Things that go rot in the night – a review of biodeterioration

Glyn Morton

> ‘Putrefaction
> is the End
> Of all that nature
> doth Entend’
>
> *Herrick*

Micro-organisms have a simple approach to life; they use whatever is available as a food source, attach themselves to practically all surfaces, multiply and build up biomass. Everyone is familiar with the phenomenon of rotting, the natural decay and recycling of materials by a wide range of life forms, including micro-organisms. This process is termed biodegradation and it is perceived as a beneficial or positive process. Biodeterioration may be defined as ‘the deterioration of materials of economic importance by micro-organisms’; it is perceived as a deleterious or negative process. Biodeterioration has been classified as follows:

Mechanical biodeterioration. This occurs when the material is damaged as a direct result of the physical activity of an organism, such as its movement or growth. An example of this kind of biodeterioration is the damage caused to electrical cabling as a result of insect or rodent attack.

Chemical assimilatory biodeterioration. This is perhaps the most common form of biodeterioration. It occurs when a material is degraded for its nutritional value. The breakdown of cellulosic materials such as wallpaper by cellulolytic fungi is an example.

Chemical dissimilatory biodeterioration. This occurs when a material is damaged as a result of the production and release of metabolic products that may corrode, pigment or toxify the material. The poisoning of grain by mycotoxins, and the release of pigments into plastic films are examples of this process.

Soiling. This visible form of biodeterioration occurs when the mere presence of an organism or its excrement, renders the product unacceptable. The function of the material may be impaired by the presence of the organisms, as in the fouling of ships’ hulls by barnacles and algae.

It is essential to appreciate that more than one of these processes, or indeed all of them may be occurring at the same time.

Materials of economic importance known to be subject to biodeterioration include:

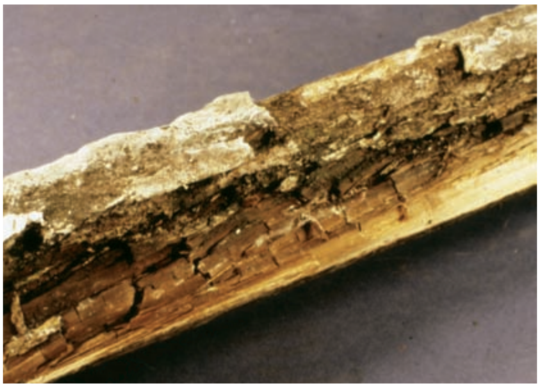
- Stored agricultural products
- Wood and allied constructional materials
- Pharmaceuticals and cosmetics
- Polymers, rubbers and plastics
- Glass
- Archival material
- Pulp paper
- Textiles and leather
- Fuels and lubricants
- Metals
- Paints
- Stone, concrete and buildings
- Adhesives and sealants

The list is extensive and it includes most of the industrial materials that readily come to mind. It is difficult to accept that some of these materials (glass, metal, stone) are susceptible to microbial attack. It is beyond the scope of this article to discuss all the materials listed. Therefore, selected examples of microbial biodeterioration familiar to the author will be reviewed.

The role of biofilms

Biofilms are an extremely important and integral part of biodeterioration.

The removal of those biofilms which may be unsightly or considered to be a hazard to health can be a costly and time-consuming business. When the colonization of the surface of any material occurs, the term biofilm is invariably used. At one time this term was confined to surfaces in constant contact with water, i.e. at the solid/liquid interface. The definition has now been extended to any interface, i.e. air/solid, liquid/liquid and air/liquid, where growth of micro-organisms occurs. To a microbiologist a biofilm represents a zone where the deleterious effects brought about by the presence of micro-organisms and their extracellular metabolites are concentrated or focussed. Slime production, the result of polymeric materials produced by a wide variety of micro-organisms – bacteria, fungi and algae – is associated with biofilms. For many years workers in industry have recognized the problems caused by slimes that develop in process machinery, in storage tanks and cooling towers and on many surfaces in contact with liquids (Fig. 1).



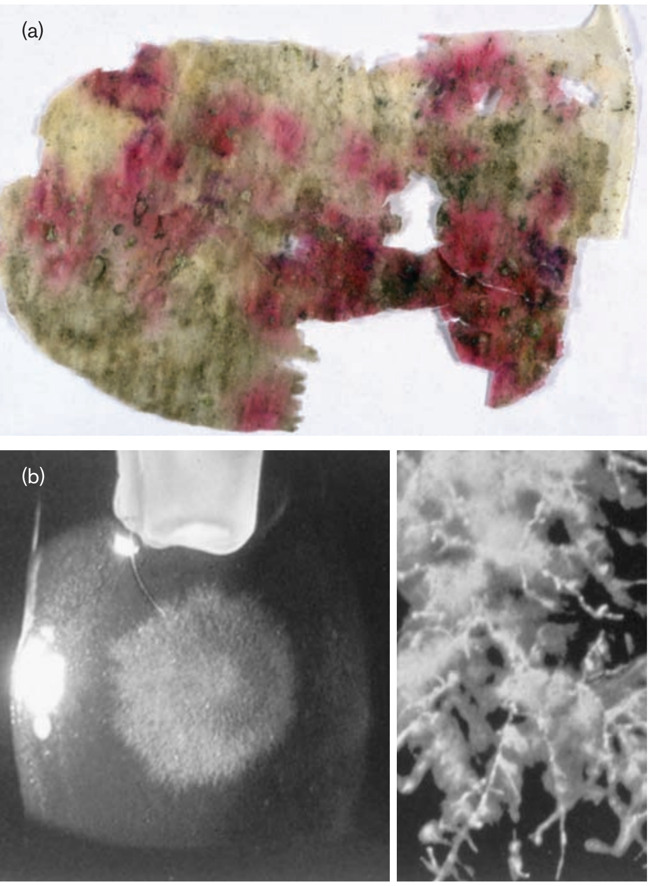
ABOVE (TOP):
Fig. 1. Bacterial slime from within a pipeline.
COURTESY JOHN GILLATT, THOR UK LTD.

ABOVE (BOTTOM):
Fig. 2. A piece of timber with brown rot.
COURTESY G. MORTON

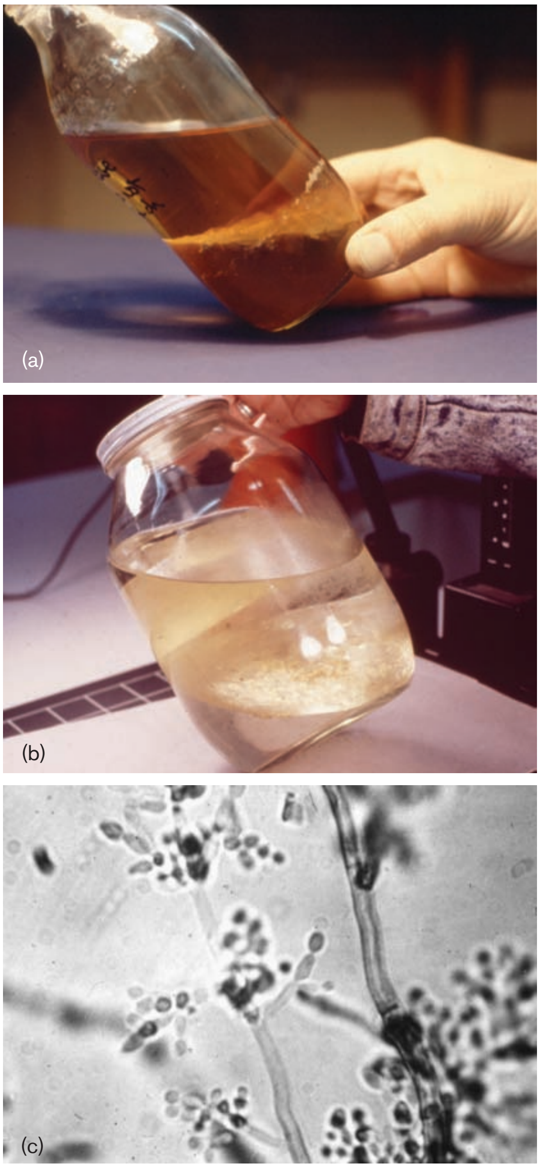
Examples of the biodeterioration of materials of economic importance

Wood

The rotting of wood is probably the most well known example of decay caused by fungi. For practical purposes the type of rot derives its name from the appearance and integrity of the attacked wood. Chemically, wood is made up mainly of cellulose and lignin. When both of these components are consumed by a fungus, the wood becomes lighter in colour and the term ‘white rot’ is used. Some fungi consume more cellulose than lignin and the wood becomes brown in colour, hence the term ‘brown rot’ (Fig. 2). Other types of decay include wet



BELOW:
Fig. 3. (a) Small sample of deteriorating PVC roofing material with fungal (green) and actinomycete (red) pigmentation (COURTESY G. MORTON). (b) Fungal colonization of a soft plastic contact lens. The image on the right shows the fungal hyphae within the lens material (COURTESY ADVANCE MEDICAL OPTICS LTD).



RIGHT:
Fig. 4. (a) Contaminated diesel fuel. (b) Lacing at the fuel water interface. (c) *Hormoconis resinae.* COURTESY G. MORTON

rot, soft rot and staining. Brown, white and wet rots are caused by fungi that produce large, noticeable fruiting bodies (macrofungi), whilst soft rot and staining are mainly caused by microfungi. All wood needs to be wet before it can rot, yet decayed wood sometimes looks dry (especially within buildings) when it is infected with dry rot. As John Palfreyman and Nia White describe on pp. 107 the fungi responsible for this condition, such as *Serpula lachrymans*, are able to import water from other regions of the infected timber, via special filaments.

Plastics

Plastics possess a broad range of chemical and physical properties that may be tailored to meet the particular requirements of industry. Specifically, they have been formulated for durability to resist weathering and therefore to resist microbial biodeterioration. Because plastics are both cheap and relatively easy to produce they have replaced traditional materials such as wood, metal and rubber in a broad range of industrial applications. Some of the materials that are classified as plastics are readily attacked by micro-organisms. These include natural rubber and synthetic rubbers, regenerated and modified celluloses, polyesters and polyurethanes. Commercially produced plastics, including polyethylene, polypropylene, polystyrene, polyvinyl chloride and the polyamides (nylons) are generally considered to be inert, but there is evidence to suggest that they are susceptible to microbial attack under certain conditions. Rubbers and plastics contain a wide variety of additives that are susceptible to damage by microbes. These include plasticizing compounds such as adipates, ricinolates and sebacates which are used to confer flexibility to rigid plastics such as PVC. The effects are often severe (Fig. 3a) and in some cases unexpected. (Fig. 3b).

Micro-organisms in fuels, lubricants and coolants

For any micro-organism to grow actively in a hydrocarbon it must have water and a supply of nutrients. Micro-organisms are able to grow over a range of pH, temperature and oxygen values. They can utilize a wide range of organic and inorganic nutrients, and they also produce extracellular emulsifying agents which enable them to come into close contact with the hydrocarbon droplets. It is not surprising that they grow actively in formulations containing hydrocarbons. The problems caused by micro-organisms include bioslimes, a loss of useful additives and the formation of metabolic products, which indirectly contribute to corrosion problems.

Fuels. In the presence of water and other nutrients present in fuel systems, diesel fuel and aviation kerosene will support the growth of a range of bacteria and fungi. One particular fungus, *Hormoconis resinae* or the 'kerosene fungus', flourishes in aviation fuel which is screened regularly for the presence of this, and other unwelcome microbial passengers (Fig. 4).

Metal-working fluids. Metal-working fluids, or cutting fluids, are used in industry to facilitate machining processes. They are needed to prolong tool life, improve surface finish, remove swarf, reduce frictional heat between the tool and the chip, and to reduce power consumption. Any reduction in the efficiency of these functions constitutes a problem. Metal working fluids are classified according to their chemical composition and fall into four major groups: neat oils, oil-in-water emulsions, 'semi-synthetic' oil-in-water emulsions and chemical solutions. Oil-in-water emulsions are the most widely used industrial cutting fluids. Neat oils are not usually considered to be susceptible to biodeterioration, since free water is seldom present. The growth of micro-organisms (mainly bacteria) in oil-in-water emulsions, can result in emulsion instability, lowering of pH, production of foul odours, the formation of stable emulsions, and increased corrosive activity. Microbial growth (mainly of fungi) in semi synthetic fluids and chemical solutions results in lowering of pH, production of fungal biomass and foul odours. This microbial invasion can be readily appreciated when one considers that commonly employed additives in modern metal-working fluids can be biodegraded by micro-organisms. These include emulsifiers, extreme pressure additives, and corrosion inhibitors. Of particular concern is the fact that pathogens have been isolated from metal-working fluids, often co-existing with non-pathogens, and transmitted in 'mists' generated by the machines.

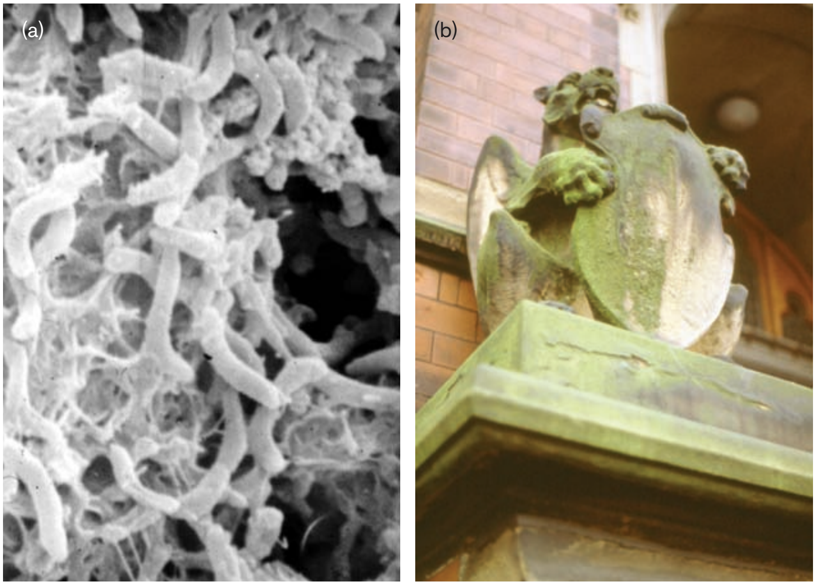
Biocorrosion of concrete and stone

Biocorrosion can be defined as any corrosive effect on the surface of a material caused by micro-organisms. Biologically influenced corrosion (BIC), microbial corrosion (MC) and microbially influenced or induced corrosion (MIC), are among the terms used to describe biological corrosion of metals. The mechanisms by which biofilms contribute to corrosion are influenced by the availability of oxygen in the environment. Under aerobic conditions, localized biofilm deposits can cause the formation of anodic and cathodic areas on the surface of a metal. These areas become a series of differential chemical cells, each inducing the transfer of electrons with loss of cations causing pitting. Sulfur-oxidizing bacteria produce sulfuric acid in quantities sufficient to bring about the corrosion of metals. Under anaerobic conditions sulfate-reducing bacteria (SRB) are the major cause of corrosion in low oxygen or oxygen-free environments (Fig. 5a), as described in more detail by Iwona Beech on p. 115.

The surfaces of stone or concrete are readily colonized by micro-organisms (Fig. 5b). The decay of these surfaces is dependent on the production of corrosive metabolites.

Since the introduction of Portland cement almost 50 years ago, concrete has become one of the most widely used synthetic materials within the construction industry. It is composed of cement powder, water and aggregates of various sizes, such as sand or gravel. The main constituents of cement powder are lime, silica, alumina and iron oxide. Upon curing, the cement paste hydrolyses to form hydrated calcium silicates (C-S-H gels) and Portlandite [$Ca(OH)_2$]. The arrangement of these crystals allows channels to form within the concrete structure. The formation of these channels within the concrete permits the capillary action of water, which may contain micro-organisms. Thus, as water permeates deeper into the concrete, fissures are formed, allowing the deposition of organic material and the further ingress of micro-organisms. Workers in the 1940s and 1950s established that thiobacilli were the causative agents of MIC of concrete structures in sewers due to the production of sulfuric acid. This acid reacts with the calcitic binding material of the concrete causing its destruction. Two other sulfur compounds are detected on sewer walls, namely sulfur dioxide and thiosulfate. Thiosulfate is a reaction product of sulfur dioxide with molecular sulfur and forms a good substrate for thiobacilli.

Freshly prepared concrete has a pH of 12–13 compared to the highly acidic pH (2·5–0·5) of corroded concrete. It is considered appropriate to view the presence of *Acidithiobacillus thiooxidans* as an indicator of corrosion rather than pH values resulting from bacterial sulfuric acid generation that is partially buffered by different concrete types.



ABOVE:
Fig. 5. (a) Biofilm of SRB (COURTESY CHRISTINE GAYLARDE). (b) A griffin colonized by algae and fungi (COURTESY G. MORTON).

SRB are usually associated with metal corrosion rather than with the deterioration of concrete. These bacteria, however, are widespread in nature and active in locations made anaerobic by microbial digestion of organic material. Whilst thiobacilli are considered to be responsible for the degradation of concrete above ground, research indicates that nitrifying bacteria, which are responsible for the oxidation of ammonia via nitrous acid to nitric acid, play a major role in the degradation processes occurring below ground. The action of nitric acid on the calcareous binding material of concrete results in the production of calcium nitrate, a soluble salt, which is either lost from the concrete resulting in the formation of corrosion pits, or remains, thus adding a salt to the pore water.

RIGHT:
Fig. 6. Decaying concrete floor in a flooded cellar.
COURTESY K. MCCORMACK

FAR RIGHT (TOP):
Fig. 7. (a) Infected paint in a can. (b) Algal growth on the outside wall of a public house.
COURTESY JOHN GILLATT, THOR UK LTD

FAR RIGHT (BOTTOM):
Fig. 8. Mould growth in a suitcase.
COURTESY KENNETH SEAL

Further reading

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Organic acid corrosion of concrete

Mycelial development on a surface can be associated with the formation of mucilaginous sheaths. Sheath development in some genera of fungi is triggered by physical contact with the substratum. Obvious similarities exist between the proposed functions of the fungal mucilages and the extracellular polysaccharides of bacterial biofilms. Fungi isolated from the surfaces of monuments, the facades of buildings and from degrading concrete include many genera that are representative of air and soil flora. This points to the susceptibility of concrete to biodeterioration by heterotrophic micro-organisms. This author has isolated fungi from decaying concrete floors in flooded cellars (Fig. 6).

Emulsion paint

Only water-based-paints are susceptible to biodeterioration during their manufacture which may give rise to in-can problems. Thinning of the paint results when the thickener, usually a cellulose ether, is attacked by cellulase enzymes produced by bacteria and fungi introduced into the formulation via contaminated components. Talc, which is used as an extender in paint formulation, has been cited as a possible source of contamination. The detection of contaminants at the surface of emulsion paint (Fig. 7a), together with gas evolution (the production of 'off odours') have also been attributed to microbial contamination.

Films of oil- and water-based paints are colonized by micro-organisms on the outside (Fig. 7b) and inside of buildings. This aspect of biodeterioration can be both unsightly and hazardous to health.

The control of biodeterioration

Despite the availability of a wide selection of biocides for use against biodeteriogens, the number of formulations that is deemed acceptable is constantly reviewed because of their potentially hazardous effect on the environment. Furthermore, there is a large body of evidence and thus concern, that micro-organisms within biofilms (including certain pathogenic organisms) are less susceptible to the activity of biocides than their planktonic counterparts. Until we are able to control biodeterioration without the use of biocides, it is here to stay.

Ladies and gentlemen – I rest my case (Fig. 8)!

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