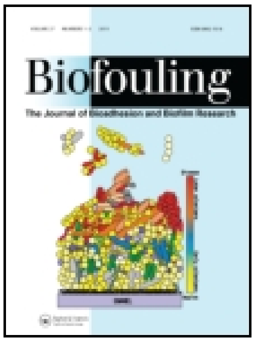

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Deteriogenic Biofilms on Buildings and their Control: a Review

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Concrete, stone, brick, plaster, wood, plastic, painted surfaces and metal are all colonised by bacteria, algae and fungi which accelerate their deterioration. The mechanisms of deterioration, the main microbial genera involved and factors which may affect the degree of colonisation and attack are discussed. The chief factor determining microbial growth on constructional materials is moisture. Thus it is important for architects and engineers to consider critical points in the humidity profile of a building at the design stage. Damp surfaces are readily colonised by microbial cells settling from the air. This leads to the formation of a biofilm, which can trap dust and other particulate materials, increasing its disfiguring effect. In addition, the biofilm can act as a reservoir for potentially dangerous microorganisms such as the bacteria responsible for legionnaires' disease and allergenic fungal and actinomycete spores. Materials may be protected against microbial growth by the use of biocides. The use of such toxic agents is critically reviewed.

Keywords: algae; bacteria; biocides; biofilms; constructional materials; fungi

INTRODUCTION

Colonisation of building surfaces by microorganisms, bacteria, algae and fungi, causes aesthetic and physical damage to the structure, and can lead to human health problems. The weathering of the materials is accelerated by the presence of the biofilm, which contains active and dormant microorganisms and products of their metabolism, such as acids and polymeric materials. The polymers, generally polysaccharides, act as glues, trapping dirt and other particulate materials, increasing the disfiguring effects of the biofilm and making the structure more difficult to clean.

The most common microorganisms on the exterior surfaces of buildings are fungi, algae and blue-green bacteria, which can resist repeated cycles of drying and rehydration. A complex biofilm system may develop on such surfaces. The colonisation process begins with autotrophs, which require only inorganic materials for growth, and these are followed by heterotrophic (organic nutrient-requiring) organisms (May *et al.*, 1993). Both groups may accelerate weathering processes. The major microbial activities which are important in the deterioration of constructional materials are shown in Table I.

Active biofilms are found in any location where microorganisms and moisture are present. Their

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TABLE I Microbial activities involved in deterioration of constructional materials

Microbial activity	Damage caused	Materials affected
Surface growth	Discoloration, water retention	Concrete, ceramic tiles, stone, bricks, plaster, wood, plastic, paint, roofing tiles
Acid production	Corrosion, erosion	Concrete, stone, metal
Hydrolytic enzymes	Increased fragility, erosion	Wood, paint
Chelation	Corrosion, etching	Metal, concrete, stone, glass
H_2S production	Corrosion	Metal
Growth of microbial filaments	Physical damage to surface, increase in permeability	Concrete, stone, wood, plaster, painted surfaces, plastics
Inhomogeneous growth/activity	Corrosion due to concentration cells	Metal
Metabolic activity	Blistering, embrittlement	Painted surfaces; plastics

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formation is affected by the types of organisms, the nature of the surface and the environmental conditions (Costerton *et al.*, 1987; Walker & Keevil, 1995). In tropical environments, or in other areas of high humidity, such as bathrooms, biofilm formation is extremely rapid (Allsopp & Seal, 1986; Lim *et al.*, 1989). Materials in dry conditions are the least susceptible to biofilm formation and biodeterioration. Thus the best way to reduce risks to a minimum is to maintain low humidity and to avoid large temperature fluctuations, since the latter may cause condensation (Grant *et al.*, 1989); however, this is often impracticable. The advent of air conditioners has helped to reduce the problems within buildings, but often with increased hazard to the external structure. Where the air conditioner condensate falls on the outer wall of the building this commonly induces the growth of algae and fungi and eventually leads to loss of any protective coating and crumbling of the underlying structure.

BACTERIAL PROBLEMS

Fungi and algae are not the only microorganisms involved in biofilm formation and reduced durability of structures. Bacteria can also play an important role. While fungal and algal growths are often visible to the naked eye, bacteria can be present on an apparently clean surface in sufficient numbers to exert adverse effects. Such effects can include concrete and metal corrosion due to production of inorganic acids (Cragnolino & Tuovinen, 1984; Bock & Sand, 1986; May *et al.*, 1993), or blistering of paint due to other microbial metabolic activities (Stranger-Johannessen & Norgaard, 1991). Chemolithotrophic and oligotrophic bacteria, which grow at very low nutrient levels, may condition a surface, making it more amenable to colonisation by other microorganisms (May *et al.*, 1993).

Microbial corrosion of concrete, mortar and metal has long been known to be caused by chemolithotrophic bacteria, such as *Thiobacillus*, *Nitrosomonas*, and *Nitrobacter* (Wasserbauer *et al.*, 1988; Wilimzig & Bock, 1995), which utilise inorganic salts as electron acceptors during cellular energy production, resulting in the formation of inorganic acids (sulphuric, nitric). A review of these activities can be found in Craglino and Tuovinen (1984). Nitrous and nitric acids and their ammonia salts, produced by nitrifying bacteria, have also been shown to be a dominant factor in the degradation of asbestos cement (Wasserbauer *et al.*, 1988). In addition, it has been realised that heterotrophic bacteria are also important. Such bacteria have been detected in high numbers on the surface of deteriorating stone (Tayler & May, 1991), although their role in the

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decay process has not yet been defined. It is suggested that they excrete organic acids, causing leaching of rock-binding materials, and produce extracellular polymeric substances, which lead to water absorption and changes in porosity and permeability of the substrate (Warscheid *et al.*, 1991). They can also cause discoloration of the surface, which is particularly important in the case of monuments or other works of art (Sorlini *et al.*, 1994). Enzymic activities of bacteria can be important in some cases of degradation. *Ochrobactrum anthropi*, isolated from soil, produces an enzyme that breaks down condensation products of urea and formaldehyde (ureaform) and hence attacks board adhesives (Jahns *et al.*, 1997). In the case of metal corrosion, recent problems with copper pipework in hospitals in the UK have resulted in intense research activities on the heterotrophic bacteria found in the biofilm, which are not only resistant to the normally toxic copper ions, but are also directly involved in the corrosion process (Walker *et al.*, 1992; Percival *et al.*, 1997). Replacement of the whole system with stainless steel pipework, although expensive, seems to have been the only solution.

Among all the microbial groups, bacteria stand out in their ability to grow at low oxygen concentration. Hence they can be very active in anoxic environments, within pipes and stagnant storage tanks, as well as beneath biofilms in otherwise well-oxygenated areas. Many bacteria are active fermenters under such conditions and produce acids, leading to corrosion of the structure or to spoilage of a product stored within it. Other bacteria (the sulphate-reducing bacteria, SRB) are the principal organisms involved in anaerobic metal corrosion (Postage, 1984; Hamilton, 1985). There is a wide literature on these organisms because of their importance in the oil industry, where they not only corrode pipelines and storage tanks, but also cause souring of petroleum by their production of sulphides. They are the major group of organisms involved in the corrosion of underground metal structures (Postgate, 1984) and it is well accepted that their effects are much more intense when present in the sessile state, that is, in biofilms, than when free in the surrounding medium (Gaylarde & Johnston, 1980; Gaylarde & Videla, 1994).

The anaerobic bacterial species, *Clostridium xylanolyticum*, causes tunnelling decay of wood (Rogers & Baecker, 1991). This type of deterioration is seen as distinctive troughs using scanning electron microscopy (SEM) and was originally thought to be due to fungal action (Clausen, 1996). It is thought that anoxic microniches in the wood structure are caused by localised respiratory activity of aerobic biofilms, allowing growth of the anaerobic species, which produces a very active xylanase enzyme, destroying the integrity of the wood substrate. Other members of the genus *Clostridium* produce cellulase enzymes, which alter the crystalline structure of the cellulose microfibrils, changing the permeability of the wood and opening the structure to fungal penetration (Boutelje & Bravery, 1968; Greaves, 1971). Certain facultative bacteria, such as *Bacillus polymyxa*, can break down the pectin component of wood cells (Knuth & McCoy, 1961). Bacteria which attack the structural components of wood cause reductions in compression strength, bending strength and modulus of elasticity (Boutelje & Bravery, 1968) and such attack can occur even when the wood has been treated with preservative (Singh *et al.*, 1992; Eaton, 1994). Some of the more important bacteria directly involved in biodeterioration of constructional materials are shown in Table II.

In addition to structural damage, bacteria in biofilms in buildings can cause health problems. The best known example is *Legionella pneumophila*, which can cause a life-threatening pneumonia, legionnaires' disease. This microorganism is widespread within the environment and is found in high numbers in both natural and man-made aquatic environments (Grimes, 1991). It is spread *via* small air droplets and the disease is contracted by inhalation of these droplets. Sources of infection include hot water systems, especially in large institutions such as hospitals (Plouffe *et al.*, 1983;

TABLE II Some bacteria important in the deterioration of building materials

Material	Bacterial groups	References
Concrete, stone and mortars	Sulfur-oxidising bacteria (*e.g. Thiobacillus*), heterotrophic bacteria (*e.g. Arthrobacter, Micrococcus, Pseudomonas*), nitrifying bacteria	Cragnolino & Tuovinen, 1984; Koestler *et al.*, 1985; Sorlini *et al.*, 1994; Tayler & May, 1994; Wales & Sagar, 1985; Wasserbauer *et al.*, 1988; Wilimzig & Bock, 1995
Metal	SRB, sulfur-oxidising bacteria (*e.g. Thiobacillus*), iron bacteria (*e.g. Gallionella*), iron-reducing bacteria (*e.g. Vibrio, Shewanella*), acid-producing bacteria (*e.g. Clostridium*)	Cloete & de Bruyn, 1995; Cragnolino & Tuovinen, 1984; Gaylarde & Videla, 1987, 1994; Liu *et al.*, 1997; Walker & Keevil, 1995
Painted surfaces	*Actinomyces, Alcaligenes, Bacillus, Flavobacterium, Pseudomonas*	O' Neil, 1988
Plastics and rubbers	*Acinetobacter, Actinomyces, Moraxella, Pseudomonas, Nocardia*	Zyska, 1988
Wood	*Acinetobacter, Alcaligenes, Bacillus, Citrobacter, Clostridium, Corynebacterium, Enterobacter, Erwinia, Pseudomonas, Rhodococcus, Serratia, Streptomyces,* a nitrogen-fixing consortium	Boutelje & Bravery, 1968; Dutkiewicz *et al.*, 1992; Koestler *et al.*, 1985; Line *et al.*, 1997; Rogers & Baecker, 1991

Hsu *et al.*, 1984), cooling towers and evaporative condensers (Tobin *et al.*, 1981; Broadbent *et al.*, 1991; Bentham, 1993), fountains, machine cutting coolant, misting devices and spa baths (Anon, 1991). Factors which predispose man-made environments to infection with *L. pneumophila* include the temperature of the system, stagnation, which often occurs in the dead ends of distribution system pipework and in storage tanks (Verissimo *et al.*, 1990), and the presence of certain nutritional sources. These may include the material of the system itself, scale, sediments and non-*Legionellaceae* microorganisms (Vickers *et al.*, 1987; Anon, 1991; Rogers *et al.*, 1991; Surman *et al.*, 1995). The presence of other microorganisms in the system is important. *L. pneumophila* may be associated with protozoa, cyanobacteria, algae and other bacteria, which enhance its survival and growth (Tison *et al.*, 1980; Fliermans *et al.*, 1981; Pope *et al.*, 1982; Wadowsky *et al.*, 1985; Grimes, 1991). Biofilms in man-made constructions provide ecological niches well-suited to *L. pneumophila*. Warm water, below 60°C, is significantly more likely to be infected with these bacteria (Plouffe *et al.*, 1983; Vickers *et al.*, 1987) and thus, in the built environment, communal air conditioning systems and cooling towers are particular sources of infection (Broadbent *et al.*, 1991; Grabow *et al.*, 1991). Fifty four percent of cooling towers examined in England and Wales have been found to be contaminated with *Legionella* (Colbourne & Trew, 1986).

The design of the water distribution system in a building can influence the likelihood of *Legionella* colonisation and survival. The use of polymeric materials to replace traditional metallic plumbing materials has been on the increase for many years. Organic compounds which leach from the surfaces of these components provide nutrients for the microorganisms which colonise them

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(Ashworth & Colbourne, 1987). *L. pneumophila* grows on rubber sealing washers and gaskets within hot water systems (Dennis, 1993). Of the various materials used in plumbing systems, copper has been found to be the most resistant to biofilm formation, whilst ethylene-propylene and latex are the most susceptible (Rogers *et al.*, 1991). Hence the choice of constructional materials can be critical for the well-being of the building and the health of its inhabitants.

The physical presence of a biofilm can also result in health hazards. For example, Pearson and Brown (1990) report the production of substantial quantities of methane gas in a tunnel forming part of an aqueduct system. The methane entered through leakages in the tunnel wall and was trapped and concentrated in the biofilm (containing heterotrophic and methane-oxidising bacteria). Physical removal of the biofilm was necessary.

FUNGAL PROBLEMS

Discoloration of building materials is often thought to be primarily due to fungi, since they can be highly pigmented and their growth is obvious to the naked eye, but it should be noted that algal and bacterial biofilms can also cause superficial red, orange, brown, green and black staining.

Filamentous fungi are the most important deteriogenic microorganisms for wooden structures. They not only produce enzymes which destroy the components of the wood, but can also permeate the structure because of their filamentous form. Yeasts have been found to be associated with wood decay (Jimenez *et al.*, 1991), but the major damage is produced by filamentous fungi and includes such infections as dry rot, caused by a species of fungus (*Serpula lachrymans*) which can grow well in dry conditions, as well as the more common brown and white rots, caused by cellulolytic fungi such as *Lentinus lepideus* and ligninolytic fungi, such as *Trametes versicolor*, respectively. The type of damage depends on the genera of fungi present and their activities, but the extent of the damage varies with the type of wood. Soft woods, such as pine, are generally much more susceptible than hard woods like mahogany and heartwood is almost always more resistant than sapwood (Highley, 1995).

The brown rot fungi are the most important group associated with deterioration of in-service timber. These fungi degrade cellulose and hemicellulose without affecting the lignin component of the wood and cause rapid depolymerization and loss of strength with relatively little weight loss (Green & Highley, 1997). The mechanisms of colonisation and degradation are still not well-defined, but various cations play an important role in these processes (Jellison *et al.*, 1997) and so, as in the case of materials such as concrete, non-destructive techniques of assay such as electron paramagnetic resonance and synchrotron X-ray fluorescence can be used to advantage (Illman & Bajt, 1997).

There has been relatively little work on the deterioration of stone, concrete and cement by fungi, since traditionally the sulfur-oxidizing bacteria have been deemed to be most important (Cragnolino & Tuovinen, 1984). However, Resende *et al.* (1996) reported the production of acids by several filamentous fungi isolated from stone buildings in Brazil and McCormack *et al.* (1996) presented evidence for the acid attack of the fungus *Aspergillus glaucus* on concrete. Gu *et al.* (1998) demonstrated weight loss and calcium release from concrete exposed to a *Fusarium* isolate and were able to demonstrate the penetration of the hyphae into the concrete structure, using SEM. In a review of stone deterioration by fungi, May *et al.* (1993) discussed the involvement of bacteria and, to some extent, algae. Fungi produce a variety of inorganic and organic acids, which can demineralise various stone substrates (Griffin *et al.*, 1991). The filamentous form of the microorganisms enables them to penetrate the weakened structure (Koestler *et al.*, 1985), especially when extra nutrients, in the form of dirt or algal and bacterial biofilms, are present (Gómez-Alarcón *et al.*, 1994).

Fungal growth on plasterboard has been reported to be a significant health risk because of the production of mycotoxins (Räty *et al.*, 1994) and it is well known that sealants used in bathrooms are extremely susceptible to fungal growth. Moriyama *et al.* (1992) isolated 34 different genera of fungi from surfaces in Japanese bathrooms.

One area in which fungi have relatively little involvement is in corrosion of metal, which is more frequently attacked by bacteria. The best documented cases of fungal biocorrosion are those caused by *Hormoconis resinae*. This filamentous fungus degrades many hydrocarbons, producing organic acids which corrode fuel storage tanks (Videla, 1986). The importance of biofilm formation by this organism in the corrosion of aircraft fuel tanks made of aluminium was demonstrated by Salvarezza and Videla (1986) using SEM. After removal of the biofilm, the outline of fungal hyphae was seen, etched on the metal surface by localised acidic fungal metabolites. In addition to metal, the fungus also has the ability to degrade protective coatings based on hydrocarbons, such as the synthetic rubber Buna-N (Miller *et al.*, 1964). This polymer has been used to line fuel storage tanks and fungal attack exposes the underlying material to the aggressive attack of other microorganisms, or of chemical species.

The activity of fungal biofilms on plastics, particularly polyurethanes, has been investigated by a number of workers (Pathirana & Seal, 1982; Wales & Sagar, 1985; Bentham *et al.*, 1988; El-Sayed *et al.*, 1996). Fungal enzymes are able to break down the polyurethanes or metabolise the plasticizers in various polymers (Berk *et al.*, 1957), resulting in embrittlement and loss of strength. This is very significant in polymeric varnishes, where fungal action causes increased permeability and renders the coating ineffective as a protective layer (Bravery, 1988). On the whole, however, plastics are resistant to microbial attack and the major problems of microbial growth are aesthetic, *i.e.* discoloration of the surface, and, where internal structures such as plastic bathroom fittings are involved, health hazards. Biofilms can harbour pathogenic and toxigenic fungi such as *Aspergillus flavus*, as well as non-pathogenic but allergenic fungal (and actinomycete) spores. These may be responsible, at least partially, for the so-called sick building syndrome (Räty *et al.*, 1994), which causes the loss of many working days per year in commerce.

Such biofilms occur not only in bathrooms, but also on wall and ceiling materials in water-damaged rooms (Andersson *et al.*, 1997), where they can lead to debilitating respiratory problems in the inhabitants of the building. Grant *et al.* (1989) studied the moisture requirements for fungal growth in houses and showed that the lowest water activity (Aw) allowing growth on malt agar of *Aspergillus* and *Penicillium* species commonly found in buildings was 0.76–0.79 at 20°–25°C. Reducing the temperature to 12°C increased this minimum to 0.87, indicating that high humidity need not lead to microbial problems at low temperatures. On woodchip wallpaper, at 25°C, minimum Aw values for fungal growth were higher (0.84–0.97), but these were reduced to 0.79–0.89 on paper covered with a water-based paint. The authors recommended that susceptible surfaces should be kept at Aw values of below 0.8, which can be achieved by various conditions of air temperature and relative humidity. Some of the wide variety of fungi implicated in the deterioration of building materials are listed in Table III.

PHOTOTROPHIC MICROORGANISMS

Algae have an important role in the disfigurement of buildings. They are particularly prevalent in shaded areas of high humidity, such as rural environments or more wooded urban areas. Wee and Lee (1980) found that the filamentous green alga *Trentepohlia odorata* was the most

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TABLE III Some fungi involved in deterioration of constructional materials

Material	Fungal types	References
Concrete and stone	*Alternaria, Aspergillus, Aureobasidium, Botrytis, Candida, Cladosporium, Curvularia, Exophiala, Fusarium, Mucor, Paecilomyces, Penicillium, Phoma, Sporobolomyces, Trichoderma, Verticillium*	Gu *et al.*, 1998; Hirsch *et al.*, 1995; Leznicka *et al.*, 1991; Lim *et al.*, 1989; Line, 1997; May *et al.*, 1993; McCormack *et al.*, 1996; Räty *et al.*, 1994
Metal	*Aspergillus, H. resinae, Penicillium, Trichoderma*	Salvarezza & Videla, 1986; Videla, 1986
Painted surfaces	*Alternaria, Aspergillus, Aureobasidium, Cephalosporium; Cladosporium, Curvularia, Exophiala, Fusarium, Geomyces, Mucor; Penicillium, Stachybotrys, Stemphyllium, Trametes, Trichoderma, Ulocladium, Verticillium*	Bravery, 1988; O'Neil, 1988; Stranger-Johannessen, 1988
Plastics and rubbers	*Aspergillus, Chaetomium, Cladosporium, Cryptococcus, Fusarium, Hormoconis, Penicillium, Rhizopus, Stemphylium, Trichoderma*	Bentham *et al.*, 1988; Miller *et al.*, 1964; Pathirana & Seal, 1982; Zyska, 1988
Wood	*Alternaria, Aspergillus, Aureobasidium, Candida; Ceratocystis, Ceratocystiopsis, Cladosporium, Coriolus, Cryptococcus, Gloeophyllum, Gliocladium, Hansenula, Lentinus, Penicillium, Phanerochaete, Phialophora, Phoma, Pleurotus, Postia, Rhodotorula, Serpula, Trichoderma, Verticillium*	Blanchette *et al.*, 1990; Clausen, 1997; Dutkiewicz *et al.*, 1992

common coloniser of high-rise buildings in Singapore. This organism typically produces streaks of orange growth on exposed surfaces, the coloration being due to oil droplets stored within the algal cells. However, neither Joshi and Mukundan (1997) nor Gaylarde and Gaylarde (1998b) found *Trentepohlia* to be a major coloniser of painted buildings in India and Brazil, respectively. As algae require little nutrient, being able to produce cell structural materials from CO_2, inorganic minerals and light, they are ready colonisers of clean surfaces on new buildings. Oil-based paints and certain paint pigments, however, are inhibitory (Stranger-Johannessen, 1988) and biofilm formation on these materials is considerably delayed, as it is on new concrete, where the pH (approximately 12) is too high for microbial growth. After exposure to leaching by rain containing dissolved CO_2, however, the material becomes conditioned and algal and fungal biofilms readily form.

The cyanobacteria are often included in the algae, but Stanier *et al.* (1978) proposed that they should be classified under the rules of the Bacteriological Code. These organisms normally show a distribution similar to algae, but are more resistant to drought and extreme temperatures. Grant (1982) considered that cyanobacteria are

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of greater ecological importance as pioneer organisms than any other bacterial class. His review, although now slightly dated, should be consulted by anyone interested in terrestrial fouling by algae and cyanobacteria. Danin and Caneva (1990), working in the relatively dry environment of Jerusalem, suggested that cyanobacteria induce weathering of stone and rock in the following steps: 1) attachment of cells in small fissures; 2) growth within the fissure; 3) water uptake and expansion of the cell mass, thus exerting pressure within the structure; 4) precipitation of carbonates and oxalates around the cells; 5) opening of the fissure due to these internal pressures; 6) entry of dust, pollen grains, *etc.*; 7) partial death of cyanobacterial cells and establishment of bacteria, fungi and small animals such as mites within the fissure; 8) increasing internal pressure on the superficial layer of the structure leading eventually to its detachment (spalling).

Ortega-Cal *et al.* (1991) isolated a wide range of algae and cyanobacteria from deteriorated stone monuments in Spain and, using SEM, showed the penetration of the cells into the upper stone layers. They also applied Koch's postulates, demonstrating that the organisms isolated in nature were able to cause deterioration of the materials in laboratory experiments when they were inoculated on to the surfaces of stone test pieces. Gómez-Alarcón *et al.* (1994) demonstrated in the laboratory that fungi isolated from a weathered sandstone church were able to colonise sandstone cubes in the presence of algal biomass (*Monoraphidium braunii*), and that, in the presence of the alga, different types of deteriogenic fungal products were formed. Further work is needed to demonstrate the role of these various microorganisms, and their interactions, in the deterioration of buildings.

Cyanobacteria have been found to be the dominant photosynthetic microorganisms on painted surfaces in India (Joshi & Mukundan, 1997), Brazil and Mexico (Gaylarde & Gaylarde, 1998b). Filamentous cyanobacteria were most common in India; *Plectonema* was found in 60% of the samples, with *Lyngbya* and *Nostoc* being the next most abundant groups, while the only green algae identified from acrylic painted surfaces were the single-celled coccoid algae, *Trebouxia* and *Chlorella*. In Brazil and Mexico, considerably more coccoid and colonial cyanobacteria were found (Gaylarde & Gaylarde, 1998b), indicating either a basic difference in populations, or an important distinction in detection and identification techniques. Gaylarde and Gaylarde (1998a) maintain that their methods are more capable of detecting coccoid and colonial cyanobacteria than the traditional techniques. Table IV shows some of the phototrophs which have been isolated from disfigured buildings, or have been shown to be capable of biodeterioration.

Cyanobacteria can be distinguished from algae by microscopic and microbiological culture analyses, and by the use of gene probes and other DNA analysis methods (Rippka *et al.*, 1979; Holt *et al.*, 1994). The differentiation of the two groups is important, since methods of control may also differ. Algae and cyanobacteria are major deteriogens of light-exposed surfaces in buildings, their negative effects being aesthetic (soiling) and retention of water, thus predisposing the surface to colonisation by potentially more damaging organisms such as fungi, mosses and higher plants (Grant, 1982; Gómez-Alarcón *et al.*, 1994). Hence the treatment and control of these biofilms is important.

CONTROL OF BIODETERIOGENIC BIOFLIMS

Biodeterioration may be prevented by using materials resistant to microbial attack, such as stainless steel or some plastics, by altering the environmental conditions to reduce microbial growth (*e.g.* lowering humidity, altering pH), by rigorous cleanliness, or by applying a protective coating, such as paint or varnish, to the material. The use of biocides is frequently adopted (May *et al.*, 1993), since the first two options are often

TABLE IV Photosynthetic microorganisms which can cause biodeterioration of building materials

Material	Algae	Photosynthetic bacteria	References
Concrete and stone	*Apatococcus, Bracteacoccus, Chlamydomonas, Chlorella, Chlorococcum, Chlorokybus, Chlorosarcina, Clorosarcinopsis, Ecdysichlamys, Haematococcus, Friedmannia, Klebsormidium, Leptosiroid, Muriella, Neochloris, Oedogonium, Palmellococcus, Pseudodendoclonium, Scenedesmus, Stichococcus, Stigeoclonium, Tetracystis, Trebouxia, Trentepohlia,* Bacilliariophyceae, Chrysophyceae, Eustigmatophyceae, Rhodophyceae, Xanthophyceae	*Aphanocapsa, Aphanothece, Calothrix, Chaemisiphon, Chroococcus, Gloeocapsa, Hyella, Microcoleus, Myxosarcina, Nostoc, Phormidium, Plectonema, Pleurocapsa, Schizothrix, Scytonema, Synechocystis, Tolypothrix*	Danin & Caneva, 1990; Gómez-Alcarcón *et al.*, 1994; Grant, 1982; Grant *et al.*, 1989; Ortega-Cal *et al.*, 1991; Rippka *et al.*, 1979; Schlichting, 1975
Metal	Hydrogenase-positive Chlorophyta	*Nostoc, Anabaena,* purple bacteria	Stanier *et al.*, 1959; Schlichting, 1975
Painted surfaces	*Chlorella, Chlorococcum, Eustigmatus, Trebouxia, Trentepohlia, Ulothrix,* diatoms	*Chroococcus, Gloeocapsa, Gloeothece, Lyngbya, Nostoc, Oscillatoria, Plectonema, Scytonema, Synechococcus, Synechocystis*	Gaylarde & Gaylarde, 1998b; Grant, 1982; Grant *et al.*, 1989; Joshi & Mukundan, 1997; Jozsa *et al.*, 1995; Morton, 1986; Wee, 1988; 1980
Plastic	*Stichococcus*		Favali *et al.*, 1978

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impossible or too expensive and the last, when coating is possible, does not give complete protection since paints and varnishes are, themselves, subject to microbial attack (Gillatt & Tracey, 1987; Bravery, 1988; Ford *et al.*, 1995).

Biocides are toxic chemicals which can affect both microscopic and higher organisms, including humans. They must be carefully selected for appropriate activity and handled with attention to safety regulations. The most important parameters to be considered when choosing a biocide for use in constructional materials are a) the range of microorganisms to be controlled, b) the compatibility of the chemical with the materials to be protected, c) the toxicology of the biocide and requirements for its safe disposal and d) the cost of the product. The mode of application must also be carefully chosen, whether the chemical is to be applied as a wash, as is generally the case with hypochlorite, or in a vehicle which will fix it to the surface (*e.g.* in a paint). The limitations of biocides used in the USA for the preservation of stone buildings are discussed by Schnabel (1991) and more general considerations on the use of biocides are to be found in Gaylarde (1995).

MODE OF ACTION OF BIOCIDES

Because of the wide range of materials utilised in the constructional industry and the various types of microorganisms involved in their deterioration, it is necessary to have recourse to a broad range of biocides. These products can be roughly classified into four groups, according to their chemical structure and mode of antimicrobial action (Table V).

The type of damage produced by the biocide on the microbial cells determines its final effect, that is, microbiostatic or microbiocidal. Microbiostatic agents react reversibly with cell components such

TABLE V Characteristics of biocide groups

Group	Characteristics	Examples
Oxidising agents	Wide range of activity, can be cheap	Halogens, ozone, organic peroxides
Protein denaturants and enzyme inactivators	Potential for specificity, but may be too ecotoxic	Aldehydes, phenolics, heavy metals, isothiazolones
Surfactive agents	Cleansing and dispersant activity, generally less adverse environmental effects	Quaternary ammonium or phosphonium compounds, household soaps
Inhibitors of sterol synthesis	Fungicidal and algicidal only	Triazoles, imidazoles

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as nucleic acids and proteins, whilst microbicidal compounds cause irreversible damage which leads to lysis of the cells or to coagulation of the cytoplasm (Denyer, 1996). However, the inhibitory or cidal effect of the biocide is determined not only by its chemical nature, but also by the concentration used. A biocide may be inhibitory at low and cidal at high concentrations and thus it is extremely important to use the correct dose. In addition to failure to reduce cell numbers, inappropriately low concentrations of the product may lead to the development of biocide-resistant populations of microorganisms (Larson & Ventullo, 1991), resulting in the need to change to a different formulation.

For the control of microbial growth on constructional materials, the optimum method of biocide use is to include the compound in the material itself, which can be done in the case of PVC, for example (Bessems, 1996), or to incorporate it into a coating (Gillatt & Tracey, 1987). In this way, high levels of biocide may be used in the material or coating layer, thus providing good control, while only low concentrations, leaching from the surface, reach the environment. The recent trend for paints and other surface coatings to be water-, rather than solvent- based (Springle, 1996) has resulted in these products becoming more susceptible to microbial growth. Hence more effective biocide formulations are needed, whilst retaining environmental acceptability.

ROLE OF SURFACE COATINGS AND THE EFFECTS OF MICROORGANISMS

Paints and other surface coatings confer two main properties on a structure, protection and decoration. Both of these properties may be prejudiced by microbial growth. On exterior surfaces, rain and wind deposit minerals, small fragments of plant, arthropod and lichen origin, as well as spores and microbial cells. The development of these deposits depends on the nature of the paint and the environmental conditions. On gloss paint, observations suggest that the major colonisers are fungi and bacteria, whilst on water-based and acrylic paints, complex biofilms containing algae and cyanobacteria develop, although the macroscopic appearance may suggest merely fungal growth. Filamentous algae, actinomycetes and fungi can alter the painted surface by penetrating the film and attacking, or exposing to attack, the underlying structure. Microbial growth is influenced by the nature of the underlying substrate. For example, the products of lignocellulose photodegradation leaching from beneath a painted wooden surface can be used as nutrients by *Aureobasidium pullulans* on that surface (Shoeman & Dickinson, 1997). Penetration of the film by microbial growth from beneath can also occur when the material has been inadequately prepared before application of the paint. This can be prevented, or at least delayed, by treating the

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surface with biocide and allowing it to dry completely prior to painting.

PREVENTING OR TREATING MICROBIAL GROWTH ON BUILDINGS

As already mentioned, biocides are toxic chemicals. Their use should be the last option considered. A well-designed construction will require minimal use of biocides. It will avoid difficult-to-clean areas, will not use rough textured surfaces and will ensure that the structure stays as dry as possible by incorporating damp-proofing materials and using naturally draining (pitched) roofs. Internal spaces will be ensured adequate air circulation and materials which are particularly prone to microbial attack, such as wood, will be protected by suitable surface coatings. Application of water resistant coatings is a good strategy, but only when the material is well prepared beforehand. Applying such a coating over damp, or already infected, materials merely makes the problem worse, as the water necessary for microbial growth is prevented from escaping. However, the new "microporous" coatings have been designed to allow evaporation of water from the substrate whilst preventing the ingress of moisture from the environment. In practice, buildings are rarely designed with the avoidance of biodeterioration as the main objective, and aesthetic considerations may take precedence. Hence, the need for biocides will continue.

PROPERTIES REQUIRED OF A BIOCIDE

From the user's point of view a biocide should have the following general properties: 1) effective against the problem-causing microorganisms; 2) simple and safe to use; 3) no adverse effects on the material to be protected/treated; 4) inexpensive (low cost/benefit ratio); 5) capable of providing protection over the required time scale.

In the case of a commercial user, the last property can be determined prior to bulk purchase by carrying out sensitivity tests on organisms isolated from the appropriate environment. Morton (1986) reviews methods for testing algicide activity and Gaylarde (1995) considers the advantages and disadvantages of various biocide testing methods. Field, rather than laboratory tests give the most reliable results, but are time-consuming. An example of such testing is given by Bolívar and Sánchez-Castillo (1995), who reported the identification of 35 species of cyanobacteria and 45 species of algae from a marble fountain in the Alhambra, Granada, Spain, and demonstrated the effect of treatment with a quaternary ammonium biocide on the populations. The biocide was reasonably effective, the most resistant microorganisms being *Chaemisiphon*, *Chlorosarcinopsis* and *Tetracystis*. Lim *et al.* (1989) tested eight different fungicide-containing paints for their ability to control fungal growth on walls in Singapore. Most of the test surfaces were recolonised within six months. Laboratory testing of individual biocides indicated that copper 8-hydroxyquinoline was the most effective against the four fungal species isolated from the walls.

Biocide manufacturers have to meet the following additional requirements: 1) long shelf-life, 2) low ecotoxicity, 3) biodegradability. The last two have become increasingly important recently as governments have become more concerned with environmental problems arising from the unregulated disposal of biocides (Halleux, 1990).

ENVIRONMENTAL PROBLEMS ASSOCIATED WITH BIOCIDES

Enhanced public perception of environmental matters and increasingly restrictive legislation (Halleux, 1990) have led to changes in the development and introduction of new biocides. The need to conform to the new legislation has substantially increased the cost of bringing new products to the market, so that few companies consider that the development of new products is worthwhile as long as older, cheaper products are still allowed to be sold. Although some of the most toxic biocides have been withdrawn from the market, several products which may be carcinogenic in man (*e.g.* formaldehyde) and others that are persistent in the environment (*e.g.* copper compounds) or yield persistent secondary products (*e.g.* chlorine) remain in use. Few new products can compete in price with these established agents and there is a need to ensure that the climate for research and development is favourable for the introduction of superior novel agents, especially products with lower environmental impact.

The European Biocidal Products Directive, to be used in the control of biocides in the countries of the European Union (Murray-Smith, 1996), amongst other things, obliges biocide manufacturers to carry out extensive toxicological and ecotoxicity testing on their products and to provide data on human exposure risks, environmental destiny and efficiency of the biocide, in addition to the overall risk of use. Risk is defined as the multiple of exposure and hazard, where exposure is equal to the release rate into the environment multiplied by the persistence of the biocide in that environment, and hazard is the toxic effect on the environment. Their ecotoxicity has already led to some of the old, established products being discontinued and the modern generation of biocidal products is largely composed of mixtures of less toxic compounds.

NEW BIOCIDES FOR USE IN CONSTRUCTIONAL MATERIALS

The development of a new biocidal product for use in the industry requires a considerable amount of investment in terms of time and money. Thus the more recent developments have made use of chemicals which are already available and which can be modified so as to confer upon them more desirable properties (Gaylarde, 1995). Such properties can include higher cidal activity, longer lasting action, more ready biodegradability, increased spectrum of activity, and solubility in hydrophobic systems. Modifications may include mixing two known biocides, converting a biocide into a slow-release (longer-acting) product, and complexing with a non-toxic compound to increase biodegradability. The size of the market is such that research and development of biocidal products will continue in spite of the high costs.

CONCLUSIONS

Both economic and health problems are caused by microbial growth on constructional materials. A whole range of microorganisms, apart from viruses, is involved and so treatment by conventional antimicrobial means is difficult. It is best achieved by environmental control, in particular by manipulating the local humidity and temperature. Surface coatings can also be used to protect particularly susceptible materials like wood, but the coatings themselves can also be attacked by microorganisms. Biocides may be incorporated into these coatings or can be used directly on the surface of the material and this can be effective for a time (relatively short in relation to the expected useful life of a building). The prompt removal of the beginnings of microbial growth, or alteration of conditions to retard biofilm formation, especially reduction of humidity, is the recommended method to reduce the problems of the durability of materials associated with microbial biofilms. Engineers and architects can contribute by applying an awareness of the requirements of deteriogenic microorganisms to the design of constructions, ensuring that susceptible materials are not used in areas favourable for biofilm formation (*i.e.* humid environments), or are protected by the application of appropriate surface coatings or incorporation of biocides. Where impermeable coatings are used, however, it is important to note that any ingress of moisture

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behind the coating will produce immense problems and such eventualities must be borne in mind when designing and building a structure. An increased interaction between architects, engineers and microbiologists is essential to reduce the incidence of biodeterioration of buildings and constructional materials.

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