REVIEW OF REINFORCED CONCRETE BIODETERIORATION MECHANISMS

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Abstract: During the last decades, studies regarding reinforced concrete (RC) deterioration have focused mainly on problems such as chloride ingress, corrosion and fatigue; however, recently, other deterioration mechanisms such as concrete biodeterioration have called the attention of researchers. Biodeterioration has shown to be critical in structures located in aggressive environments, which may include polluted air, sewage waters, deep waters, water runoff, landfill leachate, acid mine drainage, and offshore placement. Also it has been observed that concrete inner conditions such as the use of recycled concrete or demolition waste like slag, and the use of pyritic aggregates favor microbial attack threatening both durability and concrete quality. This paper presents an overview of microbial attack and biodeterioration of RC structures; it focuses mainly on biologically mediated transformations. In addition, the paper presents current research initiatives and future challenges in the field of concrete biodeterioration.

1 INTRODUCTION

Biodeterioration of Reinforced Concrete (RC) structures has recently gained momentum as a mayor structural deterioration mechanism. Biodeterioration is a phenomenon that has been observed in structures located in aggressive environments; for instance sewage waters, deep waters, water runoff, landfill leachate, acid mine drainage, and offshore placement. Several research studies have found that the activity of some microorganisms on the inner concrete matrix can severely impact the structure's life generating high reparation or replacement costs [28].

Concrete is a material composed mainly of cement, aggregates and water. In particular, the basic constituent, i.e., Portland cement, has a chemical composition consisting of Dicalcium Silicate ($2CaOSi_2$), Tricalcium Silicate ($3CaOSi_2$), Tricalcium Aluminate ($3CaOAl_2O_2$), Tetracalcium Aluminoferrite ($4CaOAl_2O_3Fe_2O_3$), Calcium Sulfate or Gypsum (CaSO4·2H2O) and others [20]. It has been observed that with this chemical structure, the presence of sulfur and calcium compounds in the concrete matrix, and of iron in both aggregates and steel reinforcement, favors the attack of certain damaging microorganisms.

The main objective of this paper is to describe current research initiatives and future challenges in the field of concrete biodeterioration.

2 DEFINITION AND BASIC CONCEPTS

Biodeterioration can be described as “any undesirable change in the material properties caused by the vital activities of organisms” [28]. Thus, biodeterioration is a multi-disciplinary field that encompasses both engineering and biology concepts. Biodeterioration problems have been observed and studied in various material types such as wood, metals and concrete [28-29].

Biodeterioration mechanisms can be classified according to the effects on the material [28]; these might be: a) physical or mechanical breaking; b) aesthetic, promoted by mold, mycelium, microalgae, and major biomass producers that cause fouling or soiling [11]; and c) chemical, which takes place when microorganisms use concrete materials as a growth substrate or excrete harmful products into the material damaging its structure. A crucial aspect of concrete deterioration is the damage caused to the material inner structure, which frequently leads to an increase in porosity that reduces the strength and facilitates cracking and chloride ingress [8-28].

The biodeterioration process in RC can be divided in two stages: initiation stage; and secondary or development stage [14]. During the former substrate conditioning for living organisms (pH lowering, moisture gain, biofilm formation) or inner changes (adverse chemical reactions, cracking from swelling or shrinkage) produce often small changes in appearance. In this stage *bioreceptivity*, i.e., the intrinsic capability of a material to allow colonization by living organisms [8], plays a key role in the process. Bioreceptivity of concrete, mortar and stone exposed to indoor and outdoor environments has been identified as a favorable quality for microbial growth [21-25]. According to Prieto et al. [25], bioreceptivity can be measured using seven categories (from inappreciable to very intense) based on a qualitative assessment of the color change.

On the other hand, during the development stage, the growth of microorganisms, and/or the excessive cracking may facilitate chemical attack (e.g., due to chlorides) adversely affecting the material integrity; i.e. increment of porosity, loss of weight, and strength reduction (Fig 1).

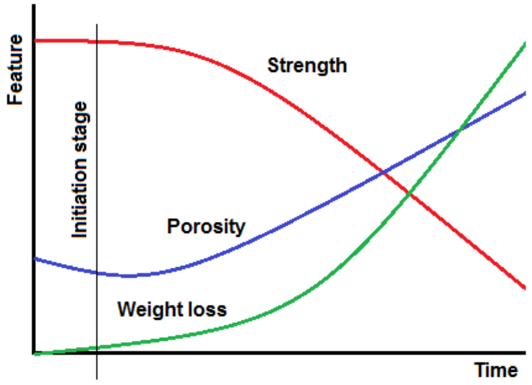

Fig 1: Material changes trend from biodeterioration.

3 BIODETERIORATION OF INFRASTRUCTURE

3.1 Drinking water systems

Problems associated to bacteriological growth, biofilm formation and microbial corrosion of pipes have been reported in drinking water systems. The most important triggers to these problems are temperature, water age, concentration of organic compounds and residual chlorine concentration. Bacteriological regrowth, biofilm formation and microbial corrosion are the main biological issues associated to drinking water systems. Also operational practices affect the growth of microorganisms like nitrifying bacteria and general bacteriological re-growth modifying their influence over the distribution systems materials [19].

3.2 Sewer systems

In sewer systems, carbonation and presence of hydrogen sulfide make the initial pH of pore water to drop from 12 or more (original pH of concrete) to about 9. Under these new conditions, microbial growth initiates with its correspondent metabolic byproducts. For example, sulfur oxidizing bacteria (SOB) produce sulfuric acid that reacts with calcium hydroxide forming gypsum (CaSO4 • 2H2O), which later reacts with Tricalcium Aluminate leading to formation of ettringite (3CaO • Al2O3 • 3CaSO4 • 32H2O) [23]. For H_2S concentrations between 30 and 400 ppm SOB can cause deterioration (thickness reduction) in sewers at rates ranging from 1.4 to 7.6 mm/year in periods of 2 months to 14 years. Also sulfate reducing bacteria (SRB) living in biofilm attached to sewer walls or immersed in wastewater convert anaerobically sulfates (typically 20 and 50 mg/L wastewater) to sulfides [14].

Carbonation and sulfate attack combination accelerate damage in deeper layers of RC pipes. In some experiments reported in [10], these two attack mechanisms were investigated. In these experiments, 100 mm-side cubic samples were exposed to 20% carbon dioxide, 70% relative humidity and four sulfate forms during 360 days. The results reported a superficial weight loss ranging from 13.5% to 20.24% and a deep weight loss of about 11.88%. The compressive strength and splitting strength losses were up to 10% and 19% respectively [10].

In addition, swelling and cracking can appear due to delayed ettringite formation, which weakens the concrete matrix and accelerates other damaging mechanisms such as steel corrosion. Even more harmful effects can be observed when there is chloride ingress, carbonation and sulfate attack. Such a case is described by Moradian et al. [23]; a sewage system buried in soils containing considerable amounts of sulfate and chloride, and where the inner environment was rich in sulfates and carbon dioxide, had to be intervened in less than 10 years.

3.3 Transportation system components

Use of deicing salts and freeze-thaw processes can lead to steel corrosion in cracked and porous concrete pavements and bridge decks. Also the recycling of pavements, the presence of ammonia-nitrogen, nitrate-nitrogen and orthophosphate-phosphorus increase the porosity of concrete, changes the shape and size of porous structures and increase the clogging vulnerability of road materials [13]. Microorganisms in runoff can reach geotextile layers and stay there for long periods of time. Their growth involves chemical reactions that may affect the substrate of the concrete.

3.4 Landfills

Solid waste disposal in Landfills and land reclamation have also shown problems as a result of microbial attack. Demolition materials are commonly used in this type of structures. The use of construction materials like Drywall made of gypsum and sheets of paper, constitute up to 30%, by wet weight, of the demolition waste disposed off in Landfills. As a result of this process, researchers have reported up to 12000 ppm of H_2S produced. The simultaneous presence of gypsum, moisture, anaerobic conditions, a carbon source, neutral pH environment and medium temperatures (30 to 38°C) give the optimal conditions for growth of sulfur reducing bacteria (SRB); SRB metabolize gypsum to hydrogen sulfide. In turn, presence of H_2S and carbon facilitate the proliferation of sulfur oxidizing bacteria (SOB) in aerobic environments [30].

3.5 Soil stabilization systems

Soil stabilization methods used to handle expansion problems are frequently treated by mixing Portland cement with soil. The resulting material can be classified as a cement mortar that can suffer from bioderioration problems. During the hydration of cement, more than twenty-three minerals are formed, which produce up to 15% ettringite/mass causing the swelling of the soil. Ettringite and gypsum are the main sulfate-binding after 28 days of curing being more important the amount of sulfate than that of ettringite [7]. This chemical structure combined with polluted sub-superficial water and groundwater could be a source of microbial attack. Further research on these improved soils is required.

4 BIODETERIORATION OF CONCRETE COMPOSITES

Pyritic aggregates in RC are a source of energy for microorganisms. In nature, pyrites and pyrrhotites are the most abundant minerals containing iron sulfide. Pyrite (FeS_2), is associated with igneous and metamorphic rocks and mineral veins and it is formed when these materials are subjected to high temperatures. When formed under low temperature it is related to organic-rich sediments. Pyrite is unstable under atmospheric conditions and is oxidized in the presence of water and oxygen. Microbial and chemical processes oxidize pyrite producing swelling and cracking in the material that contents it. [24].

Waste rock with pyrite content up to 30% and acidification of groundwater in coal mining are problems that have been largely investigated [26]. Current scarcity of good quarry in some parts of the world has forced the use of pyrite-bearing rock like concrete aggregate [32]. The content of sulfur and ferrous compounds inside the resultant concrete offers a source of food for SOB and SBR bacteria allowing for its biodeterioration.

5 BIODETERIORATION AND CHLORIDE INGRESS

In RC structures, the corrosion of the reinforcement can be facilitated when in contact with chlorides. Corrosion of steel reinforcement in RC structures affects adversely their ductility, their strength, and their fatigue life [9-17].

Shortly after the casting, high pH values (>12) in the concrete matrix allow the steel reinforcement to be protected by an oxide film. Chloride ions can reach the surface of the concrete primarily because of marine environments or application of de-icing salts to road surfaces. When chloride ions ingress into the concrete matrix and come into contact with the reinforcement, a process called depassivation occurs initiating its corrosion [3]. This process accelerates when concrete ages. The presence of CO_2 or H_2S in the environment may lower the pH down to around 9 promoting microorganisms to grow and modify the porosity [14]. In RC structures exposed to environments that combine bacteria proliferation and chloride availability, porosity and cracking caused by bacterial attack increase facilitating diffusion of chloride within the concrete matrix leading to reinforcement corrosion [4].

6 EFFECT OF MICRORGANISMS IN RC STRUCTURES

6.1 Types of microorganisms

Microorganism growth can be achieved when a source of carbon, an electron donor and a final electron acceptor exist. Microbes are called *heterotrophs* when the source of carbon is organic, or *autotrophs* when linked to carbon dioxide. The dynamics of microorganisms is based on the transfer of an electron from a donor to an acceptor. Microorganisms are called *aerobic* if the electron acceptor is oxygen or *anoxic*, if the electron acceptor is different from oxygen. In the absence of an external electron acceptor, electrons can be redistributed within the electron source, partially oxidizing some carbon atoms and reducing other carbon atoms (*anaerobic metabolism)* [14]. The primary organisms involved in concrete biodeterioration include bacteria, fungi, algae and lichens [28].

6.2 Algae, fungi and lichens

Fungal growth has been observed in buildings, monuments and underground structures. The most common fungi observed are *Alternaria, Aspergillus, Cladosporium* and *Penicillium* [2]. Chemoorganotrophic bacteria and fungi with or without the presence of photoautrotrophs may collectively act as primary microbial colonizers preparing the surface for subsequent microbial succession [12].

Stichococcus sp., *Chlorella* sp. And *Cyanobacterium Gloeocapsa* are the most common algae genus found and used in tests related to construction materials [21]. On the other hand Coccoid and colonial Cyanobacteria, *Endoliths, Trentepholia, Thyrea, Aspicilia, Verrucaria, Caloplaca* are the Lichens associated to biodeterioration of terracotta, mortar and painted plaster [11].

Colonization of outdoor buildings surfaces from cyanobacteria, algae, bryophytes and lichens leads to form complex communities that facilitate the development of heterotrophic bacteria, protozoa, molluscs, and arthropods. Many of them are thermo-tolerant (65-70°C) when dry but thermo-sensitive when wet (20-55°C) and physical treatments based on wetting and heating (45-55°C) or plastic wrapping have been proposed to inhibit the proliferation of microoragnisms [31].

6.3 Bacteria

Bacteria are the most aggressive microorganisms to RC elements. In an adequate environment they metabolize atmospheric or linked-materials compounds leading to chemical reactions harmful to concrete. This process is called Microbially Induced Concrete Corrosion (MICC) and can be developed in sewage systems, water treatment facilities, swimming pools, cooling towers and hydraulics facilities [27].

In sewage, there is a continuous transformation of H_2S into partially oxidized sulfur (thiosulfate, elemental sulfur and polysulfate species). The existence of nutrients and the turbulence of flow facilitate the ingress of H_2S into the pipe walls.

In this environment *Thiobacillus* species can grow using atmospheric CO_2 as a source of carbon [27-28]. Then, as pH is reduced, a better environment in created for other bacteria to grow, reproduce and die.

Neutrophilic Sulfur-Oxidizing Microorganisms (NSOM) include *T. thioparus* (4.5-10), *T. novellus* (5-9.2), *T. neapolitanus* (4-9), *T. intermedius* (1.7-9); while Acidophilic Sulfur-Oxidizing Microorganisms (ASOM) include A. cryptum (4.6 to 5.3). *and T. thiooxidans* (0.5-4). *T. thiooxidans* (newly *Acidithiobacillus thiooxidans*) produce sulfuric acid (H_2SO_4) that attacks the matrix of concrete producing Calcium Sulfate ($CaSO_4$) [18] and very expansive ettringite capable of causing internal cracking and pitting [22-27-28].

Also *Thiobacillus ferrooxidans, Leptospirilium ferrooxidans* and *Acidiphilium cryptum* have been observed in sewer pipes [33] and *Cyanobacterium Chroococcidiopsis* and *Cyanobacterium Pleurocapsa* were found in biofilms of buildings and monuments [11].

ASOM can move into the corroding layer of concrete but NSOM cannot do it. Bacteria activity may modify corrosion rates making them to vary between 2 to 4.7 mm/year [5-18-27-33]. On the other hand it has been observed that in environments rich in ASOM, microbiological deterioration is more deleterious than chemical deterioration (immersion in sulfuric acid) leading to an additional material weight loss of up to 8% in the first case [22].

Giannantonio et al. [12] studied the main microbial communities present in exposed concrete surfaces. *Proteobacteria, Acidobacteria, Firmicutes, Actinobateria, Cyanobacteria, bacteroidetes* and *Planctomycetes* were identified, being the gamma-proteobacteria the most abundant (75%). Three bacterial phylotypes: *Actinomycetales, Xanthomonadales*, and *Rhodospirillales* were identified to be the most abundant (more than 70%) of microbial community composition in sewers while only 4% of the total community belonged to *Acidithiobacillales* (e.g. A. thiooxidans) [6].

Pitting steel corrosion is also a major concern in steel corrosion. Johnston and Voordouw [15] reported that the influence of SRB in the steel pitting can cause losses of 0.050, 0.090 and 0.095 mm/year for oxygen/sulfide rates of 1.0, 1.6 and 2.4 respectively. These results suggest that biotic growth generates greater material distortion than chemical attack or abiotic growth.

A summary of most common bacteria strains used in concrete and related materials biodeterioration tests is shown in Table 1.

Table 1: Related tests to effect of bacteria in concrete

AUTHOR	MATERIAL AND MICROORGANISMS
Monteny et al. 2001.	Material: Concrete made with sulfate resistant Bacteria: Sulfur-oxidizing bacteria (Thiobacillus-like bacteria) and biopolymers.
Hernandez et al. 2002	Material: Concrete. Crowns of sewer pipes. Bacteria: Thiobacillus ferrooxidans, Thiobacillus thiooxidans, Leptospirilium ferrooxidans and Members of the genus Acidiphilium.
Roberts et al. 2002	Material: Mortars of calcium aluminate, microsilica and Portland cement. Bacteria: Row sewage from the City of Houston
Aviam et al. 2004.	Material: Mortar of Portland Cement. Bacteria: Thiomonas intermedia and Halothiobacillus neapolitanus.
Bielefeldt et al. 2009	Material: Concrete of new sewage collection pipe. Bacteria: Acidiphilium cryptum, Thiobacillus neapolitanus, Thiobacillus thioparus, Acidithiobacillus thiooxidans.
Lors et al. 2009.	Material: Mortar of Portland Cement. Bacteria: Acidithiobacillus thiooxidans.
Giannantonio et al. 2009b	Material: Concrete (painted / unpainted surfaces) Bacteria: Phylum Proteobacteria, mainly Gammaproteobacteria.

7 POSITIVE EFFECTS OF BACTERIA

Bacteria have been used also as a way to improve concrete performance; in this case, instead of describing the process as biodeterioration, it is called bioremediation. Bioremediation uses microbes for producing benefic changes in the properties of a material and seems to be an alternative to deal with biodeterioration. For example Kaur et al. [16] studied the effects of fungal (*Eupenicillium crustaceum*) treated waste foundry sand (WFS) on concrete properties. They found that fungal treated material had a compressive strength gain (28 d) of 24%. In addition, water absorption and porosity dropped down 44% to 50% as compared to the untreated material. This improvement can be explained by the ability of the fungal culture to form biominerals and conduct biodeposition (bacterial carbonate precipitation). Possible interaction of lichenous, mycorrhizal and saprotrophic fungi with natural rock systems, soil and buildings, gypsum and granites and their influence in the formation of secondary biomineral on the attacked substrates are proposed as future research initiatives.

According to Achal et al. [1], the use of *Bacillus* sp. CT-5 (isolated from cement) leads to biomineralization of calcium carbonate and improves the compressive strength by 36%, reducing water-absorption up to 83% in cubes of mortar. A minor gain (18%) was observed in compressive strength of cement mortar samples subjected to *Bacillus pasteurii* and *Pseudomonas aeruginosa*.

8 BIODETERIORATION TESTS AND PROCEDURES

There are many test methods available to identify bacterial activity on concrete. First, mineralogical-microbiological methods can be used to describe materials' surface topography, microorganisms morphology, material composition, and other properties using electromagnetic radiation or electron diffraction. Some of the most common tests include Scanning Electronic Microcopy (SEM), Energy Dispersive Spectroscopy (EDS), Energy Dispersive X/Ray Spectroscopy (EDAX), X/Ray Powder Diffraction (XRPD). There are also chemical tests which focus on identification and quantification of the chemical components and their reactions within the materials. These include quantitative (gravimetric and volumetric) and qualitative analysis.

9 FUTURE RESEARCH CHALLENGES

Ongoing research is being conducted to investigate the effect of the conjunction of microorganisms availability and pyritic-aggregate-concrete in wet or saturated environments. Also the influence of bacterial attack on porosity, mechanical strength and diffusivity of chlorides in mortar is being investigated by the authors. These issues require more research specifically in the involved microbiological dynamics.

Additional research needs in the field may include:

1. Study of microbial attack in RC structures built within polluted sub-superficial water or stabilized soils.
2. Study of the effect of microbial attack on structures built on reclaimed lands.
3. Understanding of microbiologic issues of microorganisms linked to biodeterioration of RC elements is highly recommended.
4. Study of the combination of biodeterioration and chloride attack over offshore structures and energy infrastructure
5. Review and study of possible remedial strategies.
6. Study of possible application of biodegradation in creating new green materials.
7. Development of comprehensive models to explain the biodeterioration processes in each one of previous topics.

10 SUMMARY AND CONCLUSIONS

Biodeterioration of RC structures, also called Microbially Induced Concrete Corrosion (MICC), is a facilitator and a principal actor of the global deterioration process. Physical and chemical biodeterioration are the most aggressive classes of deterioration that are commonly promoted by the bacterial activity. Biodeterioration can affect concrete and reinforcement bars directly or indirectly from biogenic consequences (cracking, porosity increase) and chloride ingress.

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