

Mini Review

Microbiologically induced deterioration of concrete - A Review

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Abstract

Microbiologically induced deterioration (MID) causes corrosion of concrete by producing acids (including organic and inorganic acids) that degrade concrete components and thus compromise the integrity of sewer pipelines and other structures, creating significant problems worldwide. Understanding of the fundamental corrosion process and the causal agents will help us develop an appropriate strategy to minimize the costs in repairs. This review presents how microorganisms induce the deterioration of concrete, including the organisms involved and their colonization and succession on concrete, the microbial deterioration mechanism, the approaches of studying MID and safeguards against concrete biodeterioration. In addition, the uninvestigated research area of MID is also proposed.

Key words: microbial deterioration, concrete corrosion, biogenic sulfuric acid.

Introduction

The life-cycle of concrete architectures should consider all factors that might cause a structural system to perform unacceptably at any point during its lifetime. This includes extreme events (*e.g.*, earthquakes, cyclones) or the progressive and sustained loss of capacity caused by operational or environmental factors. In general terms, deterioration can be defined as a loss of structural capacity with time as a result of the action of external agents or material weakening (Sanchez-Silva and Rosowsky, 2008). It has many dimensions and depends on the type of structure, the constitutive material, the environmental conditions and the operation characteristics, as well as other factors. Progressive deterioration has perhaps the broadest impact on the long-term performance of infrastructure systems and the largest potential economic consequences. It has been observed that the loss of structural capacity with time is caused mainly by chloride ingress, which usually leads to steel corrosion (loss of effective cross-section of steel), concrete cracking, loss of bond (aggregate-hydrated cement paste) and spalling (Bastidas-Arteaga *et al.*, 2008). Among these causes of structural degradation, it has been noted that deterioration arising from biological sources is significant in harsh envi-

ronments. Nevertheless, the role of biologically-induced degradation with respect to reinforced concrete structures remains uninvestigated. Biodeterioration has been defined in the literature as: “any undesirable change in the properties of a material caused by the vital activities of organisms”; and “the process by which “biological agents (*i.e.*, live organisms) are the cause of the structural lowering in quality or value” (Rose, 1981). Biodeterioration is usually referred to as microbiologically induced deterioration (MID).

Biodeterioration of concrete structures is caused by organisms that grow in environments on concrete surfaces that offer favorable conditions (*e.g.*, available water, low pH etc.). Conducive environments may have elevated relative humidity (*i.e.*, between 60% and 98%), long cycles of humidification and drying, freezing and defrosting, high carbon dioxide concentrations (*e.g.*, carbonation in urban atmospheres), high concentrations of chloride ions or other salts (*e.g.*, marine environments) or high concentrations of sulfates and small amounts of acids (*e.g.*, sewer pipes or residual water treatment plants).

Considerable researches has examined biodeterioration of concrete structures by living organisms, including underground structures, sewage systems, at-sea structures

and wastewater treatment systems (Davis *et al.*, 1998; Islander *et al.*, 1991; Okabe *et al.*, 2007; Peccia *et al.*, 2000; Vincke *et al.*, 2001). The costly effect of MID on various structural systems is often underestimated since the microorganisms often accelerate processes that would occur in their absence at slower rates. It has been estimated that biodeterioration-related structural problems cost billions of dollars a year in infrastructure maintenance and repair (Sanchez-Silva and Rosowsky, 2008).

Dynamics of the MID of Concrete Structures

Organisms play a significant role in the deterioration of concrete

Recent experimental developments have provided a better understanding as to how biological and physicochemical processes associated with MID affects the long-term durability and mechanical properties of concrete structures. Deterioration of concrete is often found in structures exposed to aggressive environments, such as environments promoting sulfate attack or chloride ion penetration. Although concrete mix proportions are commonly designed to comply with acceptable design life requirements, poor quality control, improper characterization, unanticipated changes in the environmental conditions or exposure to aggressive environments can produce premature deterioration and reduce the load carrying capacity. The most common and widely studied cause of progressive deterioration in concrete structures is chloride ingress. It has been reported (Sanchez-Silva and Rosowsky, 2008) that biological processes can accelerate this deterioration process by severely modifying the physicochemical properties of the reinforced concrete. Although little attention has been given to biodeterioration, some studies (Bastidas-Arteaga *et al.*, 2008; Gaylarde *et al.*, 2003) have shown that live-organisms may play a significant role in the deterioration of concrete structures. This could be particularly important in marine structures (Jayakumar and Saravanane, 2010) such as ports and offshore platforms and is reportedly more common in structures such as sewage systems and waste water treatment plants (Cho and Mori, 1995).

There are enough evidences to show that a wide variety of organisms can cause concrete deterioration (Table 1). The action of microorganisms on concrete structures can be classified according to their effects on concrete surfaces, concrete matrices, and on cracking and crack growth (Amann *et al.*, 1990; Aviam *et al.*, 2004). According to Sanchez-Silva and Rosowsky (2008), the action of microorganisms affect the concrete mainly by contributing to the erosion of the exposed concrete surface, reducing the protective cover depth, increasing concrete porosity, and increasing the transport of degrading materials into the concrete that can accelerate cracking, spalling, and other damage and reduce the service life of the structure.

Table 1 - Organisms involved in the deterioration of concrete.

Organisms	References
Bacteria	
<i>Thiobacillus intermedius</i>	Giannantonio <i>et al.</i> , 2009; Magniont <i>et al.</i> , 2011
<i>Thiobacillus neapolitanus</i>	Magniont <i>et al.</i> , 2011; Mustafa, 2009
<i>Thiobacillus novellus</i>	Magniont <i>et al.</i> , 2011; Mustafa, 2009
<i>Thiobacillus thioparus</i>	Magniont <i>et al.</i> , 2011; Mustafa, 2009
<i>Acidithiobacillus thiooxidans</i>	Lahav <i>et al.</i> , 2004; Magniont <i>et al.</i> , 2011; Mustafa, 2009; Vollertsen <i>et al.</i> , 2008
<i>Thiomonas perometablis</i>	Vollertsen <i>et al.</i> , 2008
Fungus	
<i>Alternaria</i> sp	Ghafoori and Mathis, 1997
<i>Cladosporium cladosporioides</i>	Ghafoori and Mathis, 1997
<i>Epicoccum nigrum</i>	Ghafoori and Mathis, 1997
<i>Fusarium</i> sp	Ghafoori and Mathis, 1997; Giannantonio <i>et al.</i> , 2009
<i>Mucor</i> sp	Ghafoori and Mathis, 1997
<i>Penicillium oxalicum</i>	Ghafoori and Mathis, 1997
<i>Pestalotiopsis maculans</i>	Ghafoori and Mathis, 1997
<i>Trichoderma asperellum</i>	Ghafoori and Mathis, 1997
<i>Aspergillus niger</i>	Lajili <i>et al.</i> , 2008
<i>Alternaria alternata</i>	Warscheida and Braamsb, 2000
<i>Exophiala</i> sp.	Warscheida and Braamsb, 2000
<i>Coniosporium uncinatum</i>	Warscheida and Braamsb, 2000
Algae	
<i>Chaetomorpha antennina</i>	Javaherdashti and Setareh, 2006
<i>Ulva fasciata</i>	Javaherdashti and Setareh, 2006
Lichen	
<i>Acarospora cervina</i>	Edwards <i>et al.</i> , 1999
<i>Candelariella</i> ssp	Edwards <i>et al.</i> , 1999

Microbial colonization on concrete

After construction, concrete is usually immune to biological attack because of its high alkalinity. Little microbial activity occurs at such a high pH (Sand, 1987). This high pH is the result of the formation of calcium hydroxide *i.e.* Ca(OH)₂, as a byproduct of the hydration of cement. Usually, the erosive action of water and/or the friction of structural elements with other materials generate roughness on the concrete surface (Ribas-Silva, 1995). This condition, in addition to the availability of moisture and nutrients, facilitates the colonization of microbes on concrete surfaces. However, the colonization of sulfur-reducing and sulfur-oxidizing bacteria on concrete has always been associated with the sulfur cycle in their environment, especially in aquatic environments (Satoh *et al.*, 2009; Yilmaz, 2010). Sulfate is distributed in the aquatic and marine environments world wide. The anaerobic sul-

fur-reducing bacteria can convert sulfate into sulfide, which in turn combines with hydrogen to form hydrogen sulfide. Over time, the pH of the alkaline concrete surface is gradually reduced by the carbonation and neutralization of hydrogen sulfide that builds up in various systems (Lahav *et al.*, 2004; Matos and Arires, 1995; Nielsen *et al.*, 2005; Zhang *et al.*, 2008). Subsequently, the volatile hydrogen sulfide is subject to oxidation into sulfuric acid by sulfur-oxidizing bacteria (Satoh *et al.*, 2009; Vollertsen *et al.*, 2008; Zhang *et al.*, 2008).

When the pH is lowered towards neutral, a lower pH on the concrete surface creates conditions for further microbial colonization by neutrophilic and/or acidophilic organisms. Typically, *Thiobacillus sp.* (syn. *Acidithiobacillus sp.*, including *T. thioparus*, *T. novellus*, *T. neapolitanus*, *T. intermedius* and *T. thiooxidans*) play key roles in these colonization events (Mori *et al.*, 1992; Parker, 1947). When microorganisms settle on a concrete surface, they form a biofilm (Domingo *et al.*, 2011), which is followed by the chemical biodeterioration of concrete. According to Bastidas-Arteaga *et al.* (2008) biodeterioration of concrete is mainly caused by bacteria, fungi, algae and lichens (Cho and Mori, 1995; Gu *et al.*, 1998; Javaherdashti and Setareh, 2006; Nica *et al.*, 2000).

Microbial succession on concrete

Microbial growth further reduces the surface pH of concrete, thereby leading to significant biogenic release of polythionic and sulfuric acid (Diercks *et al.*, 1991; Islander *et al.*, 1991; Milde *et al.*, 1983; Sand, 1987). Once the pH of the surface of the concrete drops below 9 in the presence of sufficient nutrients, moisture and oxygen present, some species of sulfur bacteria like *Thiobacillus sp.* can attach to the concrete surface and reproduce (Mori *et al.*, 1992). *T. thioparus* was found to be the first bacteria to colonize new concrete pipe surfaces, disappearing gradually as deterioration became more severe. As the pH continues to fall to moderate or weakly acidophilic conditions, *T. novellus*, *T. neapolitanus* and *T. intermedius* establish on the surface of concrete (Milde *et al.*, 1983; Sand, 1987). At pH levels below 5, *T. thiooxidans* starts to grow and produces high amounts of sulfuric acid, and the pH drops to as low as 1.5 (Sand and Bock, 1984). When the pH reaches 3, *T. thiooxidans* grows vigorously. The low pH favors the formation of elemental sulfur, and *T. thiooxidans* rapidly oxidizes it directly to sulfate ion. The pH continues to decline to about 1.0, at this point it becomes inhibitory even for *T. thiooxidans*. The climatic community will be dominated by *T. thiooxidans* and the acidophilic heterotrophs capable of utilizing organic waste products excreted by *T. thiooxidans*. This succession no doubt differs in its details in specific cases. Parker (1951), for example, emphasized *T. thioparus* and *T. thiooxidans* in studies in Australia. Sand and Bock (1984) found no *T. thioparus* in their studies in Germany.

Microbial deterioration mechanism and process

Bacteria and microscopic fungi are the main microorganisms influencing the concrete biodeterioration. Biogenic organic acids (acetic, lactic, butyric and the like) and carbon dioxide, which are produced by various microorganisms, can be extremely corrosive towards concrete (Bertron *et al.*, 2004; Cwalina, 2008; Siripong and Rittmann, 2007). The most corrosive agent leading to rapid deterioration of concrete pipelines in sewers is H₂S, which also attacks concrete floors in barn buildings housing animals and in sewer and wastewater treatment plants. The sulfur-oxidizing bacteria present oxidize the H₂S dissolved in the moisture to sulfuric acid (H₂SO₄), commonly referred to as biogenic sulfuric acid, which is believed to be responsible for biodeterioration. This biogenic release of acid degrades the cementitious material in concrete, thereby generating gypsum (CaSO₄ of various hydration states) (Mori *et al.*, 1992) and possibly ettringite (3CaO•Al₂O₃•CaSO₄•12H₂O or 3CaO•Al₂O₃•3CaSO₄•31H₂O), which possess expansive properties. Gypsum can act as a protective layer for concrete in the same way that initial corrosion protects metals (like the oxide layer on aluminum). If this “protective” coating of gypsum is removed, the concrete surface can be exposed to acid attack accelerating the damage to the surface. In addition, the mixture of gypsum and calcium aluminates in the concrete produces ettringite which increases internal pressures caused by its rather large volume and leads to the formation of cracks (Aviam *et al.*, 2004). With the removal of the deteriorated materials by sewage flow, the concrete corrosion process is accelerated as new surfaces are exposed to these processes (Mori *et al.*, 1992).

Microorganisms can penetrate inside the concrete matrix even if there are no observable cracks in concrete (Sanchez-Silva and Rosowsky, 2008). The most common mechanism for their ingress is via microcracks or through the capillaries in the concrete. Some research has been performed concerning the analysis of concrete structures to verify whether microorganisms could be responsible for some of the damage observed. Laboratory analysis of concrete samples has shown that many microorganisms such as fungi (yeasts, *Cladosporium*, mycelia, hypha etc.), bacteria (actinomycetes, *Thiobacillus*, among others), algae (the most popular are diatom algae) and even protozoa, can be found within the concrete matrix. The consequences of microorganisms within the microstructure are different. Although there is insufficient experimental evidence, it has been observed that the action of microorganisms on the concrete matrix increases concrete porosity, which in turn can change the diffusivity of the concrete (Sanchez-Silva and Rosowsky, 2008). Higher porosity values can also lead to higher surface wear, reducing the depth of the protective concrete cover over the reinforcement. Higher diffusivity and lower concrete covers can facilitate other deterioration processes such as corrosion of the reinforcement.

Approaches to Studying MID

The identification of the most important microorganisms in biodeterioration processes on concrete structures is still incomplete. These organisms must be defined after carrying out careful experiments so that treatment procedures can be developed. Currently both qualitative and quantitative methods are utilized to identify and determine the abundances of the microorganisms as well as their metabolic activity. By analyzing such chemical aspects such as the redox and acid-base reactions of the microorganisms, information regarding their colonizing abilities and corrosive properties can be obtained. Several methods for studying MID have been developed, the most popular being characterization of the population structure, molecular techniques, accelerated tests etc. (Minteny *et al.*, 2000; Nagel and Andreesen, 1992; Schallenberg *et al.*, 1989).

The characterization of the population structure of microbial communities uses traditional cultivation methods for enrichment and isolation (Diercks *et al.*, 1991; Islander *et al.*, 1991). This method provides a comprehensive snapshot of the bacteria that are associated with (and perhaps responsible for) deteriorated concrete (Amann *et al.*, 1995). On the other hand, molecular techniques have proven useful for accurate description of the microbial communities in environmental samples. Specifically, a comparison of microbial 16S rRNA gene sequences to sequences present in the databases has been used as the basis for polygenetic analysis. In addition, the profiles of bacterial communities on deteriorated concrete surfaces have been analyzed by denaturing gradient gel electrophoresis (DGGE, 59). However, neither 16S rRNA gene library screening nor DGGE are definitive methods for quantitative population analysis, and the ability to determine bacterial relative abundance by these methods is limited (Vincke *et al.*, 2001). Fluorescent *in situ* hybridization (FISH) provides an alternative approach towards quantitative population analysis in these environments (Edwards *et al.*, 1999; Hernandez *et al.*, 2002; Okabe *et al.*, 2007; Peccia *et al.*, 2000; Schrenk *et al.*, 1998), and studies using this approach have suggested that sulfur-oxidizing microorganisms likely are responsible for promoting sulfuric acid production in sulfide rich environments (Satoh *et al.*, 2009).

One of the most widely used ways to investigate the chemical resistance of concrete is to carry out accelerated tests in the laboratory. The advantage of this method is that the entire life of the specimen in question can be simulated. An acceleration of the process can be achieved in different ways (Attiogbe and Rizkalla, 1988; Cohen and Mather, 1991; Ghafoori and Mathis, 1997; Vincke *et al.*, 1999; Wafa, 1994; Wei *et al.*, 2010), a typical design is shown in Figure 1. Biogenic sulfuric acid corrosion is often a slow corrosion process (1 mm/year to a maximum of 5 mm/year) (Mori *et al.*, 1991). It would require several years to investigate the difference in the durability of various materials in nature. Researchers have tried to simulate corrosion as it

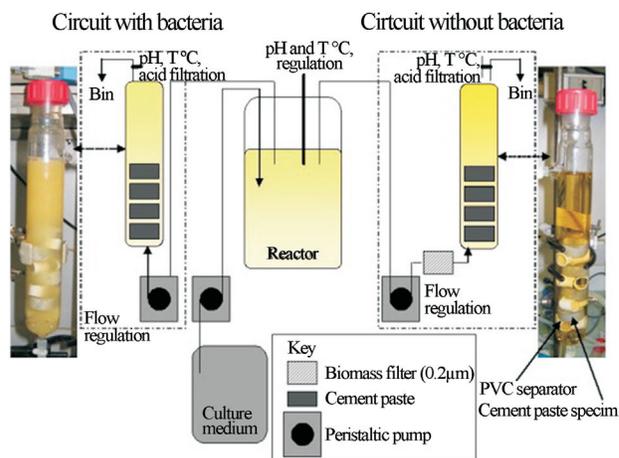


Figure 1 - Schematic diagram of the Buid-Mat-test (cited from Magniont *et al.*, 2011).

happens *in situ*. By creating optimal conditions (temperature, nutrients) for the bacteria, which are not always available *in situ*, the rate of corrosion can be increased by constant exposure of concrete under those optimal conditions.

Measures Against Concrete Biodeterioration

Biodeterioration of concrete is primarily dependent on the availability of water and nutrients. Thus, material specific parameters, like porosity and permeability, and architectural conditions, which determine exposure and environmental factors at the site, will determine the intensity and rate of biocorrosive attacks. The control of biodeterioration processes should start with the adoption of measures that will prevent favorable growth conditions for the damaging microorganisms (Warscheida and Braamsb, 2000). The application of water repellants or consolidants to the concrete and stone has to be planned and carried out with regard to the prevailing exposure conditions of those structures (Dai *et al.*, 2010; Wendler, 1997). Protection of concrete structures from microbial degradation can be enhanced by treatments with biocides or adding protective coatings such as water repellants. Changing the composition of the concrete mixture alters such variables as alkalinity and silica fume, as well as modification to polymers. The corrosion rate is inversely related to alkalinity and the silica reacts with $\text{Ca}(\text{OH})_2$ in the presence of water to form cementing compounds consisting of calcium-silicate hydrate. The silica fume concrete improves the strength efficiency and durability characteristics (Yilmaz, 2010). Beeldens *et al.* (2001) reported that the use of polymer-modified mortar and concrete can improve the durability of concrete sewer pipes. The microstructure of the material is influenced by its polymer composition (Morin *et al.*, 2011; Mustafa, 2009). As the polymers can form films, cement hydrates and polymers are arranged in a network in which

the aggregates are embedded (Ohama, 1995). Biocides are another approach to reducing the harmful microbial effects on concrete. Alum *et al.* (2008) examined different biocide formulations containing class F fly ash, silica fume, Zn oxide, copper slag, ammonium chloride, sodium bromide, and cetyl-methyl-ammonium bromide as concrete constituents with germicidal property. They studied (in both field and laboratory) concrete mixtures containing 10% ZnO and concluded that this mixture was comparable to proprietary commercial biocides. Since knowledge of the microbial community in its natural setting is limited, particularly the dynamic nature, both genetically and physiologically, in which it adapts to its changing environment, none of the aforementioned measures has proven effective in curbing the effects of biodeterioration (Gu *et al.*, 2011).

Concluding Remarks

MID is the result of attack of biogenic substances of great corrosive aggressiveness, which are the products of the metabolic activity of proliferating microorganisms (Cwalina, 2008). It must be taken into account that microorganisms cause both the initiation, as well as the intensification, of concrete corrosion processes. In addition, effective protection against MID requires the use of integrated management methods, including of modifications of concrete mix design, coatings and treatments with biocides.

Current information on microbial corrosion of concrete is limited to the microorganisms that have been successfully isolated in pure culture from natural environments, particularly *Thiobacillus* species. The role of other microorganisms, for example, fungi, acetogenic bacteria, and ammonia-oxidizing archaea, in concrete degradation needs further investigation to enhance our knowledge (Gu *et al.*, 2011). With development of molecular techniques involved in this area of research, the study of specific groups of microorganisms involved in the degradation process is underway. However, the true roles of uncultured bacterial activity on concrete, especially in their natural, environment, remains poorly understood.

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