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Biodeterioration of Concrete Structures in Coastal Zone

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ABSTRACT

Cracking in concrete structures is an expensive problem, especially common along coastal areas worldwide. There are several causes for this deterioration process, such as aging, ingress of aggressive components into concrete, such as chloride, and biodeterioration. It has been estimated that biodeterioration related structural problems cost 140 billions of dollars a year in infrastructure maintenance and repair. Researchers have shown that green algae, cyanobacteria, and mussels can be associated with microbiologically induced corrosion (MIC) of construction materials and they can all be found in coastal area, including Milwaukee, USA. This paper presents an overview and analysis of the current state-of-knowledge about biodeterioration of concrete, as well as future research needs. On the basis of identified knowledge, a research agenda has also been developed for the identification of critical structures, assessment of the biodeterioration of concrete, and sustainability of concrete structures exposed to coastal zone.

Keywords. Biodeterioration, concrete, coastal zone, sustainability

INTRODUCTION

It is crucial to assure durability of concrete structures, especially the ones located in coastal regions, to avoid catastrophes and to guarantee economic viability. Although data are not available, in terms of costs with biodeterioration of concrete structures (Sanchez-Silva et al. 2008), a study conducted by CC Technology Laboratories, Inc. (2001) estimated that the total direct cost of corrosion in infrastructure in the United States was close to about $140 billion annually.

Deterioration of structures in coastal region is usually associated with aging and chloride ingress, but also with biodeterioration. Biodeterioration of concrete is the disintegration of the material caused by biogenic action. Traditionally, biodeterioration of concrete structures is related to microorganisms (bacteria, fungi, algae, and/or lichens), but it can also be associated to settlement of macroscopic organisms, such as mussels (Perez et al. 2003) or with organisms that erode and perforate the concrete (Gaylarde et al. 2003). Biodeterioration can be classified into physical or mechanical; fouling or soiling (aesthetic); and chemical (Gaylarde et al. 2003).

Although the contribution of microorganisms to the deterioration of materials as a whole may be in the range of 30% (Sand 2001), relatively little attention has been given to biodeterioration of concrete (Sanchez-Silva et al. 2008). This is possibly due to the fact that biodeterioration is difficult to separate from other damage processes, it is difficult to access at a given time, since it is not a continuous process and the engineering community is not familiar with biodeterioration mechanisms (Sanchez-Silva et al. 2008). However, it is important to understand the mechanisms of biodeterioration of concrete in order to be able to design better strategies for inspection, protection, and repair of concrete structures in coastal zone.

OVERVIEW OF CURRENT STATE OF KNOWLEDGE ABOUT BIODETERIORATION OF CONCRETE

Mechanisms. Mechanisms of biodeterioration are listed on Table 1. Organisms can grow on concrete surfaces under certain conditions: elevated relative humidity, long cycles of humidification and drying, or freezing and thawing; high carbon dioxide concentrations; high concentration of chlorides or other salts; high concentration of sulphates and small amounts of acids. Attack of organisms to concrete can be: (a) physical or mechanical (by eroding or perforating concrete); (b) fouling or soiling, by forming a layer of colored biofilm; and, (c) by chemical reaction by using a structural component as food source or by excreting waste products that affect the material (e.g., sulphite) (Gaylarde et al. 2003). When biofilms cover concrete surfaces, they can form localized anodic sites, preventing diffusion of oxygen, and surrounding areas become cathodic, promoting corrosion (Little et al. 1997).

Table 1. Mechanisms of biodeterioration

Mechanisms	Examples
Physical or mechanical attack	Can be from fungi, cyanobacteria, algae, mussels
Fouling or soiling	Discoloration, biofilms enable growth of other organisms, traps moisture
Chemical attack	Microbes utilize ions present in cement, minerals solubilized by metabolites, enzymes break down mortar

All of the aforementioned conditions can be found in Lake Michigan coastal zone, especially in most favourable locations where there is more concentration of microbial pollutants, such as inside of the harbors (Newton et al. 2011) and near sewer pipelines, where biogenic sulphuric acid corrosion is often a concern (Parker 1945a; Parker 1945b; Wei et al. 2010; Hudon 2011), or where there are rocky substrates where algae can grow, such as piers and breakwalls. In Lake Michigan, large quantities of decaying algae (*Cladophora*) can be found in the shoreline (DNR 2012). Algae and photosynthetic bacteria use light to produce oxygen that can accumulate within a biofilm. During dark periods they respire, converting oxygen to carbon dioxide. Oxygen can depolarize the cathodic reaction, leading to differential aeration cells and leading to increased corrosion rates (Little et al. 1997). On the other hand, when cement-based materials are exposed to atmospheric carbon dioxide or carbonic acid, a reaction producing carbonates (carbonation) takes place which is accompanied by shrinkage (Naik et al. 2007). This reaction is accelerated if relative humidity is within 50 to 75 % (Allahverdi et al. 2000). Also, algae use calcium from concrete for their metabolism, producing organic acids, which leads to concrete decay (Jayakumar et al. 2010a; Jayakumar et al. 2010b; Jayakumar et al. 2011).

Cyanobacteria have been cited as responsible for the degradation of cultural heritage monuments. They are phototrophs and require light, water, and mineral ions to grow (Crispim et al. 2005), which are conditions that can be found in a coastal zone. They can be associated with degradation of concrete in freshwater. Although cyanobacteria have been found in Lake Michigan waters, it has been identified as a minor population. Betaproteobacteria accounted for the largest percentage of sequences ranging from 42% to 65%. There was one exception from Green Can 12 m environment where Gammaproteobacteria sequences comprised the majority of sequence types (43%) and Betaproteobacteria was second most dominant taxa (40%) (Mueller-Spitz 2009). Microbial population in Lake Michigan is very diverse and more research is needed to establish the role of bacteria present in biofilm and mechanisms of biodeterioration of concrete.

Biodeterioration of concrete structures can also be caused by settlement of macroscopic organisms, such as zebra mussels. In North America, zebra mussels (*Dreissena polymorpha*) are invasive species and have first appeared in the Great Lakes region, in Lake St. Clair in 1986. Zebra mussels have high fecundity and a wide range of environmental conditions, and strong attachment of adults to solid substrates. Zebra mussels are a severe nuisance to humans and a threat to the ecology of the Great Lakes (Marsden 1992). Zebra mussels are also a concern for concrete structures in water because it appears that environmental factors that favor zebra mussels are also conditions where concrete is most stable (high pH and salt concentrations). Concrete surfaces gradually deteriorate due to normal weathering, which erodes the portland-cement matrix. Observations indicate that zebra mussels are most likely to colonize on these roughened surfaces (USACE 1992). In South America, the golden mussels (*Limnosperma fortunei*) are invasive species from Asia. Mussels may invade the concrete structure from the surface and may cause fissures; they may separate concrete constituents and facilitate water ingress into the structures increasing steel rebar corrosion. They also may allow lixiviation of the hydrated cementitious products, facilitating development of fungi and bacteria. Mussels can also degrade the matrix of the cement, reducing concentration of calcium in areas in which they are settled, affecting physical properties of the concrete structure (Perez et al. 2003).

Little is known about biodeterioration of underwater structures in the Great Lakes region and there is very limited literature available. There is a need for more research and publication. Accelerated corrosion of steel structures caused by MIC have been reported in freshwater lakes such as Lake Superior at a rate similar to that commonly observed in saltwater ports but not seen in freshwater environments (Clark 2010). In the City of Milwaukee, USA, underwater diving inspections of concrete structures (bridges and piers) are conducted every five years. These structures are mainly inspected for scour issues and concrete deterioration. The area of major concern is along the water line, where the splash zone is located. That is the region that is mostly exposed to physical deterioration due to atmospheric conditions. Although concrete deterioration has been detected in underwater concrete structures in Milwaukee (see Fig. 1), it has not been a major concern (Liberto 2012).

RESEARCH AGENDA

Identification of critical structures. Concrete structures that should be primarily investigated are the ones that are exposed to severe microbial and chemical pollutants conditions and also regions where algae growth are more predominant, as discussed previously. Concrete deterioration can be caused initially by the reduction of pH in the concrete (e.g., due to the presence of sewage and natural sulphites in the water, more common in harbor waters, or due to bio-reaction) and then by the action of various living organisms, such as bacteria and fungi, present in the form of a biofilm.

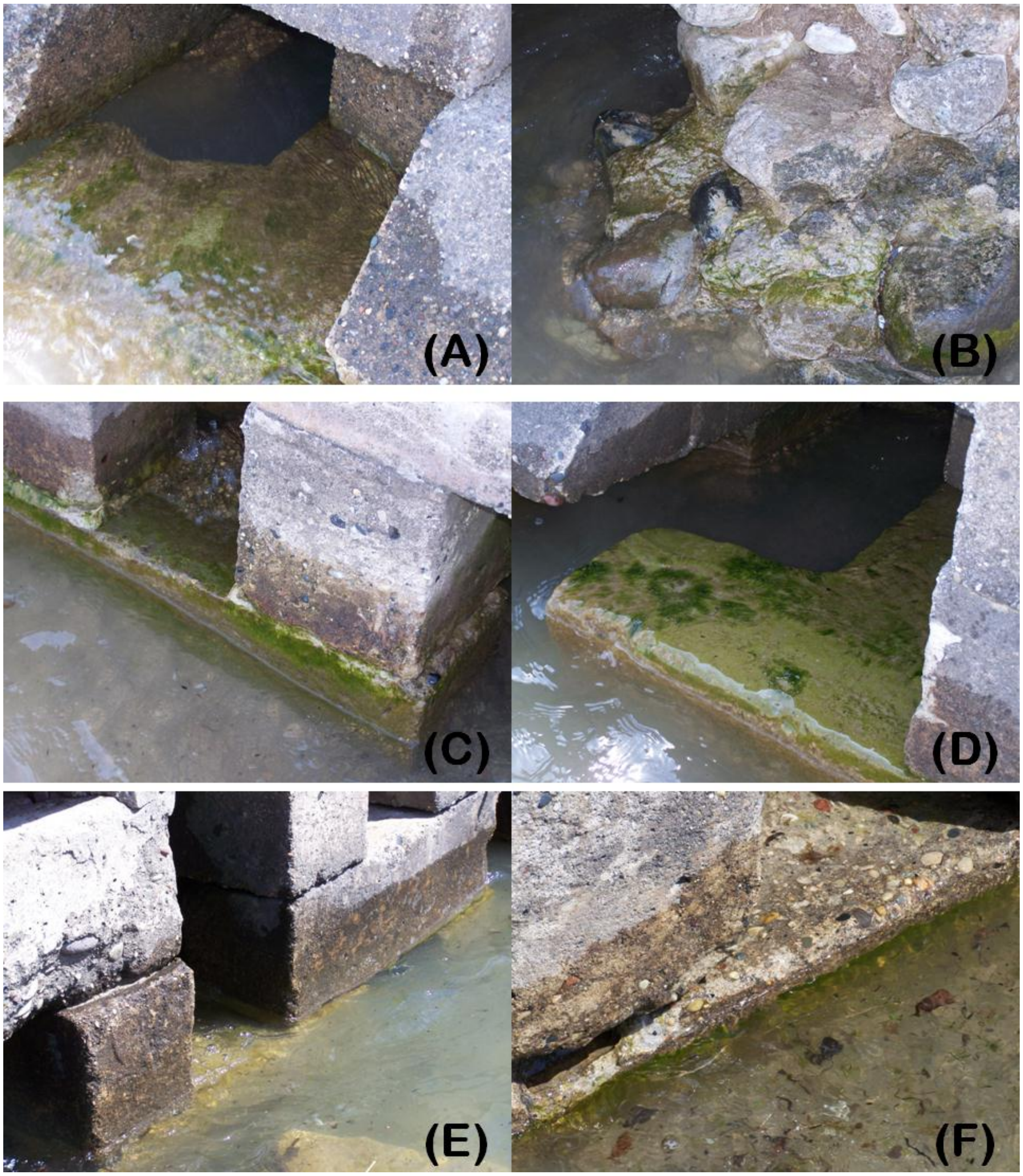

Figure 1. Growth of biofilm on structural components at Atwater Beach, Milwaukee, USA. Biofilm was observed in piers located at the south of the beach (A) and (B), piers in the middle (C) and (D), and piers at the north of the beach (E) and (F). Pictures were taken on May 14, 2009.

Assessment of the biodeterioration of concrete. MIC detection and verification techniques have been reported (Little et al. 1997) and involve inspection of corroded materials, test specimens, or corrosion deposits to identify specific types and numbers of bacteria (e.g., sulphate-reducing bacteria [SRB] and metal-depositing bacteria), or corrosive by-products, such as chlorides, acids, or sulphides. Electrochemical techniques have also been reported (Mansfield et al. 1992) and they include measurements of corrosion potential, redox potential, polarization, resistance, electrochemical impedance, electrochemical noise, polarization curves, and electrochemical hydrogen permeation techniques have been applied to studies of microbiologically influenced corrosion (MIC). In addition, computerized X-ray microtomography (ACT), a radiological imaging technique has been proposed for the monitoring of biological weathering of natural building stones and concrete. With this technique, three dimensional (3D) images of the entire inner structure of the material can be obtained, together with quantitative data (Graef et al. 2005).

Sustainability of concrete structures exposed to coastal zone. A sustainable concrete structure is one that is constructed so that the total societal impact during its entire life cycle is minimal. The design of sustainable concrete accounts for the short-term and long-term environmental consequences in the design. The use of “green” materials should be considered in the design, promoting low energy costs, high durability, low maintenance, reducing project and operating costs of the infrastructure construction (Naik 2008). The use of blended cement has been encouraged. The advantages of blended cements include increased production capacity, reduced greenhouse gases (GHG) emissions, reduced fuel consumption in the final cement production, and recycling of pozzolanic material (PM) (Worrell et al. 2004). Also, modifications of the concrete mixture design have to be taken into account. The concrete mixture modification usually involves increasing the alkalinity of coatings that can be sprayed, painted, or rolled onto the concrete surface (Cwalina 2008).

CONCLUSIONS

More research is needed on the mechanisms that accelerate biodeterioration in concrete structures in coastal zone, especially in the Great Lakes region. Also, continuing development of concrete mixture design to prevent or reduce biodeterioration of concrete is needed. This information can be used as a management tool of inspection and maintenance of concrete structures in coastal zones, such as pipes, piers, and breakwalls.

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