Biodeterioration of Construction Materials: State of the Art and Future Challenges

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Abstract: Deterioration plays an important part in the life cycle of infrastructure systems. Among all causes of deterioration (aging, chloride ingress, etc.) the action of live organisms has shown to be critical in, for example, underground structures, sewage systems, and at-sea structures. This phenomenon is usually overlooked, in part, because in most cases live organisms accelerate other processes that may eventually lead to unacceptable structural performance or cause failure (e.g., corrosion, cracking). By the direct or indirect action, it has been estimated that biodeterioration-related structural problems cost billions of dollars a year in infrastructure maintenance and repair. The paper shows that for all major civil engineering materials, in the long term and under the appropriate environmental conditions, biodeterioration may severely affect infrastructure components and their ability to perform as designed. This is particularly relevant given the large amount of existing infrastructure that has been exposed to aggressive environments for long periods of time. This paper presents an overview of the activity of live organisms on three widely used construction materials: wood, concrete, and metals. A description of the main organisms that affect each material and the associated biodeterioration mechanisms are described. In addition, this paper discusses the uncertainties associated with modeling biodeterioration and outlines the main areas for further research.

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Introduction

A comprehensive life-cycle cost analysis should take into consideration 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 operation or environmental factors. The latter has perhaps the broadest impact on the long-term performance of infrastructure systems and the largest potential economic consequences. Within this context, it has been observed that biodeterioration of structural materials may contribute significantly to continued loss of capacity of some structures located in aggressive environments. For instance, it is well known that it plays a significant role in the deterioration of structures in which wood is the major component. However, relatively little attention has been given to biodeterioration in large infrastructure systems where reinforced concrete and steel are the dominant constitutive materials.

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Biodeterioration occurs at the boundary between engineering and biology (usually microbiology). Therefore, it is necessary to consider both the physical and chemical mechanisms by which microorganisms attack the material, and the consequences on its mechanical properties. In wood, the mechanical properties of the material are altered mainly by live organisms that use it as a food source. In concrete structures biodeterioration affects the concrete matrix increasing porosity and contributing to crack growth. In metals placed in aggressive environments (i.e., at sea), microorganisms contribute significantly to the corrosion process. In summary, the action of live organisms accelerates damage processes that may eventually lead to unacceptable performance or cause failure.

This paper presents an overview of biodeterioration of the most widely used infrastructure construction materials, discusses the future challenges in this area, and suggests specific directions for needed research. The objectives of this paper are as follows:

1. Outline the significance of biodeterioration for materials used to construct large infrastructure systems;
2. Describe biodeterioration processes in wood, metals, and reinforced concrete;
3. Describe the uncertainties involved in modeling biodeterioration; and
4. Propose new directions for further research.

Definition of Degradation and Biodeterioration

Deterioration is a loss of structural capacity with time as a result of the action of external agents or material weakening. It has many dimensions and depends, among others, on the type of structure, the constitutive material, the environmental conditions, and the operation characteristics. Along these lines, a widely accepted definition of *biodeterioration* was proposed by Hueck

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(1968) as: "any undesirable change in the properties of a material caused by the vital activities of organisms." Similarly, Rose (1981) defines biodeterioration as the process by which "biological agents (i.e., live organisms) are the cause of the [*structural*] lowering in quality or value." It is important to distinguish between biodeterioration and biodegradation, which can be used mistakenly as equals. According to Allsopp et al. (2006), biodegradation is concerned with the use of microorganisms to modify materials with a positive or useful purpose while biodeterioration is referred to the negative impact of live-organisms activity.

Classification of Biodeterioration

According to Gaylarde et al. (2003) biodeterioration can be classified into

1. Physical or mechanical;
2. Fouling or soiling (aesthetic); and
3. Chemical: (1) assimilatory and (2) dissimilatory.

Physical or mechanical biodeterioration refers to all actions that directly affect the component's material and mechanical properties. This often is related to the process by which live organisms disrupt the material structure by growth or by movement but do not use the material as a food source (e.g., root damage, gnawing by rodents). *Fouling or soiling* (i.e., aesthetic) *deterioration* is caused by the presence of organisms, their dead bodies, excreta, or metabolic products forming a microbial layer on the surface of the structure known as *biofilm*. This deterioration type is primarily associated with the presence of microorganisms causing an unacceptable appearance but the performance of the material is not affected. Finally, *chemical biodetrerioration* can be divided into *assimilatory* and *dissimilatory*. The former occurs when the organisms use the structural component as a source of food (i.e., carbon and/or energy source), thus modifying the properties of the material (e.g., degradation of fuels, metals). In dissimilatory chemical biodeterioration, on the other hand, the live organisms' excreted waste products or other substances (e.g., H_2S, FeS) adversely affect the material.

Cost of Biodeterioration

The economic consequences resulting from biodeterioration are difficult to quantify and to the best knowledge of the writers, there is little reliable information on this topic. Challenges in estimating the costs associated with biodeterioration are related to the following issues:

1. Biodeterioration is difficult to separate from other damage processes. In most cases, biodeterioration accelerates other damage mechanisms, which may eventually become the actual cause of unacceptable performance or failure of the structure;
2. The consequences of biodeterioration are not easy to assess at a given time. Biodeterioration is not a continuous process and depends upon changes in climatic as well as on other environmental conditions; and
3. The engineering community is not familiar with biodeterioration mechanisms; therefore, in many cases, damage identification focuses only on well known failure mechanisms, overlooking the possible influence of live organisms.

Despite these difficulties, several studies recognize the existence of biodeterioration and the potential impact on the economy. In the case of wood construction, cost estimations reported by several authors state that the replacement of decayed wood alone consumes 10% of the timber cut annually in the United States; this does not include cost of replacement, liability, and cost of preservative treatment. In 1988, this value was estimated to be \$613 million (Anderson 1990). Currently, it is estimated that subterranean termites only, which are the most destructive insect pests of wood in the United States, cause more than \$2 billion in damage each year. This is more property damage than that caused by fire and windstorm combined. Similar figures have been reported all over the world, for instance, Sand and Bock (1991) found that 1% of the cost of buildings in Hamburg, Germany must be spent each year on maintenance due to effects of deterioration arising from physical, chemical, and biological attacks (approximately \$25–\$30 billion). In addition to usual maintenance costs, extreme environmental events such as hurricanes and tropical storms may also create the conditions for biodeterioration to take place. Reinsurance companies such as Munich-Re Group (2005) state that following a hurricane, mold damage is inevitable and the long-term consequences have proven to be very expensive.

On the other hand, information about the direct cost of biodeterioration on reinforced concrete structures is almost nonexistent. In the case of steel structures, some estimates have been made in certain areas (e.g., for marine structures) but the data are not reliable. A study conducted by CC Technology Laboratories, Inc. (2001) estimated the total direct cost of corrosion in infrastructure in the United States is close to \$137.9 billion annually. Experience has shown that a significant percentage of corrosion problems are related to microbially induced corrosion.

Based on the estimation of costs mentioned above, it becomes clear that the direct consequences of biodeterioration, although largely uncertain, are well above what the engineering community might think. These figures certainly have a significant impact on the life-cycle costs of large infrastructure systems that cannot be overlooked.

Dynamics of Live-Organism Attacks

New infrastructure components are highly resistant to the direct attack of microorganisms due to the fact that: (1) the potential microbial nutrients are not readily supplied by the materials; and (2) infrastructure is usually found in environmental conditions that restrict microbial growth (e.g., high pH and temperature). However, as part of normal structural deterioration and environmental changes, biodeterioration may become a hazard whose consequences may result in significant losses. Since biodeterioration is concerned with live organisms, the dynamic nature of the environmental conditions such as variations in humidity and temperature, the availability of nutrients, and the permanent movement of species are very important. Any attempt to realistically model biodeterioration attack must include time-dependent considerations as well as individual characteristics of the organisms involved.

The most common live organisms associated with biodeterioration of construction materials are as follows:

1. Marine borers (e.g., gribble and shipworms);
2. Insects (e.g., termites and wood-boring beetles);
3. Fungi (soft rots, white and brown rots), primary and secondary molds, stainers algae, and lichens; and
4. Microorganisms (e.g., bacteria)

The action of marine borers focus mainly on wood structures such as wooden piers and harbor piles, ships, barriers, and other

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forms of wood in marine environments. Although there are many species of marine borers, the major wood borers are the gribble (crustacean). Some marine borers do not use wood itself as a food source, but rather search for microscopic algae, bacteria, and soft-rot fungi located in and on the wood. Others, such as shipworm (mollusk), digest cellulose. The consequences of most marine borers on steel structures are minor. In concrete structures, marine borers participate actively in the erosion of the concrete surface and may eventually accelerate crack growth rate. The action of other large marine borers, which is restricted to very specific cases, is beyond the scope of this paper.

Insects have a substantial effect on wood structures but not on concrete or metallic materials. Many insects use wood structures based on seasonal requirements; for instance, bees, wasps, earwigs, and many others used it as shelter. The two main types of insects affecting wood structures are termites (i.e., Isopera) and wood-boring beetles (Coleoptera). The effect of termites in regions where wood construction is common is on the order of a billion United States dollars annually and in the tropics, maintenance costs may reach a value of 10% of the property each year (Allsopp et al. 2006).

Biodeterioration is usually concerned with the consequences of relatively small living organisms (i.e., microorganisms and fungi). The existence and growth of microorganisms requires appropriate environmental conditions such as the availability of water, light, oxygen, and nitrogen; all within an environment with the appropriate temperature and pH. The water requirement for microorganisms is expressed by the so-called *water activity* of the environment (a_w). The water activity is defined as: $(\ln(a_w) = -(\nu \cdot m \cdot \theta)/55.5$; where ν=number of ions formed by each solute molecule; m=molar concentration of solute; and θ=molar osmotic coefficient (Rose 1981). Pure water has a value of $a_w = 1.0$ and this value decreases when solutes are dissolved in it. Microorganisms can grow in media with $0.63 < a_w < 0.99$. It is known that bacteria require values of $0.93 < a_w < 0.99$, while yeast or molds grow in lower values of $0.88 < a_w < 0.91$. In addition to water availability, microbial invasion also requires the existence of nutrients. Apart from light, the two major classes of nutrients are those that provide a source of energy and nitrogen. They are provided by the enzymatic breakdown of compounds in the materials and by the environment.

Consequences of Action of Live Organisms on Structural Materials

Wood

General Considerations

Wood is the most common material used in one- and two-story residential construction in North America and in many developed countries (Kim et al. 2006). The low durability of wood construction is mainly caused by the lack of attention given to construction details that favor the growth of microorganisms, which, in the long run, weaken the main structural system and affect severely the exterior walls (Carll 2000). For instance, the sheathing and framing members permanently absorb free water from condensation or leaks around the perforations of the building envelope (Kim et al. 2006). Then, as air flows through the exterior wall cavity and is restricted by various combinations of air barriers, vapor barriers, sealants, and insulation, walls tend to stay wet for longer periods, providing an opportunity for decay fungi to become established (Smulski 2000a,b).

Conditions Necessary for Wood Deterioration

Wood deterioration due to the action of live organisms results from the relationship between the internal wood characteristics and the surrounding environment. Wood deterioration depends significantly on the presence of water. The amount of water stored in a wood component is measured in terms of the moisture content, which is a relationship between the weight of water contained in the wood to the dry weight of the wood element. Laboratory testing has shown that optimal wood moisture levels for most decay fungi are between 40 and 80% (Scheffer 1973). As long as wood structures are kept dry (i.e., moisture content below 20%) damage as a result of the action of microorganisms is unlikely (Levy and Dickinson 1981). On the other hand, timber that is kept permanently wet (e.g., marine structures) is also at little risk of decay. The greatest hazard for wood structures is in ground contact or in environments with well defined wet and dry cycles. In addition, the orientation of fibers has been found to have a marked effect on the internal movement of water having an impact on the colonization of wood by fungi (Corbett 1965). Water flows permanently within the wood structure increasing local moisture and oxygen concentrations that may favor the actions of different microorganisms. *Aerobic microorganisms* require free atmospheric oxygen to survive, while *anaerobic microorganisms* can grow without the presence of oxygen; therefore, in anaerobic regions only bacteria are usually present, while in regions with appropriate oxygen and humidity, fungal activity can be significant.

In addition to the presence of oxygen and water, most biological activity requires the presence of nutrients. The availability of nutrients is closely related to the ratio of carbon to nitrogen in wood. When this ratio is very high, the low availability of nitrogen reduces the potential of fungi to attack the wood. The nitrogen content of wood ranges from 0.03 to 1%, whereas in other plants this value ranges between 1 and 5%. Other factors that favor the growth of microorganisms (i.e., fungi) are pH values between 3 and 6 and temperatures in the range of 0–45°C, although the ideal temperatures for fungi growth are between 15 and 45°C.

Wood Damage Mechanisms

Wood deterioration results from the destruction of: (1) cellulose; (2) hemicellulose; or (3) lignin; these are the components that provide wood with its strength. This deterioration may start in standing trees as well as during the postharvest and transportation processes. In most cases, once any of the biodeterioration mechanisms start, the structural resistance decreases very quickly. The biomechanism by which the wood is damaged depends upon the type of organism. This section describes briefly how different organisms degrade wood.

The first group encompasses the so-called marine borers which are very dangerous for wood ships and wood structures built in ocean environments such as wharves, jetties, and breakwaters. The process by which some large marine borers search for larvae and other microorganisms may also scratch the material surface damaging the structural component. In addition, larvae colonization settles and bores beneath the surface, reducing the structure cross section even further (Levy and Dickinson 1981).

A second group of wood degrading agents includes insects such as Isoptera or termites and wood-boring members of the

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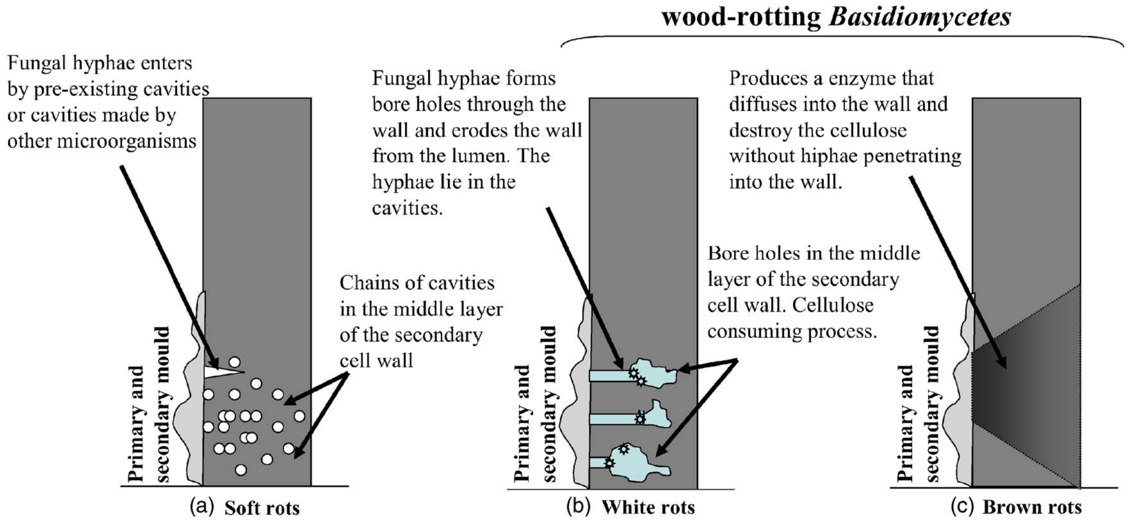

Fig. 1. Damage effect of soft, white, and brown rot on wood structure

Coleoptera (or wood-boring beetles). Termites can be found in tropical and subtropical regions and comprise a large number of species that can be divided into: (1) dry wood termites and (2) subterranean termites (Rose 1981). Termites construct nests inside timber removing much of the internal wood. It is important to point out that wood-boring insects should be mentioned in any account of microbial deterioration of wood, since many exhibit a form of symbiosis with bacteria and fungi without which they are unable to complete their life cycle.

Within the third group there are smaller organisms usually grouped in the form of molds, which can be divided into primary and secondary molds. Primary molds consist of fungi and they do not degrade the wood cell wall significantly; however, they are very active colonizers. Secondary molds can be more active on wood structures but only after partial breakdown of the wall by other fungi (Levy and Dickinson 1981). Within the same category, but different from molds are the stainers, which are characterized by the pigmentation of the hyphal walls (usually black or brown in color). Some of these species appear to be capable of causing soft rot. Soft rot is a type of fungus that penetrates into the wood forming chains of cavities that weaken the structure of the material [Fig. 1(a)].

Finally, the wood-rotting Basidiomycetes are the most common and aggressive microorganisms. They are classified as *dry-rot* and *wet-rot* fungus. Dry rots tend to be yellow and white, while wet rot are more green-brown; commonly, they are called *white* and *brown* rots, respectively. The former (i.e., dry rot) can attack the wood at a lower water content (about 25%), while in most other types of decay these values are about 50%. White rots completely destroy both cellulose and lignin. The *dry-rot* fungus is very aggressive and can travel over brickwork and masonry and can penetrate plaster and mortar. This type of fungus requires conditions of static dampness typical of badly ventilated closed-up cavities [Fig. 1(b)]. It is costly and difficult to eradicate. Brown rots slightly modify lignin but destroy holocellulose [Fig. 1(c)]. They produce an enzyme that diffuses into the wall destroying the cellulose. Brown rots require environments with relative humidity above 50% to develop but are able to tolerate fluctuating conditions of wood moisture and air humidity (Allsopp et al. 2006).

Structural Degradation Process

The structural degradation of wood is a complex phenomenon that depends highly on the relationship between the structure, the characteristics of the organism, and the environment. Microorganisms use the wood as a food source reducing its overall weight. It has been observed that brown-rot fungi can reduce the wood weight by up to 70%, soft-rot fungi up to 60%, and white rot-fungi up to 97%. The final value depends on the type of wood and the species considered. The weight loss (biomass loss) is a common measure of decay capability and is expressed as

$$W_L = \frac{W_o - W_{\text{decayed}}}{W_o^d} \tag{1}$$

where W_o=original weight; W_{decayed}=decayed weight; and W_o^d=original oven dry weight. Weight loss is generally expressed on an oven dry basis (ODW). Experimental data have shown that there is proportionality between the percentage of wood weight loss and loss of strength (e.g., toughness, impact bending, work to maximum load, and modulus of rupture) for values of weight loss up to 10%. For instance, Kim et al. (2006) analyzed the seismic performance of wood frame shear walls when subject to attack by brown-rot fungus at various levels of decay. They performed an accelerated testing program focusing on the hysteretic behavior of nailed connections between sheathing and framing. Maximum tensile and compressive loads decreased with increasing incubation time. These results were then used as inputs to a nonlinear numerical model of complete shear walls to illustrate the effect of decay on both cyclic and dynamic wall performance. Shear wall performance when subject to a brown-rot incubation period of 30 weeks exhibited very large displacements, in excess of the drift limit requirements for life safety (Kim et al. 2006).

The process of wood degradation in terms of weight loss is illustrated conceptually in Fig. 2. It can be divided into four stages. In the first stage, the environmental conditions, the wood properties, or any immunization measure control the appearance and development of fungi. This region may not exist if biodegradation has already started at the time the structure is built. After any of these circumstances change, the hyphae of decay fungi penetrate the wood, initiate colonization, and release enzymes.

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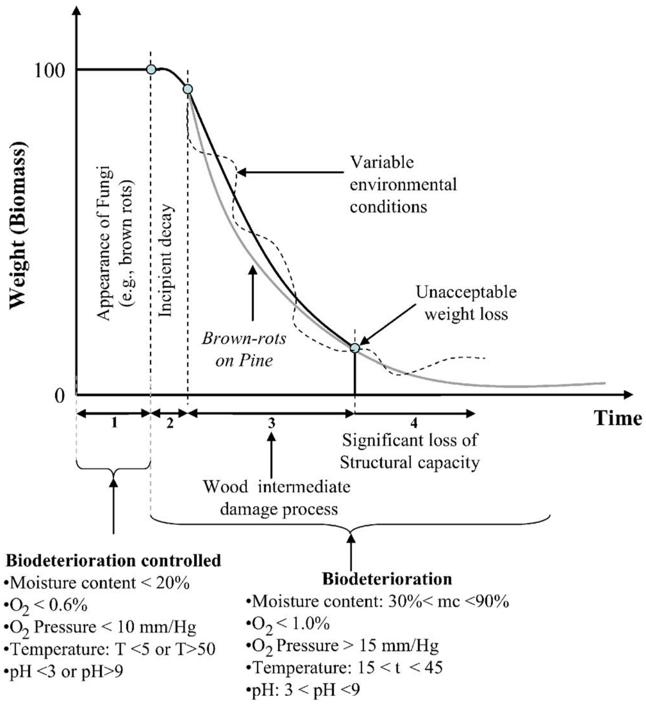

Fig. 2. Phenomenological decay of wood resistance as result of action of fungi

The early colonization of wood is usually called the *incipient* or *hidden stage* of decay and is characterized by subtle changes in color and texture. In the third stage, there is a period of rapid decay also called the *intermediate* decay stage. The speed of the decay depends on how favorable the environmental conditions are for the decay action and fungus. These conditions may change, reducing or accelerating the speed of the process. Experimental data have shown that for brown rots on pine, this decay follows an exponential form, while the action of white rots on the same woods cannot be characterized as easily. It is suggested that the overall trend might follow an exponential form, although further research is required to properly characterize a decay curve. The last stage is defined by a point where the structural damage is extensive (e.g., 60% weight loss) and beyond which wood cannot perform as a structural component; the process that follows leads to total disintegration of the element.

Metals

General Considerations

Biodeterioration of metals does not result from the direct action of microorganisms on the material, but from the associated processes that accelerate corrosion. Videla (1996) defines biocorrosion, microbial corrosion, or microbiologically influenced (or induced) corrosion (MIC) as "an electromechanical process, where the participation of the microorganisms is able to initiate, facilitate, or accelerate the corrosion reaction without changing its electrochemical nature." Metal corrosion is a widely studied problem that is relevant to many fields (e.g., civil infrastructure, naval engineering, aerospace, etc.). Microorganisms modify the two-component system (i.e., metal solution), characteristic of abiotic corrosion, to a three-component system (metal-solution-microorganisms) (Videla 1996). It has been observed that certain metal/solution interfaces may change significantly in the presence of microorganisms and corrosion rates can be many times greater than in their absence (Costello 1969).

Microbiologically Influenced Corrosion Process

Microorganisms initiate or accelerate corrosion by a wide variety of activities that include modification of the metal/solution interface, destabilizing protective films or corrosion products on the metal surface, and inducing pitting attack in areas where microbial adhesion takes place (Videla 1996). Dimensions of microorganisms (i.e., fungi and bacteria) involved in this process vary but they are small. This allows them to colonize areas where there are small pits or to adhere to solid surfaces forming very active biofilms. The *biofilm* formation starts when small organic molecules become attached to an inert surface. Microbiological cells are then adsorbed, allowing colonization by microorganisms (bacteria and fungi). Biofilms of up to 100 μm thick are not unusual and in nearly all cases contain entrapped bacteria. These films become complex biological ecosystems, consisting of colonies, consortia, newly arrived cells, dying cells, extracellular products, polymers, and trapped inorganic material (Videla 1996). As the biofilm grows, an anaerobic zone on the colonized surface develops. Trapped ions can create localized chemical and physical gradients at the metal surface activating an electrochemical cell and causing pitting (Watkins 1994).

The activity of microorganisms related to metal corrosion is classified in terms of

1. Oxygen use;
2. Acid producers; and
3. Slime formers.

Because these classifications consider the same microorganisms, they overlap. Only the first two will be explained in more detail since they both contain valuable information about the corrosion process.

In terms of oxygen consumption, the most common form of biocorrosion occurs in aerobic environments. In this case, colonies of microorganisms, which can be of various classes (bacteria, fungi, algae, etc.), grow in a region where nutrients such as water and oxygen are available. Under aerobic conditions, the dissolution of metal, as metallic cations, releases an excess of electrons that are captured by nearby cathodic sites. The overall reaction leads to the formation and subsequent precipitation of insoluble corrosion products.

The second classification of microorganisms (i.e., acid producers) is based on the source of energy. Microorganisms that get their energy from a chemical source are: (1) sulfate-reducing bacteria (SRB); (2) iron and manganese bacteria; and (3) sulfur-oxidizing bacteria. Microorganisms that obtain their energy from other sources (e.g., light) do not play a significant part in corrosion and will not be discussed in this paper.

Since the inner layers of the biofilm are often anaerobic, some bacteria use hydrogen (H) and sulfate (SO_4^{-2}) or other reduced-sulfur compounds for growth. SRB are the most important bacteria associated with corrosion under anaerobic conditions. These bacteria reduce sulfate (SO_4^{-2}) to sulfur (S), which reacts with hydrogen H available and iron (Fe) to form hydrogen sulfide (H_2S) and iron sulfide (FeS), which are extremely corrosive agents. The result is an alkaline environment in which metals can corrode. SRB can grow in soil, fresh water, or salt water and tolerate pH values between 5 and 9.5 (Watkins 1994). On the other hand, *iron and manganese bacteria* further oxidize iron from ferrous iron (FeO) to ferric iron (Fe^{3+}), which can attract chloride ions and produce ferric chloride ($FeCl_3$). Ferric chloride

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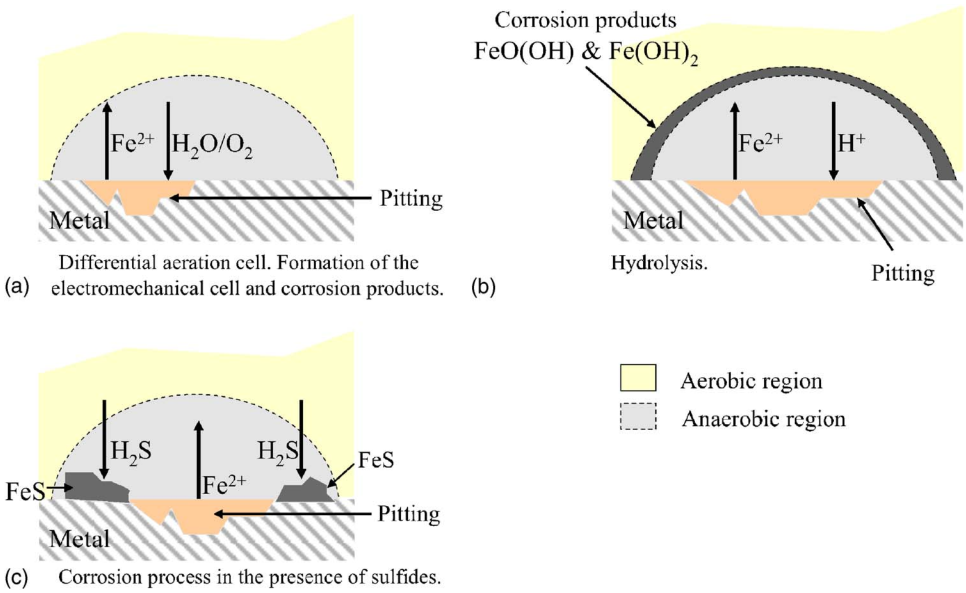

Fig. 3. Corrosion caused by concentration cell formation

is extremely aggressive and pits stainless steel and other metals. This type of corrosion is usually found at low points of tanks or pipes and mostly in the interfaces between oil and water, or air and water, e.g., splash zones. Finally, *sulfur-oxidizing bacteria* oxidize elemental sulfur producing sulfuric acid (H_2SO_4), which is highly corrosive to many metals. It is mainly caused by bacteria in the genus *Thiobacillus*, which can produce hazardous quantities of H_2SO_4 increasing the oxidation rate of Fe^{3+} (other sulfur-oxidizing bacteria are: *Thiodendron*, *Beggiatoa*, and *Sulfobus*). Suitable conditions for this type of induced corrosion are found in sewage systems or in-ground contact areas where significant quantities of industrial waste materials can be found (Videla 1996).

Electrochemical Reactions

The corrosion process is electromechanical in nature. In metals, corrosion can occur basically under these three circumstances:

1. Attack by concentration cells (underground structures and others);
2. Action of sulfides (S^{-2}) ("at-sea" structures); and
3. Effect of organic and inorganic acids (sewage systems or storage systems).

In the first case, corrosion is typically initiated by cell concentrations induced by biofilm formation (Fig. 3). Microorganisms modify the speed of the corrosion process by altering the concentration of aggressive agents such as oxygen, H_3O^+, iron ions, and metal salts. This type of corrosion depends only on the uptake of normal nutrients by the biofilm, which creates an electromechanical system with initial small anodes and large cathodes [Fig. 3(a)]. As the biofilm grows and corrosion progresses, corrosion products enlarge the concentration differences accelerating the process. The electrochemical cell results from the following chemical reactions (Heitz et al. 1996)

$$Fe \rightarrow Fe^{2+} + 2e^- \quad \text{(anodic region)} \tag{2}$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^- \quad \text{(cathodic region)} \tag{3}$$

Therefore, if the electrons are ignored the basic corrosion process can be written as

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2 \tag{4}$$

Eq. (4) combines iron (Fe), water (H_2O), and oxygen (O_2) to produce iron hydroxide ($2Fe(OH)_2$). Melchers (2006) states that this polarization [Eqs. (2) and (3)] in at-sea structures is a transient and very short-term process that is followed by equilibrium of the system. In a subsequent stage [Fig. 3(b)], corrosion products composed of hydroxides of iron go through a process of hydrolysis which causes a drop in pH and the initiation of acid corrosion (H_2S). This change from oxygen corrosion to acid corrosion (H_2S) greatly accelerates the rate of the corrosion.

The second case of corrosion is observed in the presence of sulfides, which are known to be intensive corrosion stimulators (Heitz et al. 1996). Sulfides are produced by bacterial reduction of oxidized sulfur compounds. In practice, when aerobic and anaerobic cycles occur at the same time, elemental sulfur is produced generating a concentration cell mechanism of corrosion which is rather similar to the aerobic case. Instead of oxygen, microbially produced H_2S acts as the oxidizing agent [Fig. 3(c)]. In steel, the presence of H_2S alone encourages corrosion at a rate of about 12.8 mm/year, but in the case of elemental sulfur, this rate is about 35–50 mm/year (Tiller 1990).

The overall reaction (i.e., concentration cell and electrochemical action of sulfides) of sulfate reduction leading to corrosion product ($3Fe(OH)_2$) can be formulated as (Heitz et al. 1996)

$$4Fe + SO_4^2 + 4H_2O \rightarrow 3Fe(OH)_2 + FeS + 2OH^- \tag{5}$$

In addition to the biocorrosion promoted by aerobic and anaerobic conditions, there are other mechanisms that have not been studied in as much detail but can eventually become critical. An important case results from the generation of the aggressive acid (organic and inorganic) as a result of the metabolism of Thiobacillus bacteria or certain fungi. Corrosion under these conditions results from the liberation of hydrogen as the main cathodic reaction. This leads to the formation of hydrogen sulfide (H_2S) which diffuses into the metal ($Fe + H_2S \rightarrow FeS + 2H$). Finally, it is important to mention that little work has been carried out on metals other than iron and steel.

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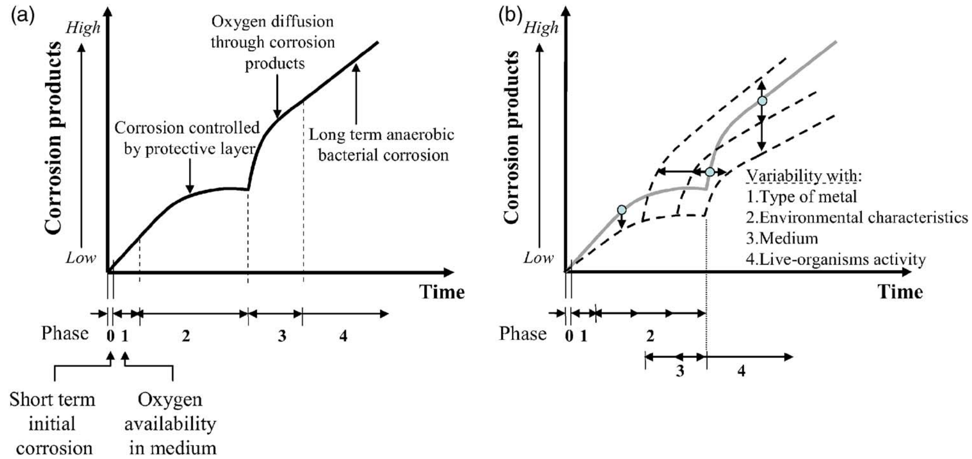

Fig. 4. (a) Phenomenological model for general corrosion of marine structures (adapted from Melchers 2005); (b) variation of model based on material properties, environmental conditions, and medium

Structural Degradation Process

Although metal corrosion depends on many factors (e.g., type of structure, environmental conditions, etc.), the problem of steel corrosion caused by immersion of structural components at sea has been widely studied (Schumacher 1979). According to Melchers (2005, 2006) the generation of corrosion products under these circumstances can be divided into five phases [Fig. 4(a)]. First there is short-term initial corrosion governed basically by chemical kinetics (Phase 0). In the second phase (Phase 1), corrosion is driven by the oxygen availability in the surrounding water. As a result of this process, corrosion products form a protective layer that slows the process (Phase 2). The next stage (Phase 3) is governed by oxygen diffusion through the corrosion product layer. Finally, bacteria concentration on the surface moves to the corroding interface, initiating a final stage of the long-term anaerobic bacterial corrosion phase (Phase 4). Based on statistical data, Melchers (2005) proposed mathematical expressions for the parameters describing the function shown in Fig. 7(a) for both general and pitting corrosion.

The conceptual model proposed by Melchers (2006) for marine structures can be extended to other cases by considering the specific characteristics of the problem. This requires modifying the corrosion function presented in Fig. 4(a) [see Fig. 4(b)] to take into account the following aspects:

1. Physicochemical characteristics of the metal (type of alloy);
2. Environmental characteristics (temperature, pH, etc.);
3. Medium (marine structures, underground pipes); and
4. Live-organism activity (type of bacteria).

Every metal corrodes differently depending upon its internal chemical characteristics. However, as reported by Melchers (2006), there are insufficient data to make precise statements as to how metal composition actually affects corrosion. Some estimates of the effects of different alloys in the model presented in Fig. 4(a) can be found in Melchers (2006). The three main environmental variables involved in corrosion are: (1) temperature; (2) oxygen availability; and (3) pH. Other factors that may be important under specific circumstances are: carbon dioxide, soil or water pollution, and wave velocity (marine structures). The third important aspect is the medium where the structure is located. In marine structures, the two main variables that participate in corrosion are: (1) temperature and (2) oxygen supply (Melchers 2006). For underground structures, several studies have shown that the parameters that most affect corrosion are: (1) salt concentration; (2) particle size; and (3) moisture content (Gupta and Gupta 1979; Gardiner and Melchers 2002). Finally, the level of bacteria activity is highly related to the medium and commonly the system combines corrosion resulting from oxygen diffusion through corrosion products and corrosion caused by SRB.

Reinforced Concrete (RC)

General Considerations

Under optimal conditions, RC structures are highly durable and experience relatively little degradation in mechanical properties (and hence, structural reliability) with time. However, deterioration of RC is often found in structures exposed to aggressive environments and subjected to, for instance, sulfate attack, and chloride ion penetration. Although concrete mix proportions are designed to comply with the design life requirements, poor quality control, improper characterization, or unanticipated changes in the environmental conditions, or the exposure to aggressive environments can produce premature degradation and change the load carrying capacity. Among all, the most widely studied cause is chloride ion (Cl^-) ingress in concrete structures. In addition to chloride penetration, biological processes can accelerate degradation by severely modifying the physicochemical properties of RC. Although little attention has been given to biodeterioration, some recent studies (Gaylarde et al. 2003; Ribas Silva 1993, 1995a,b; Ribas Silva and Pinheiro 2006; Bastidas et al. 2008) have shown that live organisms may play a significant role in the deterioration of concrete structures (Fig. 5). This is particularly important in marine structures such as ports and offshore platforms and in more common structures such as sewage systems and wastewater-treatment plants (Piedrahita 2004; Cho and Mori 1995; Morton et al. 1991).

Reinforced Concrete Biodeterioration Mechanism

The primary organisms involved in RC biodeterioration are: (1) bacteria; (2) fungi; (3) algae and lichens; and (4) all those that erode and perforate the concrete (Gaylarde et al. 2003). Organisms can grow in aggressive environments on concrete surfaces that offer favorable conditions (e.g., available water, low pH, etc.), for example, in conditions where there is:

1. Elevated relative humidity (i.e., between 60 and 98%);

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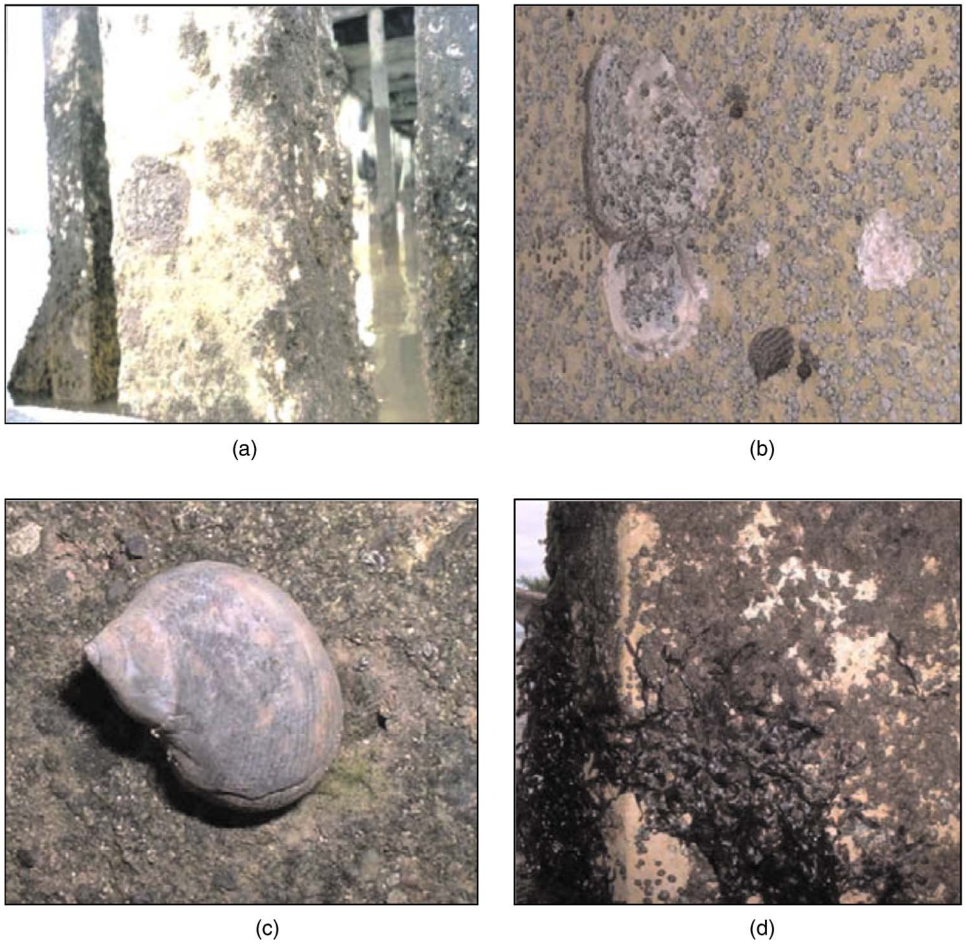

Fig. 5. Biodeterioration of concrete piles at sea: (a) concrete erosion by fungi; (b) concrete perforation; (c) concrete surface erosion by shells; and (d) algae and lichens (Courtesy of Emilio Bastidas-Arteaga, reprinted with permission)

2. Long cycles of humidification and drying, or freezing and defrosting;
3. High carbon dioxide concentrations (e.g., carbonation in urban atmospheres);
4. High concentration of chloride ions or other salts (e.g., marine environments); or
5. High concentration of sulfates and small amounts of acids (e.g., sewer pipes or residual water treatment plants).

The action of microorganisms affect mainly the concrete by: (1) contributing to erode the surface exposed; (2) increasing concrete porosity (i.e., rising the coefficient of diffusion) facilitating chloride ion ingress; and (3) accelerating crack propagation. These actions accelerate the corrosion of steel reinforcement causing a reduction of the structural capacity.

Structural Degradation Process

The action of microorganisms on concrete structures can be classified according to their consequences on: (1) concrete surface; (2) concrete matrix; and (3) on cracking and crack growth. Figs. 5 and 6 illustrate some cases of concrete biodeterioration.

Deterioration of Concrete Surface

After construction, concrete is usually immune to biological attack because of its high alkalinity (pH between 11 and 13). This high pH is the result of the formation of calcium hydroxide, i.e., $Ca(OH)_2$, as a by-product of the hydration of cement. It is important to mention that there are only few microorganisms that can grow and develop in alkaline environments. These microorganisms are called "Alkalinophilic" and can grow at very high pH levels (9–11) (Brock 1970). Over time, the pH of concrete is slowly lowered mainly by the effect of carbon dioxide (CO_2) and hydrogen sulfide on the surface. It can sometimes take years to lower the pH of concrete from 12 to 9; however, in some severe situations, it can be accomplished in a few months (Shook and Bell 1998). In some structures (e.g., wastewater systems), the presence of hydrogen sulfide gas (H_2S) also contributes to reducing the pH (Fisher et al. 2001). Both CO_2 and H_2S are called "acid" gases and they form relatively weak acid solutions when dissolved in water. CO_2 produces carbonic acid and H_2S produces thiosulfuric and polythionic acid. These gases dissolve into the water on a moist surface and react with the calcium hydroxide to reduce the pH (Shook and Bell 1998).

Eventually the surface pH is reduced to a level, that can support the growth of bacteria (pH 9–9.5) [Fig. 7(a)]. Over 60 different species of bacteria are known to regularly colonize structures, especially above the water line in wastewater pipelines (Shook and Bell 1998). The most common bacteria developed in this media are the *thiobacillus* which have the unique ability to convert hydrogen sulfide (H_2S) gas to sulfuric acid (H_2SO_4) in the presence of oxygen. A well known bacterium that affects concrete is thiobacillus thiooxidans, known also as *thiobacillus concretivorous*, (i.e., Latin for "eats concrete"). Usually, the erosive action of water and/or the friction of structural elements with

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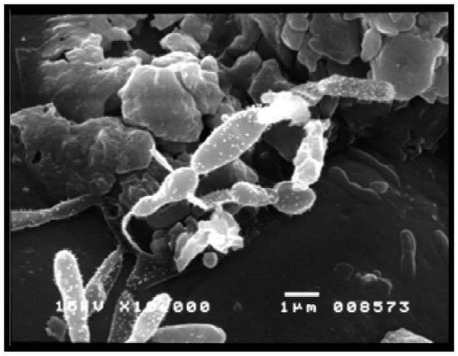
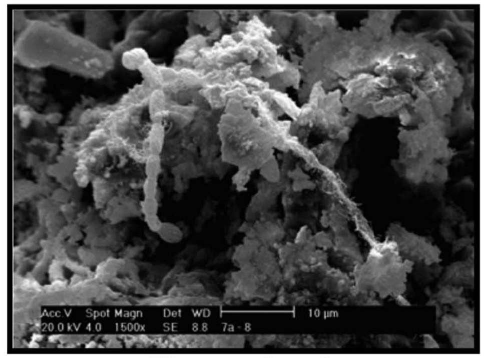
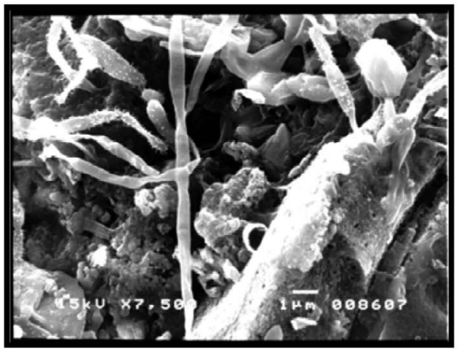


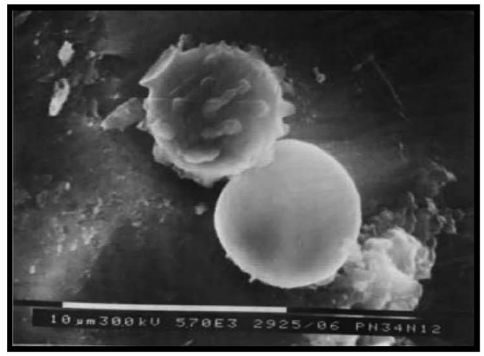
Bacillus, filamentous and cocus bacteria



Filamentous bacteria



Filamentous bacteriae and hyphae of fungus



Yeasts with bacteria on the surface

Fig. 6. Deterioration of concrete matrix as result of action of microorganisms (microphotos courtesy of M. Ribas Silva, reprinted with permission)

other materials generate roughness on the concrete surface facilitating microorganisms to adhere and form a biofilm (Ribas Silva 1995b). Once bacteria are settled in the biofilm, the sulfuric acid waste product they excrete decreases the pH of the surface below 6.5, they die off, and another species, which can withstand lower pH ranges, takes up residence. The process of successive colonization continues until species, which can survive in extremely low pH conditions, take over (Shook and Bell 1998). Roughness on the concrete surface may also favor the adherence of organisms of appreciable size such as mollusks, bivalves, crustaceans, and sipunculids (Cantera et al. 1996). They scrape and perforate the surface by means of chemical and physical processes (Fig. 5). This occurs mostly in tropical regions (Ribas Silva 1993).

Sulfuric acid attacks the matrix of the concrete resulting in the formation of many different products. The primary product of concrete decomposition by sulfuric acid is calcium sulfate ($CaSO_4$), more commonly known as *gypsum*. Gypsum does not contribute to the mechanical resistance of the material, but it is believed that acts as a protecting layer to concrete in the same way that initial corrosion protects metals. If this "protective" coating of gypsum is removed, the concrete surface can be exposed to acid attack accelerating damage to the surface (Shook and Bell 1998). The color of corroded concrete surface (yellow-brown) is caused by the direct oxidation of hydrogen sulfide to elemental sulfur when a continuous high concentrated supply of atmospheric oxygen or other oxidants is available. For instance, the upper portions of manholes exposed to high hydrogen sulfide concentrations are often yellow. In addition the mixture of gypsum and calcium aluminates in the concrete produces ettringite, which increases internal pressures leading to the formation of cracks (Aviam et al. 2004)

Diffusion into Concrete Matrix

Microorganisms are very small and can penetrate inside the concrete matrix even if there are no observable cracks in concrete. The most common mechanism for their ingress is by microcracks and capillarity. Some research has been made concerning the analysis of concrete structures in order to verify if microorganisms could be responsible for some of the damages observed (Ribas Silva and Pinheiro 2006). Laboratory analysis of concrete samples has shown that many microorganisms such as: fungus (yeasts, *cladosporium*, mycelia, hypha etc.), bacteria (actynomicete, thiobacillus, among others), algae (the most popular are diatom algae), and even protozoa can be found within the concrete matrix (Ribas Silva and Pinheiro 2006). The consequences of every microorganism on the microstructure are different. Fig. 6 shows the presence of some microorganisms on the concrete matrix. Although there is not enough experimental evidence, it has been observed that the action of microorganisms on the concrete matrix increases concrete porosity, which in turn changes the concrete coefficient of diffusion and concrete internal conductivity. This facilitates other processes such as corrosion of the reinforcement.

Cracking of Concrete

The steel reinforcement corrosion process [Fig. 7(b)] is initiated when the passive film on the surface is broken down and the reinforcement is exposed to chloride ions (Thoft-Christensen 2002b). The initiation time of reinforcement corrosion depends highly on the diffusion coefficient and on the critical chloride ion threshold, which is a property of the material. Apart from biodeterioration, it has been shown experimentally that diffusion increases with water-cement ratio and temperature (Jensen 1998;

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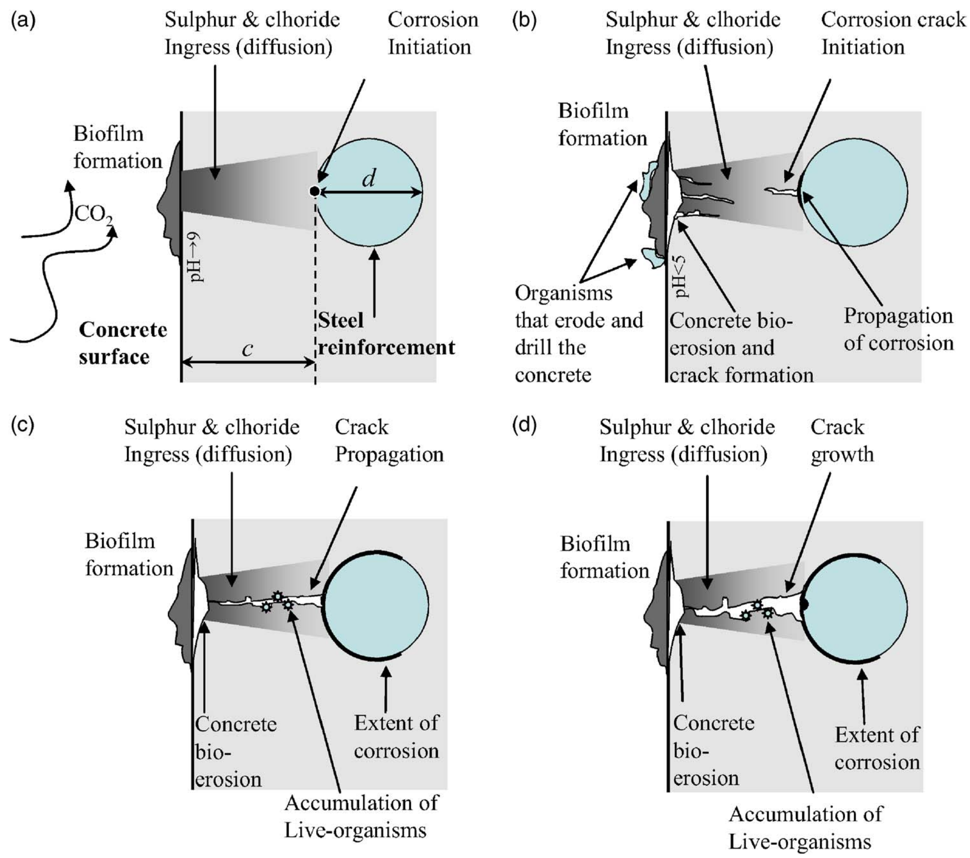

Fig. 7. Reinforced concrete biodeterioration (i.e., acceleration of corrosion process and concrete degradation)

Jensen et al. 1999). The corrosion of reinforcement results in an expansion of corrosion products, which exceeds the tensile strength of concrete, causing cracking (Stewart and Val 2003). Vu and Stewart (2005) divide the process of corrosion-induced cracking into two stages: (1) crack initiation and (2) crack propagation. Crack initiation is defined by the time for which cracks of 0.05 mm width are formed. On the other hand, the value for the limiting crack width at the end of the crack propagation phase depends on the limit state considered. Sakai et al. (1999) and Vu and Stewart (2005) defined the limit crack width as 0.3–0.4 mm for durability limit states and ACI-209 (ACI 1978) suggests a value of 0.8 mm for serviceability (aesthetics) requirements.

When the concrete is cracked, some organisms such as endolithic cells, algae, and fungi ingress through cracks generating tensile stresses that deteriorate the concrete by increasing the crack size and concrete porosity [Fig. 7(c)] (Gu et al. 1998; Ribas Silva 1995a, b). These conditions also make it possible for other organisms such as the acidophilic sulfur oxidizing bacteria (ASOM) to adhere to the biofilm, further contributing to concrete chemical deterioration [Fig. 7(b)] (Pinheiro and Ribas Silva 2003). Finally, the slow corrosion process previously initiated by diffusion accelerates significantly. The combined action of microorganisms and the expansive pressures from steel oxidation increase the concrete cracking rate, spalling, and delamination [Fig. 7(d)].

Mechanical Deterioration Model

The problem of concrete deterioration as a result of aging and chloride ingress has been widely studied by, for instance, Clifton (1993), Liu (1996), Liu and Weyers (1998); Thoft-Christensen (2000, 2002a), Stewart and Val (2003), and Melchers et al. (2007). Organisms contribute to degradation by both direct damage to the concrete surface and by accelerating corrosion and crack growth. In the case of RC structures, organisms affect the former by a chemical action and the latter by a mechanical action. Bastidas et al. (2008) proposed a model for the variation of corrosion products with time as

$$W_m(t) = \begin{bmatrix} 0 & \tau_{\mathrm{ini}} \geq t \\ f(t,\mathrm{DO}_2,A,g) & \tau_w \geq t \geq \tau_{\mathrm{ini}} \\ h(t,\mathrm{DO}_2,A,g) & t \geq \tau_w \end{bmatrix} \tag{6}$$

where τ_{ini}, τ_w=times to corrosion initiation and corrosion of the total bar surface, respectively; DO_2=diffusion coefficient of O_2 in concrete (mm^2/year); and g describes the geometry of the problem. $f(*)$ and $h(*)$=functions describing the amount of corrosion products at each time step (for more details see Bastidas et al. 2008). Eq. (6) is presented conceptually in Fig. 8(b). The challenge for this model is in obtaining the time-dependent function for the biodeterioration rate. For that, Bastidas et al. (2008) proposed a fuzzy inference model based on limited statistical data and expert opinion that considered environmental factors; however, further work on the subject is required.

Basic Concepts for Modeling Biodeterioration

The specific sources of uncertainty inherent in the biodeterioration of construction materials are shown in Fig. 9. This figure presents biodeterioration as being central to the interaction among: (1) live organisms, (2) constitutive material properties, and (3) structural elements, all within an environmental context.

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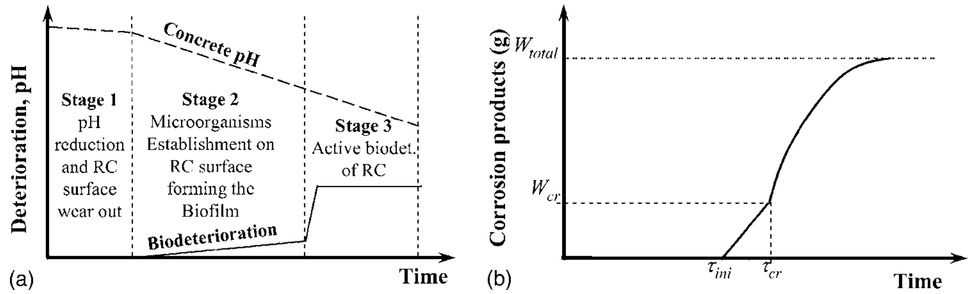

Fig. 8. Biodeterioration process (adapted from Bastidas et al. 2008)

First, there is significant uncertainty about the existence, action, and development of organisms. Their action depends mainly on the characteristics of the environment in which the structure is built. These conditions (i.e., temperature, pH, water activity, availability of nutrients, etc.) promote the appearance or not of every type of organism and define the level of activity. Since the environmental conditions are often not stable, organismal activity varies dramatically.

The uncertainty associated with living organisms should also be considered in the context of the material they are acting upon. It is in the relationship between live organisms and material that their effect becomes relevant. Depending upon the type of material, the deterioration mechanism resulting from live organisms can be chemical, mechanical, or a combination of both. The nature of the damage and the speed of the process can vary with each case. Within this interaction, the construction process, the physicochemical properties of the material, and the protection measures are important.

The third aspect that contributes to uncertainty relates to the characteristics of the structural system. The environmental conditions at the location of the structure (e.g., splash zones for marine structures, areas of strong winds, etc.) and the purpose of the construction (e.g., storage of organic or chemical, water sewage systems, etc.) are paramount when considering biodeterioration. For instance, in underground pipes, biodeterioration may cause leaking, while in ports and offshore platforms, the damage might lead to structural instability. Furthermore, the design, construction, and operation characteristics of every system are different and therefore the way in which it may be affected by microorganisms differs.

A mechanical model describing the performance of structures subject to biodeterioration should include the strong time-dependent probabilistic nature of the process which, at a minimum, should take into account the following aspects:

1. Spatial distribution of the action of the organisms;
2. Time-dependent growth and activity of the organisms;
3. Material degradation characteristics (physical and chemical); and
4. Mechanical degradation process.

The spatial distribution of damage plays an important part in the deterioration and it is particularly important in large structures (i.e., bridges, ships), or in structures with many components. Microbial effects on materials are difficult to predict even under similar environmental conditions. Therefore, different components within a structure may be damaged differently. In addition, structural deterioration is closely related to the dynamics of the microorganism's life cycle, which can be considered a nonstationary stochastic process (Fig. 10). The mean effect of the microorganism's attack on the structure is a function whose intensity varies significantly since it is conditioned to a large extent on the environmental conditions, which have a large variability. The third aspect corresponds to the material degradation process and was described in detail in "Classification of Biodegradation" for wood, metals, and RC structures. The physical and chemical characteristics and the mechanisms associated with material deterioration are a major source of uncertainty. Biodeterioration modes are site specific and depend on the environmental characteristics and their variability, as well as the material type and level of protection. All of these conditions favor or restrict the attack of different live organisms.

The last aspect to be considered is the variability and uncertainty associated with the system deterioration mechanism itself. This is important in a reliability analysis for which specific limit

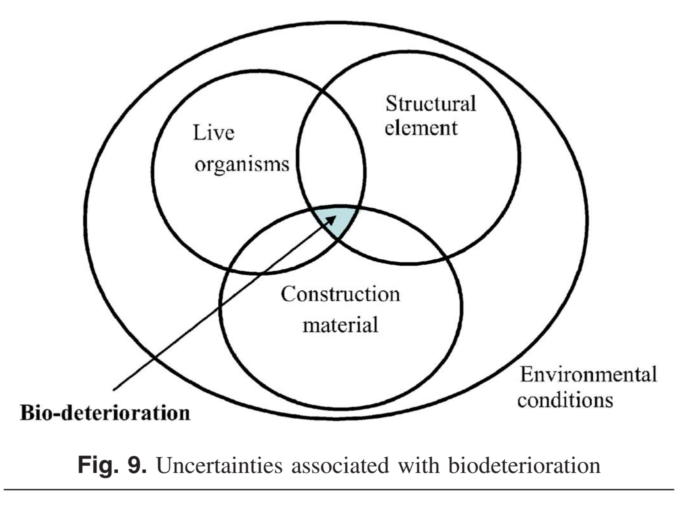

Fig. 9. Uncertainties associated with biodeterioration

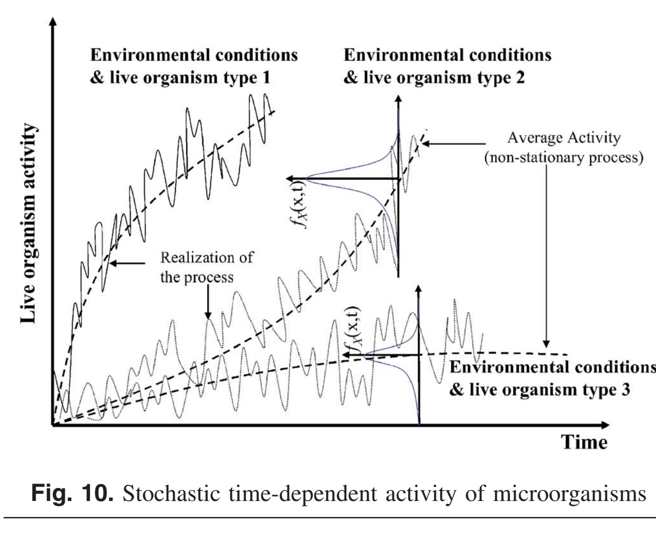

Fig. 10. Stochastic time-dependent activity of microorganisms

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state functions must be defined. Melchers (2006) proposed a general probabilistic model for marine corrosion products for "at-sea" structures based on the phenomenological description of the process as

$$W_m(t,\mathbf{E}) = b(t,\mathbf{E}) \cdot f_n(t,\mathbf{E}) + \varepsilon(t,\mathbf{E}) \tag{7}$$

where $W_m(t,\mathbf{E})$=weight loss of metal as a result of corrosion; $f_n(t,\mathbf{E})$=mean-valued function describing the actual damage process in time (i.e., corrosion); $\varepsilon(t,\mathbf{E})$=zero-mean error function; $b(t,\mathbf{E})$=bias function; and $\mathbf{E}$=vector describing the environmental and material parameters. It is important to stress that the function $f_n(t,\mathbf{E})$ focuses mainly on the damage mechanism (i.e., corrosion, cracking). Therefore, it may be extended to wood and RC based on the discussion presented in "Classification of Biodegradation" where these functions were laid out conceptually for these two materials [Figs. 2 and 8(b)]. In these cases, the appropriate correspondence for $W_m(t,\mathbf{E})$ has to be made. Also, statistical data have to be collected to define $b(t,\mathbf{E})$ and $\varepsilon(t,\mathbf{E})$.

Further Work

From the discussion presented in previous sections, it becomes evident that a great deal of work has still to be carried out to better understand the consequences of biodeterioration on construction materials. Some overall directions for future research are:

1. Identification of structural systems or environmental conditions under which biodeterioration may be critical. For every system characterize the biodeterioration damage process. This aspect requires the identification of the environmental conditions (i.e., pH, food sources, etc.) and the physical and chemical mechanism of damage;
2. Definition of "biodeterioration damage." This requires studying the consequences of live organisms when acting separately or coupled with other damage mechanisms such as corrosion or concrete cracking. In metals and RC structures, the participation of microorganisms in structural damage is still not well defined;
3. Identification of relationships between the activity of microorganisms and the mechanical properties of structural elements (i.e., modulus, diffusion coefficient). Most work so far has focused only on the changes in the material internal structure;
4. Modeling time dependency and uncertainty of mechanical properties of materials when subject to biodeterioration. Extensive experimental work in this direction is required; and
5. Develop extensive experimental research programs that include the incorporation of controlled environments. Appropriate models have to be developed to relate experimental work with real deterioration times.

Summary and Conclusions

1. Biodeterioration of construction materials may play a significant role in the life-cycle analysis of large infrastructure systems. Many factors which differ in nature, participate in this process and the uncertainties associated with both the parameters and the models are large. Extensive experimental work is required to collect data that can be used to build new models and quantify the associated uncertainties;
2. Structural biodeterioration has long been recognized as a critical factor for wood structures; however, it has been treated only in a cursory way in the broader infrastructure construction industry. Recently, its importance has been recognized in very specific problems such as sewage and underground pipes and steel structures at sea. Biodeterioration is generally not considered because: (1) it is difficult to separate from the processes that actually cause the failure (e.g., corrosion); (2) it is a process that varies substantially in time and is strongly dependent on the environmental conditions; and (3) the engineering community is not familiar with biodeterioration mechanisms; therefore, it is a problem that has frequently been overlooked. Existing data on the cost of maintenance of wood structures and metal corrosion (e.g., metal structures and steel reinforcement in concrete structures) provide evidence that losses/costs associated with biodeterioration could be far more significant than previously thought;
3. The process describing the degradation of the mechanical properties of wood, metal, and concrete structures, when subject to the action of live organisms, was described in "Classification of Biodegradation." In wood structures, biodeterioration focuses on cellulose consumption. In metals, live organisms accelerate the process of corrosion; and in reinforced concrete structures, the action of live organisms modifies the concrete matrix accelerating processes such as diffusion, causes concrete cracking, and accelerates corrosion of the reinforcement;
4. There is considerable uncertainty associated with the biodeterioration of construction materials, therefore, any biodeterioration model should take into account the stochastic nature of all of the processes involved. It is argued that both epistemic and aleatoric uncertainty results from the interaction of (1) material characteristics; (2) the dynamics of live organisms; and (3) the type of structure. Each of these factors must be considered when taking into account the particular environmental context in a life-cycle analysis;
5. Building integrated and comprehensive models of biodeterioration is not simple and there is still a great deal of work to be done in this area. However, it is suggested that a comprehensive model should include the following aspects: (1) time-dependent growth and activity of live organisms; (2) spatial distribution of the action of live-organisms; (3) material degradation characteristics; and (4) mechanical degradation process; and
6. Information about the uncertainty of the parameters involved in biodeterioration is almost nonexistent; the very limiting existing data suggest high variability. Furthermore, the data are very difficult to obtain as this is largely a site-specific problem. Extensive research is needed on specific problems to understand the uncertainties and to collect experimental and field data, particularly under the most critical (i.e., aggressive) environmental conditions.

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