacterial colonies.

Based on work by Islander et al.³ and confirmed by House,⁴ the corrosion process has three distinct phases (Fig. 1). Phase one is carbonation of the concrete. Over time, the natural process of carbonation will gradually lower the pH of the concrete to below 9. Phase two is the biological attachment phase, when neutrophilic sulfur-oxidizing bacteria (NSOB) such as *Thiomonas intermedia*, *Halothiobacillus neapolitanus*, and *Thiobacillus thioparus* will begin to colonize. Sand and Bock,⁵ as well as Cho and Mori,⁶ state that these species are required for *Acidithiobacillus thiooxidans* to colonize. Acids react with the calcium hydroxide ($Ca(OH)_2$) and calcium

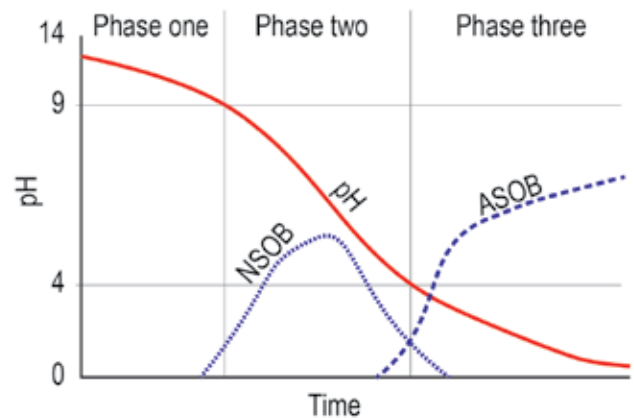


Fig. 1: A schematic representation of pH versus time for the three-stage process of MICC

silicate hydrate (CSH) constituents of concrete that provide this high alkalinity.

Phase three is the acid corrosion phase. *Acidithiobacillus thiooxidans*, an acidophilic sulfur-oxidizing bacteria (ASOB), produces a strong H_2SO_4 , rapidly deteriorating the concrete. Under extreme conditions, with high H_2S gas concentrations above the sewer liquid level, the erosion rate can reach up to 1/2 in./year (12 mm/year). Depending on concrete quality and sewer conditions, it can take anywhere from 2 to 15 years for the final phase to cause significant damage.

Sewer System Issues

From the 1940s through the 1970s, the United States experienced rapid development of suburbs, resulting in the creation of massive networks of underground infrastructure to handle sewer waste. Many of these networks consisted of combined sewer systems, designed to collect rainwater runoff, domestic sewage, and industrial wastewater in the same pipe.

In the late 1970s, Pomeroy and Parkhurst created a formula for forecasting the sulfide buildup in sewers.⁷ This model allowed sewer engineers to design structures with additional concrete as a sacrificial layer. In 1985, the United States Environmental Protection Agency (US EPA) published the “Design Manual for Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants.”⁸ This became a model for engineers to use for designing better infrastructure.

It has been suggested that the Clean Water Act of 1977⁹ and the Water Quality Act of 1987¹⁰ affected the severity of degradation in sewers by reducing the flow of the sewage.¹¹ The new regulations led to the diversion of stormwater from sewer systems, which greatly reduced both the volume of liquid and the metals that are toxic to microbes in the sanitary sewers. The reductions in flow and toxic metals thus created an environment prone to increased amounts of H₂S gas. Unfortunately, the existing predictive models did not adequately consider these changes.

The formation of H₂S begins once the sewage water is deprived of dissolved oxygen, which takes some time after entering the sewage network. Sanitary sewage is partially decomposed by numerous strains of bacteria in the water and other naturally occurring processes. This bacterial activity consumes the dissolved oxygen in the water and, at some point in time, sewage reaches anaerobic conditions. Even before the water becomes anaerobic, the sediments and the scum deposits in the bottom of the sewer may be deprived of oxygen.

Some bacteria are adapted to anaerobic conditions and do not need oxygen to survive. One of these species is *Desulfovibrio sp.*, a sulfate-reducing bacteria (SRB) that converts the sulfate in the wastewater to H₂S. The H₂S has a low solubility in water, so it will tend to escape. When there is turbulence, the H₂S sulfide gas is released into the atmosphere above the waterline. As H₂S is heavier than air, it tends to stay in the underground sewage system. As the bacteria need some time to consume the dissolved oxygen in water, the formation of H₂S increases with the transit time in the sewage system. The longer the time the sewage water needs to travel from the household to the treatment plant, the more H₂S issues will occur.

Carbon dioxide (CO₂), thiosulfuric acid, and other mild acids abiotically reduce the pH of the concrete to around 9. This process can take months or even years, depending on the concrete quality. Once the concrete pH is below 9, colonization by alkaliphile microorganisms begins. Among them, a strain of *Thiobacillus* begins to colonize that is aerobic (requires oxygen). These bacteria convert H₂S into H₂SO₄. The weak H₂SO₄ produced by this strain lowers the pH of the concrete until it dies off and another strain colonizes. Each strain of aerobic *Thiobacillus* produces a stronger H₂SO₄ than the previous one.

While all concrete can be susceptible to this degradation, not all installations have the same environmental conditions that trigger the chain reaction. There is uncertainty about exactly what conditions must be present for the reactions to



Fig. 2: Calcium sulfate (gypsum) forms a whitish foamy mass on concrete

occur. Some theories suggest a high amount of sulfur in the water supply, a high iron content in the water, very hard water, and chemicals introduced into the waste stream, just to name a few. Sites with high relative humidity are reported as having more severity as well.¹¹ More research is needed to correlate lab testing and field conditions.

Cement Hydration and MICC

During the hydration of cement, CSH is formed and provides the desirable properties of hardened concrete. Typical hydrated cement forms about 50% CSH. Another compound, Ca(OH)₂, is also formed and composes 15 to 25% of the cement paste by mass.¹² By days 3 to 7 of the hydration process, the mass of the concrete is primarily composed of three compounds: CSH, Ca(OH)₂, and calcium aluminoferrite hydrates.

Ca(OH)₂ is hydrated lime and does not contribute to the strength or other desirable properties of the concrete, except perhaps to maintain the protective high pH environment around the reinforcing steel. Ca(OH)₂ will easily react with acids and other compounds. The reaction with CO₂ forms calcium carbonate, resulting in what is referred to as concrete carbonation. When H₂SO₄ reacts with Ca(OH)₂, the result is a hydrated calcium sulfate mineral known as gypsum (CaSO₄·H₂O). As such, gypsum is a primary indicator of MICC and often appears as a whitish foamy mass on the concrete (Fig. 2).

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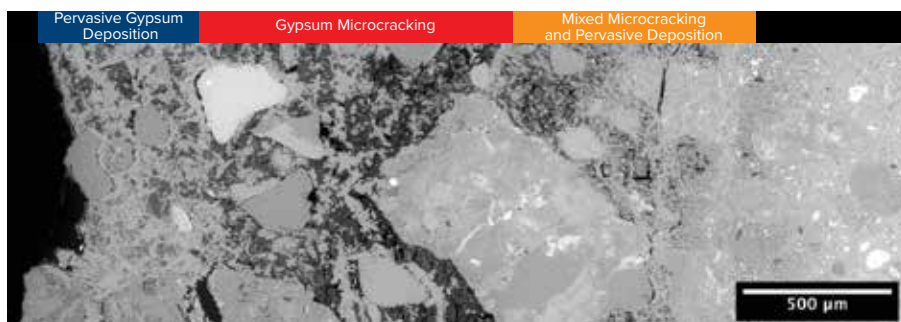


Fig. 3: A backscatter electron micrograph of alteration zones in a corroded concrete specimen (after Reference 13)

In the next step of this process, the concrete disintegrates even more. After H_2SO_4 consumes $Ca(OH)_2$, it reacts chemically with the aluminates present in the cement paste. This reaction forms ettringite, an expansive sulfoaluminate compound. As the ettringite forms, it causes internal expansion, which in turn causes cracking and spalling to occur. This chain of events allows more penetration, access to $Ca(OH)_2$, and a snowball of chemical reactions and damage to concrete (Fig. 3).

Concrete Mixtures and MICC

In a harsh environment exposed to sulfates, chlorides, or acids, it is very important to use a high-quality concrete mixture with a low water-cement ratio (w/c). According to the book *Design and Control of Concrete Mixtures*,¹² “Decreased permeability improves concrete’s resistance to freezing and thawing, re-saturation, sulfate, and chloride-ion penetration, and other chemical attack.” It is very important to reduce the permeability to increase durability. A w/c of 0.45 is good for most concrete products that are not exposed to harsh conditions. If there is a potential that the concrete will be exposed to these harsh conditions, the w/c should not exceed 0.40.

In addition to a low w/c , the use of pozzolanic and secondary cementitious materials can increase the density and lower concrete permeability. Fly ash, slag cement, and silica fume are just a few of the options. Using one or more of these mineral admixtures in the concrete mixture design will increase the strength and density while lowering the porosity and improving chemical resistance. Promising work with nanomaterials like colloidal silica also indicates significant reductions in permeability.¹⁴

Protecting Concrete from MICC

While concrete densification is important to increasing the life of the concrete structure, it will not stop the biological process that causes the *Thiobacillus* bacteria to secrete H_2SO_4 . However, concrete admixtures and surface-applied antimicrobial sealers are effective at reducing the effects of MICC.¹⁵ The effectiveness of these products can be evaluated using ASTM C1904.¹⁶

When a sewage structure is expected to be exposed to

very high concentrations of H_2S gas, the designer may choose to protect the concrete with a resin-based coating like epoxy or polyurea. These materials show good resistance to acid. However, most of them are of a hydrophobic nature—the concrete and the surrounding air must be dry enough to achieve a good bonding and polymerization. Resin-based liners do not impede the bacterial growth, so their surfaces will become very acidic with time. As long as

there is no flaw, pinhole, or puncture, H_2SO_4 will not reach the concrete beneath.

Another approach to protect sewage concrete infrastructures from H_2S corrosion is to apply a mortar made of calcium aluminate cement (CAC) and calcium aluminate aggregate. CAC is a specialty cement with a different chemistry than portland cement. CAC inhibits bacterial activity when the surface pH approaches around 4 under the activity of bacteria. CAC does not have a biocide effect (the bacteria are not killed),¹⁷ but bacteria go into stasis and stop transforming the H_2S into H_2SO_4 . As no new acid is formed, the corrosion process is drastically slowed.¹⁸⁻²⁰ Thus, it is possible to protect ordinary concrete with a mineral barrier made of CAC rather than a polymer barrier. Antimicrobial additives have also been incorporated into these barriers.

Physical barriers such as liners and coatings are another option for controlling MICC. Membrane-forming liners have the ability to bridge cracks and other imperfections such as honeycombing that may be points of accelerated ingress. However, liners and coatings require periodic inspection and repair or replacement to ensure continued satisfactory operation. Liners and coatings can be tested using ASTM C1898²¹ to validate performance in stage three of corrosion.

Summary

According to a 2002 study by the Federal Highway Administration (FHWA),¹⁷ corrosion of metals is estimated to annually result in about \$36 billion in damage to the water and sewer system in the United States. MICC is probably a lesser-known and less-documented deterioration mechanism than steel corrosion or joint leakages that owners must deal with. A better understanding of MICC and the complex ecosystem of bacteria that drive it should permit engineers to improve design practices for new systems and rehabilitate existing structures. ACI Committee 201, Durability of Concrete, is working to improve the knowledge of this worldwide issue.

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Selected for reader interest by the editors.



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