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Dry Rot and Other Wood-Destroying Fungi: Their Occurrence, Biology, Pathology and Control

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Key Words

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Abstract

Microbial biodeterioration of building materials and their contents in both modern and historic buildings is attributed to changes in the building environment. The main environmental parameters favouring the decay of materials and contents are water, humidity, temperature and lack of ventilation. The damage caused by biological agents is very familiar, as is the destruction arising from attempts to eradicate them by the use of chemicals, which not only are a cause for concern to health authorities, wildlife interests and environmentalists, but also lead to the development of resistance in the target organisms. Correct identification of the deteriogen material is important as not all deteriogens are equally destructive. Some rots and insects are present in timber when it is cut, or are acquired in storage, and these may be present in heartwood or sapwood. Fungal or insect infestation may also be dead or dormant, representing conditions in the past. Environmental control and preventative maintenance are preferable to chemical means. Buildings work as spatial environmental systems and must be understood as a whole. They separate the occupants from the external environment, thus creating a different internal environment for the occupants. The causes of decay in materials and structures are influenced by the internal building environment which has a varied microclimate depending upon structural aspects of the building. Preventative maintenance should in most cases forestall the need for major interventions, and it is beyond doubt that it reduces the cost of the conservation of buildings. Since the internal environment of a building is the product of a number of influences, it is advisable to study in detail the ecological factors such as temperature, humidity at the micro-environment levels and the response and performance of the building before undertaking an intervention involving any building. Continuous monitoring of the environment in buildings ensures the long-term health of both building materials and overall structures.

Introduction

The study of fungi is known as mycology (Gr. mykes, mushroom or fungus; lugos, discourse). The world's ecosystems are sustained and kept in balance by a rich variety of fungi. It is estimated that there are about 1.5 million species of fungi in total, of which around 70,000 (5%) have been scientifically described.

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'Building mycology' is defined as that branch of mycology dealing with the study of fungi in and around the building environment [1, 2]. This has both direct and indirect effects on the health of building materials, structures and occupants. The commonest fungi which cause damage to building structures are the dry rot fungus *(Serpula lacrymans),* cellar rot fungus *(Coniphora puteana)* and wet rot fungi *(Antrodia vaillantii, Antrodia xantha, Asterostroma* spp., *Donkioporia expansa, Paxillus panuoides, Phellinus contiguus, Tyromyces placentus).* Inhalation of airborne micro-organisms and their metabolites may cause a range of respiratory symptoms depending on the species, the circumstances of exposure and immunological reactivity of the subject [3, 4].

Today, the dry rot fungus is generally known as *S. lacrymans* (Schumach. ex Fr.) Gray in the UK, but also as *S. lacrymans* (Wulf.: Fr.) Schroet, and was previously known as *Merulius lacrymans.* It is the most important timber decay fungus in buildings in Northern and Central Europe and is also of serious concern in Japan and Australia [5]. Not only does the fungus bring about the dramatic decay of timber, but it is also able to spread through a building from one timber location to another across non-nutritional surfaces. The fungus has a serious impact on the UK housing stock and also causes concern in the conservation and preservation of buildings of historic and architectural merit [6]. Timber decay investigation and eradication is therefore big business in Britain. *S. lacrymans* is the most deadly form of fungal attack in building timbers, and buildings of traditional construction in this country are particularly vulnerable to this form of decay [7].

The vast majority of properties in the UK contain a significant amount of wood, ranging in use from structural timbers such as joists to finishings such as room skirtings. It has to be remembered that detecting the type and extent of any fungal decay and taking remedial measures could entail the loss of decorative finishes, extensive exposures and damage to the fabric of the building and consequently may be very expensive. It is not surprising to learn that the estimated annual expenditure on timber preservation works in Britain is over £ 400 million [5].

Building surveyors in particular have to look out for this destructive fungus when they are appraising properties. They have to consider the factors that may indicate the likely cause of internal decay whether past, present or future [5]. The technical and legal implications associated with *S. lacrymans* should not be underestimated. Building surveyors must alert their clients to the risk of timber decay when carrying out either a 'Structural/Building Survey' or a 'House Buyer's Report and Valuation'. Correct and early diagnosis of this form of infection in a building is essential if a later widespread outbreak is to be avoided and proper repair is to be achieved. It also minimises the chance of carrying out inadequate or excessive treatment where *S. lacrymans* is mistaken for wet rot or vice versa [5]. In addition, early correct diagnosis will help the surveyor avoid a negligence claim in the event of a future outbreak of the rot.

The dry rot fungus has occupied a specialised ecological niche in buildings in Europe because of its unique biology and is only known to occur in the wild in the Himalayas [8–13]. The ravages of the dry rot fungus are familiar, as is the destruction caused by attempts to eradicate it, particularly those involving the use of chemicals. Remedial chemical timber treatment can cause damage to the health of building occupants and is a cause for concern to environmental health authorities.

It is the lack of understanding of the biology and ecology of the dry rot fungus that has led to the use of radical treatment and consequent considerable damage to building fabric. The author has led several Himalayan expeditions for the search for wild dry rot in the Himalayas with a view to gathering information on its biology, ecology and genetics in the wild. It is hoped that the fundamental scientific knowledge gained through multidisciplinary research will enable a better understanding of the fungus and allow the development of safer, more effective and ecological techniques and strategies for its control [9–18].

As an organic material, timber is susceptible to biodeterioration from many micro-organisms [14] and insects. In addition, there are non-biological agents which aid decay including ultraviolet light and chemicals and, of course, mechanical wear and tear. The fungal infection of timber is not only unsightly and potentially hazardous to human health, it can also adversely affect the structural integrity of the timbers of a building and disrupt its use.

History of the Search for Dry Rot in the Himalayas

Recorded Outbreaks of S. lacrymans (M. lacrymans) *in India*

Bagchee [8] searched the forests of the western Himalayas from 1929 to 1952 and found fruiting bodies of the true dry rot fungus *S. lacrymans* on stumps, fallen logs and in buildings (some of them partially destroyed by fire). *S. lacrymans* was also observed on stone walls at Jandrighat, Dalhousie (7,000–8,000 ft. a.s.l.) and on logs in the forest of Gulmarg, Jammu and Kashmir (1,200–1,300 ft. a.s.l.) [19]. The majority of these findings in the forests were made on the stumps and logs of *Picea smithiana, Abies pindrow* and *Pinus griffithii* and in the buildings on *Picea morinda.* The various developmental stages, for example fan-shaped mycelium strands and young to mature sporophores were all recorded in the wild [8]. The fruit bodies of the true dry rot fungus developed in nature under dim light conditions on the lower surface of logs in contact with soil or on the cut surfaces. It was assumed from this that the species in the Himalayas lives in nature, contrary to northern Europe, and from there is introduced into houses either as spores or as mycelium in attacked wood.

A number of other wood-destroying fungi were found with *S. lacrymans,* e.g. *Fomitopsis rosea, Poria carbonia, Gloeophyllum subferruginea* and sometimes also *Trichaptum abietinum.*

Recent Expeditions to the Himalayas

The author, under the auspices of Oscar Faber Heritage Conservation, UK, has organised several expeditions to the Himalayas for a multi-national team of biologists to study wood decay fungi in the wild. The team included Dr. Nia White and Dr. Alan Score from the University of Abertay, Dundee, UK; Dr. Jorgen Bech-Anderson and Dr. Steen Elborne from Hussvamp Laboratoriet, Denmark; Dr. Fred Goldie from the UK; Dr. Bryan Walker of Oscar Faber Applied Research, UK, and Dr. Sujan Singh, who has more than 30 years experience of forest pathology throughout India.

During the 1992 expedition, the herbarium at the Forest Research Institute in Dehra Dun, U.P., India was visited, and the dried material of *S. lacrymans (M. lacrymans)* was studied with the kind help of Dr. M. D. Mahrotra, head of the Forest Mycological Laboratory.

Over a period of 23 years, the true dry rot fungus had been found in the area between Simla and Manadi in approximately 13 well-documented instances. However, since 1954 no finds have been published from Dehra Dun. According to Dr. Sujan Singh (former Head of Forest Pathology) this absence of finds may be explained by the fact that in the early fifties, the Forest Laboratory at Dehra Dun changed its research emphasis from wood-decaying fungi to forest pathology.

The original search for the true dry rot fungus had been made in the Western Himalayas. When a team revisited Narkanda (Western Himalayas) at the end of August 1993, the soil temperature had dropped to approximately 18 C, and after a thorough search of the stumps and logs previously investigated, a fruit body of the true dry rot fungus *S. lacrymans* was found. It was situated on the stump of a tree that had fallen 15 years earlier. It seems that the team may have discovered the original home of the true dry rot fungus.

What connection is there between the true dry rot fungus found in nature in the Himalayas and the one that haunts us in Europe, Asia, America and Australia? Since the true dry rot fungus in nature is found from Kashmir across Himachal Pradesh to Uttar Pradesh, a stretch of several thousand kilometres, it is likely that the fungus was spread across the area by the British and their belongings. How, though, was it able to spread to other continents, and why is it, for example, more common in Holland, Sweden, Germany and Denmark than in its homeland? In order to answer these questions, the different physical, chemical and meteorological factors both in Himalayas and in Northern Europe have been analysed.

Identification of the True Dry Rot Fungus from the Himalayas

The fruit body from Narkanda measured approximately 100×60 mm across and was 6 mm thick. It was easily detachable from the substrate. The trama was gelatinised, and greenish, skeletal hyphae were found parallel to the substrate, together with L-shaped, skeletoid hyphae. The skeletals turned dark blue in Cotton blue. The spores measured $9.0–10.5 \times 5.0–5.5$ μm and were yellowish brown. All the characteristics corresponded to what is known from finds in Europe, Japan and Australia.

Dispersal of the True Dry Rot Fungus from the Himalayas

In the period 1850–1920, large quantities of timber were exported from the Himalayas, for example from Narkanda, to England, and the fungal mycelium and spores could easily have been dispersed in this manner [Sujan Singh, pers. comm.] The term 'dry rot' appears to have first been used around 1765, and towards the end of the 18th century, decay of timber in buildings had become a serious problem [20]. In 1784, dry rot became so serious that the Royal Society of Arts offered a gold medal to anyone who could find a cure for it. This prize was won by a Mr. Batson.

Samuel Pepys reported in 1684 and 1686 that the rot in ships was an even more serious problem than that of rot in buildings. In 1915, Ambrose Bowden of the Navy Office published that dry rot was due to 'vegetation of the sap excited by the action of heat'. In his presidential address to the Essex field club on 'dry rot in ships' in 1937, Ramsbottom stated that 'foreign timbers were often floated down rivers and then immediately loaded into the confined holds of timber ships, an ideal arrangement for fungal infection; the logs were sometimes covered with fruit bodies (of fungus) before they reached the dockyard'.

The species was first validly described in 1781 by Wulfen, based on a find from Austria. He named the fungus *Boletus lacrymans,* but it has since been placed in many different genera. Today, in recognition, we call it *S. lacrymans* (Wulf.: Fr.) Schroet although in the UK it is commonly named *S. lacrymans* (Schumach. ex Fr.) Gray. Since the true dry rot fungus was known in England and Austria before the export of timber from India began, introduction to Europe must have taken place in a different way, using an unknown carrier. Although a fruit body can produce several billion spores and the probability of wind dispersal is great, the spread into Europe seems more likely to have some human involvement. Today, the fungus is known worldwide, e.g. in Europe, Asia, Japan, Australia and the US. DNA analysis of the fruit body of the true dry rot fungus found in the Himalayas has been carried out at the University of Abertay, Dundee, by Palfreyman et al. [21] to compare its genetic makeup with isolates from different continents.

Sporophore Analysis

Sporophore analysis was carried out using energy-dispersive x-ray analysis.

Comparison of the constituents of fruiting bodies from Narkanda and Denmark revealed a high and almost equal content of potassium and phosphorus. In the fruiting body from Narkanda there was, furthermore, some magnesium and aluminium. Besides the fresh fruiting body from Narkanda, 6 specimens from the herbarium in Dehra Dun also showed a high potassium and phosphorus content, although there was no calcium in any of the fruiting bodies. High potassium and phosphorus content is normal for all living cells, including the fungi.

In strand mycelium from Wildflower Hall, India and Denmark, a high calcium content was found, but only a little phosphorus and potassium. It is possible that the two latter constituents are transferred to the spore-producing fruiting body from the strands under the production of calcium oxalate. Crystals from the strand mycelium in Denmark were shown to contain large amounts of calcium. An x-ray diffractometric analysis showed that the potassium of the fruiting bodies was not in the form of crystals either in Denmark or in India. Calcium in the strand mycelium, on the other hand, was found as crystals of calcium oxalate both in India and in Denmark.

The Biology of Wood-Rotting Fungi

There are several different kinds of wood decay and mould fungi found in buildings. The basidiomycetes which cause wet rots and dry rot are the most destructive. The commonest wood decay fungi found in European buildings include dry rot and a range of wet rot fungi. The following paragraphs refer to these in detail.

In Britain, the term 'dry rot' refers to a type of timber decay in buildings caused by the true dry rot fungus *S. lacrymans.* The dry rot fungus mostly attacks soft wood and often causes extensive damage. The term dry rot is rather misleading, as moist conditions are required to initiate the growth (a moisture content in timbers of about 20% or more), and optimum growth is maintained at about 30–40%. Spore germination requires a more precisely favourable microclimate at the wood surface. When established, the fungus has the ability to grow through plaster, brickwork and masonry and can extend to a distance of several metres from its food source to attack sound timber using specialised hyphal strands (rhizomorphs). Rhizomorphs are conducting strands formed by the mycelium, and they are able to transport nutrients and water. Rhizomorphs may be up to 6 mm in diameter and are relatively brittle when dry. These characteristics adapt well to the building environment and make dry rot one of the fungi which cause the rapidest decay as well as being probably the most difficult to eradicate.

Conditions of static dampness are particularly favourable to *S. lacrymans,* but, unlike wet rot fungi, it is also able to tolerate fluctuating conditions. Active growth is indicated by silky white sheets or cotton-wool-like cushions with patches of lemon yellow or lilac tinges where exposed to light, perhaps covered with tears or water drops in unventilated conditions. This exudation of water is the way the fungus responds to the relative humidity in the atmosphere and is the explanation for the Latin name 'lacrymans'. Mycelial strands are white to grey, but often become green in colour with age through development of superficial saprophytic mould growth.

Sporophores generally develop in response to stress, for example unfavourable conditions of temperature, humidity and lack of nutrients. Sporophores are tough, fleshy, pancake and bracket shaped, varying from a few centimetres to a metre or more across. The centre is yellow-ochre when young, darkening to rusty red when mature because of spore production. The fruiting body is covered with shallow pores or folds, and the margin is white and grey. The appearance of the fruiting body together with its distinctive 'mushroom' odour, may be

Table 1. Main characteristics of fungal decay of timber

Characteristic	Dry rot	Wet rot
Mycelium	Damp conditions: masses of tears on silky white surface, with bright lemon patches Drier conditions: thin skin of silver grey in colour, with deep lilac tinges	High humidity: yellow to brownish in colour
Decaying wood	Deep cuboidal cracking associated with differential drying shrinkage Reduction in weight Dull brown in colour Resinous smell gone	Cuboidal cracking on smaller scale Thin skin of sound wood Weight loss Localised infection
Strands (rhizomorphs)	3–6 mm in diameter Brittle when dry Off-white/dark grey in colour	Thinner than dry rot Flexible when dry Creamy white in colour
Sporophores (fruiting bodies)	Tough, fleshy pancake or bracket shaped, varying from a few centimetres to 1 m across Ridged centre: yellow-ochre when young, darkening to rusty red when mature Lilac/white edged Distinct mushroom smell	Not very common in buildings Musty smell rather than mushroom smell associated with an active growth of dry rot

the first indication of an outbreak of dry rot, as fungal growth in buildings is generally concealed.

Wood damaged by dry rot has a typical cuboidal cracking along and across the grain. When the wood is thoroughly rotted, it is light in weight, crumbles under the fingers, is a dull brown colour and has lost its fresh resinous smell. Dry rot is a type of brown rot, a term relating to the manner in which it destroys the cellulose but leaves the lignin largely unaltered, so that the wood acquires a distinctive brown colour, and the structural strength is almost entirely lost. The term 'dry rot' was originally given on the mistaken assumption that it was a chemical disorder which afflicted timber once it was felled and seasoned, i.e. dried. Today, the name dry rot is commonly assumed to derive from the fact that it describes the state of wood after attack by *S. lacrymans*. The rot was not thought to be associated with dampness so, in turn, timber decay caused by moisture was called 'wet rot'.

In northern European countries there are a number of other fungi occupying similar ecological niches to the *S. lacrymans* fungus that occurs in houses. These are *Serpula himantioides* (thin-fleshed dry rot fungus), *Leucogyrophana pinastri* (spiny dry rot fungus), *Leucogyrophana pulverulenta* (small dry rot fungus), *Leucogyrophana mollusca* (soft dry rot fungus) and *Leucogyrophana mollis* (membranous dry rot fungus).

There are 4 key characteristics that can be used in the identification of fungal growths: (1) mycelium, (2) appearance of decaying wood, (3) strands and (4) sporophores. Table 1 gives a comparison of these characteristics for dry rot with those of wet rot.

Associated Rots and Moulds

Wet Rot. This type of decay is caused by a number of Basidiomycetous fungi of which the most important are *C. puteana* (cerebella), 'Poria' fungi, *P. contiguus, D. expansa, Pleurotus ostreatus, Asterostroma* spp. and *P. panuoides.* Wet rot is also called white rot, as it destroys both cellulose and lignin, leaving the colour of the wood largely unaltered but producing a soft felty or spongy texture without cross cracks. Common white rots are *D. expansa, Asterostroma* spp., *P. ostreatus* and *P. contiguus* [22]. However, many common wet rots are brown rots, for example *C. puteana, Coniophora marmorata, P. panuoides* and *Dacrymyces stillatus.* The brown rots cause the wood to become darker in colour and to crack along and across the grain; when dry, very decayed wood will crumble to dust.

Cellar Rot Fungus. C. puteana and *C. marmorata* are the commonest cause of wet rot in buildings which have become soaked by water leakage, for example, soil moisture or plumbing leaks. The fungal spores are ubiquitous and germinate readily, thus, these fungi are likely to occur whenever suitable conditions arise. The hyphae are initially white, then yellow to brownish in colour, remaining off-white under impervious coverings. *C. puteana* forms rhizomorphs that are initially yellowish when young, later becoming brown to black at maturity. They never extend from the infected wood.

The sporophore rarely occurs in buildings and consists of an olive-green to brown fruit body with a paler margin, thin skin and warty surface. The *C. marmorata* fruit body is pinkish-brown and has a smooth to lumpy surface.

These fungi cause considerable shrinkage to wood, and cracking may occur, not unlike that caused by dry rot. The rotted wood is dark brown with dominant longitudinal cracks and infrequent cross grain cracks. Freshly colonised wood usually shows a yellow coloration.

Poria Fungi. These fungi generally attack softwood in buildings. They require a higher moisture content in the wood than that required by dry rot, but they are tolerant of occasional drying and are therefore normally associated with roof leaks.

This group includes *Amyloporia xantha, Fibroporia vaillantii* and *Poria placenta.* They are commonly called white pore fungi or mine fungi. *F. vaillantii* can cause extensive damage in buildings.

The mycelium of this group of fungi forms white or cream sheets or fern-like growths, which may discolour brown on contact with iron. The rhizomorphs may be up to 3 mm in diameter, seldom thicker than twine, white to cream in colour, remaining flexible when dry, and they do not extend from their foci of infection. The sporophore is rare in buildings; it is a white, irregular lumpy sheet 1.5–12 mm thick, covered with distinct pores, sometimes with strands emerging from its margins. Spore-bearing surfaces are white to pale yellow, occasionally with pink patches (*P. placenta* only). The decay damage to wood is similar to that caused by *S. lacrymans,* but the cubing is somewhat smaller, less deep and lighter in colour. When decayed, the wood crumbles between the fingers. It is not as powdery as that attacked by *S. lacrymans,* but slightly more fibrous and gritty.

P. contiguus. This fungus attacks both softwoods and hardwoods and is commonly found on the external joinery of buildings. The mycelium may be found in wood cavities or around the sporophores in the form of tawny brown tufts. The mycelium does not form rhizomorphs as in the case of *S. lacrymans.* The sporophore is occasionally found in buildings and is thick, tough, elongated, ochre to dark brown in colour and covered in minute pores.

The decayed wood shows no cuboidal cracking like that attacked by *S. lacrymans* and *C. puteana,* and does not powder in the same way as wood decayed by the dry rot fungus but, instead, the decayed wood bleaches and eventually develops a stringy, fibrous appearance.

D. expansa. This fungus attacks hardwood, and, as it particularly prefers oak, it is largely associated with older buildings constructed with this wood. However, once the fungus colonises hardwood in a building, it may spread to adjacent softwoods.

D. expansa tends to occur in frankly wet conditions and is found particularly on wood where there has been persistent water leakage. The mycelium of the fungus is yellow to reddish brown, forms a thick felted growth, often shaped to the contours of the wood, and exudes drops of yellowish-brown liquid. The mycelium does not form strands like dry rot. The sporophore is thin, leathery, plate or bracket shaped, or thick, hard and woody. The brown and buff-coloured hymenium is a cinnamon-brown or fawn colour with numerous minute pores, often comprising several layers.

D. expansa can cause more extensive damage to oak than any other fungi found in buildings, often attacking the ends of beams embedded in damp walls. Damage may be confined to the interior of the beam and not noticed until the typical bracket-shaped fruit bodies appear. It is often associated with death watch beetle attack.

The decayed wood becomes bleached and is reduced to a lint-like consistency, leaving stringy white fibres. The decayed wood is easily crushed, but does not crack.

P. ostreatus. Commonly called oyster fungus, this species belongs to the family Hymenomycetes (Agaricales). The mycelium is whitish and forms a woolly mat; rhizomorphs are not formed. The sporophore is a white-gilled, grey-capped mushroom with an off-centre stalk.

It is occasionally found in buildings and usually associated with the decay of panel products. Decayed wood board lightens in colour; in particle boards, the chips tend to separate.

Asterostroma spp. This fungus usually attacks only softwoods in buildings, is commonly found on joinery, for example skirting boards, and is often limited in extent.

The mycelium is white, turning cream or buff colour. Hyphal strands form occasionally with a rough appearance. These remain flexible when dry and some can cross masonry over a long distance. The sporophore sheet is very thin and hardly distinguishable from mycelial sheets. Pores are not present. The damaged wood becomes bleached and develops a stringy fibrous appearance.

P. panuoides. This fungus prefers very damp conditions. *P. panuoides* causes decay similar to that caused by cellar rot, that is, deep longitudinal fissures with some fine cross-cracks. In the early stages, the wood is stained a vivid yellow, wherever mycelium is present, but in the advanced stages, the decayed wood becomes soft and cheesy.

The mycelium is fine, soft, hairy and a dull yellow with occasional tinges of violet. The hyphae develop into fine branching strands, coloured as the mycelium; they do not darken with age. The sporophore has no distinct stalk, but is attached at a particular point, tending to curl around the edges and eventually becoming fan or funnel-shaped. The colour is dingy yellow, but darkens as the spores develop. The texture of the sporophore is soft and fleshy. The gills are yellow and branch frequently. The spore print is ochraceous rust coloured.

Lentinus lepideus. This fungus occurs quite frequently on worked timber which has been imperfectly creosoted, particularly telegraph poles and railway sleepers. The wood decayed by *L. lepideus* has a strong characteristic aromatic smell resembling that of Peru balsam. The fungus is not very common in buildings. The fruiting body, rare in buildings, is a pale brown mushroom with darker coloured scales on the top and gills underneath.

The fungus mainly attacks the cellulose, leaving the lignin practically unaffected. It does not produce strands. The decayed wood typically darkens and cracks along and across the grain. The mycelium is often present in the longitudinal cracks. In buildings, the cap frequently fails to develop, giving a branched structure known as a 'staghorn' growth. A rarer species, *Lentinus tigrinus,* is only found on building timbers previously treated with creosote.

D. stillatus. This fungus is very common with other joinery decay fungi, for example white rots, and attacks both hardwoods and softwoods. The fruiting bodies are only 10–50 mm in diameter, orange-red and gelatinous when fresh, but becoming darker and harder as they dry. The fungus is usually restricted to the interior of the timber, and it gives a pocket rot appearance.

Ptychogaster rubescens. The sporophore does not occur in buildings and strand formation is very rare; they are white and brittle when dry, but more fragile than those of dry rot and occur only on rotted wood. The white mycelium produces fern-like outgrowths. Wood decay is typical of brown rot; the wood darkens and cracks both along and across the grain. Spores are produced directly on the hyphae in specialised parts of the mycelium. These take the form of dull, pinkish-brown cushions which are soft and tend to disintegrate when touched to give a fine powder.

Soft Rot. Soft rot is a form of deterioration resembling brown rot which results in the unusual softening of wood. Soft rot is a prevalent form of decay; however, it is less damaging than others and less detectable. Soft rot can be regarded as a superficial form of wet rot. It is more usually found in timber in ground contact.

More than 100 species of fungi are known to cause soft rot. Most of them could cause substantial degradation of sapwood. The most destructive of the species is *Chaetomium globosum.* Soft rot fungi have a number of distinctive physiological and ecological characteristics by which they differ from decay fungi in the way they modify wood chemically. They resemble white rot fungi in causing a comparatively small increase in alkaline solubility and are able to utilise the wood lignin extensively. Partial weakening of the lignin carbohydrate complex in cooling towers wetted by water containing chloride will increase susceptibility to soft rot. Soft rotters may lack as efficient pre-cellulolytic enzyme systems as the brown rotters. However, these species are capable of enduring the microclimate of wood surfaces, that is, they can tolerate higher temperatures, higher pHs and can grow in restricted oxygen.

Hardwoods are more susceptible to soft rot than are softwoods. Mostly the outer wood is severely damaged by soft rot, as may be revealed by probing with a knife. The amount of conspicuously degraded wood may be comparatively shallow, and the transition between it and the underlying firm wood may be quite abrupt. When wet, the wood may be so decomposed that it can be scraped from the surface with a finger nail. When dry, the surface of the wood may appear as though it has been lightly charred, and there will be profuse fine cracking and fissuring both with and across the grain.

Soft rot is mainly associated with waterlogged wood and quays, jetties, mills and boathouses may have affected wooden components.

Moulds. The great majority of moulds which are found in buildings belong to the class Hyphomycetes (Deuteromycotina). They live mainly on starches and free sugars stored in the parenchyma or surface deposits of detritus on masonry, brickwork, concrete, rendering, tiles and paving and on surfaces of damp wood, plaster, wallpaper or paint. Moulds commonly occur on surfaces as a superficial growth causing patchy surface discoloration, usually green, grey or black, occasionally pink or yellow. Some are rusty red and may be mistaken for spores of *S. lacrymans,* while others produce a fluffy mass of white growth. Some moulds colonise wood whose moisture content is above

20%, but appreciable development requires moisture contents at or above the fibre saturation point (28–32%). Moulds grow best at temperatures from 24 to 30 °C.

Moulds cause some loss in wood toughness by attacking the parenchymal cells, but they usually have only a negligible effect on other strength values. They discolour and seriously weaken such materials as paper, leather, cloth and fibre-based products such as acoustic tiles or insulation. Moulds greatly increase the porosity of wood, and moulded wood wets much more easily, thus increasing the likelihood of decay and moisture-induced deformations. The presence of actively growing moulds serves as an indication that a moisture problem exists, which may or may not present a potential decay hazard.

Common moulds in buildings are: *Cladosporium* spp., *Penicillium* spp., *Aspergillus* spp., *Trichoderma viride, Alternaria* spp. and *Aureobasidium pullulans*.

Slime Moulds. Slime moulds belong to the division Myxomycota which has a distinct plasmodial state. Myxomycetes are very common on fallen trunks and branches on the forest floor. In buildings, they are usually found on inorganic substrates such as masonry, brickwork, concrete, rendering, tiles, paving and organic substances such as damp wood, usually exterior joinery. Fruiting bodies are 1–20 mm in diameter, variable in appearance from dark green, brown or black to occasionally bright colours, sometimes on stalks or with a silvery skin or uniform coating. All produce masses of brown spores. Myxomycetes feed on bacteria within the wood and become visible only when they produce fruit bodies on the surface.

Plaster Fungi. These fungi are likely to be found on damp brickwork or plaster in buildings. Common examples are *Coprinus* spp. (Inkcap), *Peziza* spp. (Elf Cup) and *Pyronema domesticum*. These fungi feed on the surface detritus or on organic material included in walls, for example bitumised felt DPCs and hair contained in old plasters.

Coprinus spp. belong to the class Hymenomycetes (Basidiomycotina). The sporophore of Coprinus has rather a peculiar organisation found only in this genus. The monokaryotic mycelium, without clamp connections, is branched, and this produces a conidial stage in the form of erect branches, each bearing a slimy head of unicellular and uninucleate spores. In this vegetative non-fruiting (oidium) stage of the life cycle, it may cause some decay to hardwood and sapwood, for instance, to split laths. Fruit bodies are formed on the dikaryotic (binucleate) mycelium with clamp connections. They are of a small white or cream 'mushroom' type with black gills on a thin stalk, often in clumps. Black spores are often deposited as a spore print when the fruit body matures before it shrivels and collapses.

Peziza spp. (commonly called Elf Cup) belongs to the class Discomycetes (Ascomycotina). The fruiting body or ascocarp is a small, pale brown or flesh-coloured, cup-shaped structure without stalks and is up to 50 mm wide. It is pliant when fresh, but breaks easily with brittle fractures when stressed between the fingers. When dry it is hard.

P. domesticum: The fruiting bodies are small, bright orange and wrinkled, and the cup is jelly-like. The mycelium is profuse and pinkish but otherwise resembles that of *S. lacrymans*.

Stain Fungi. Staining of sapwood is usually blue to black and occurs on freshly felled wood with a high moisture content. The damage persists after the wood dries, but is usually of no significance when found in wood in buildings. The stain fungi cannot grow in waterlogged wood or below about 20% moisture content.

Stain fungi commonly harbour sapwood cells of moist wood that consist mainly of ray cells. For their early nourishment, they depend on parenchymatous tissues as in the wood rays and on sugars and starch in the cells. The virtual absence of blue stain fungi in heartwood seems to be attributable chiefly to a shortage of relatively easily metabolised carbohydrates rather than inhibitory heartwood activities. Stain fungi are also commonly called 'Sat stain', a blue stain.

Staining of wood under varnish (or invisibly under paint), usually blue or black, is often accompanied by black surface growths through the coating. It is sometimes accompanied by surface mould, but occurs under different conditions through moisture accumulations under coating systems. This is known as 'Sap stain' (stain in service).

Stain fungi can be identified in wood as black or blue-black streaks and patches in the wood or coating; sometimes dark hyphae and fruiting bodies are present (tiny nodular structures erupting through the coating and producing numerous dark spores). Staining can penetrate deeply and often cannot be removed by surface planing.

Stain fungi commonly found in buildings include *A. pullulans, Cladosporium* spp. and *Sclerophoma pithyophila,* most of them belonging to class Hypomycetes (Deuteromycotina). Some stain fungi, for example *Ceratocystis* spp., belong to Ascomycotina.

Stains are troublesome due to their objectionable appearance, disfigurement of the wood and especially under clear finishes; early failure of the surface may be brought about by rupture caused by the fruit bodies. Discoloration

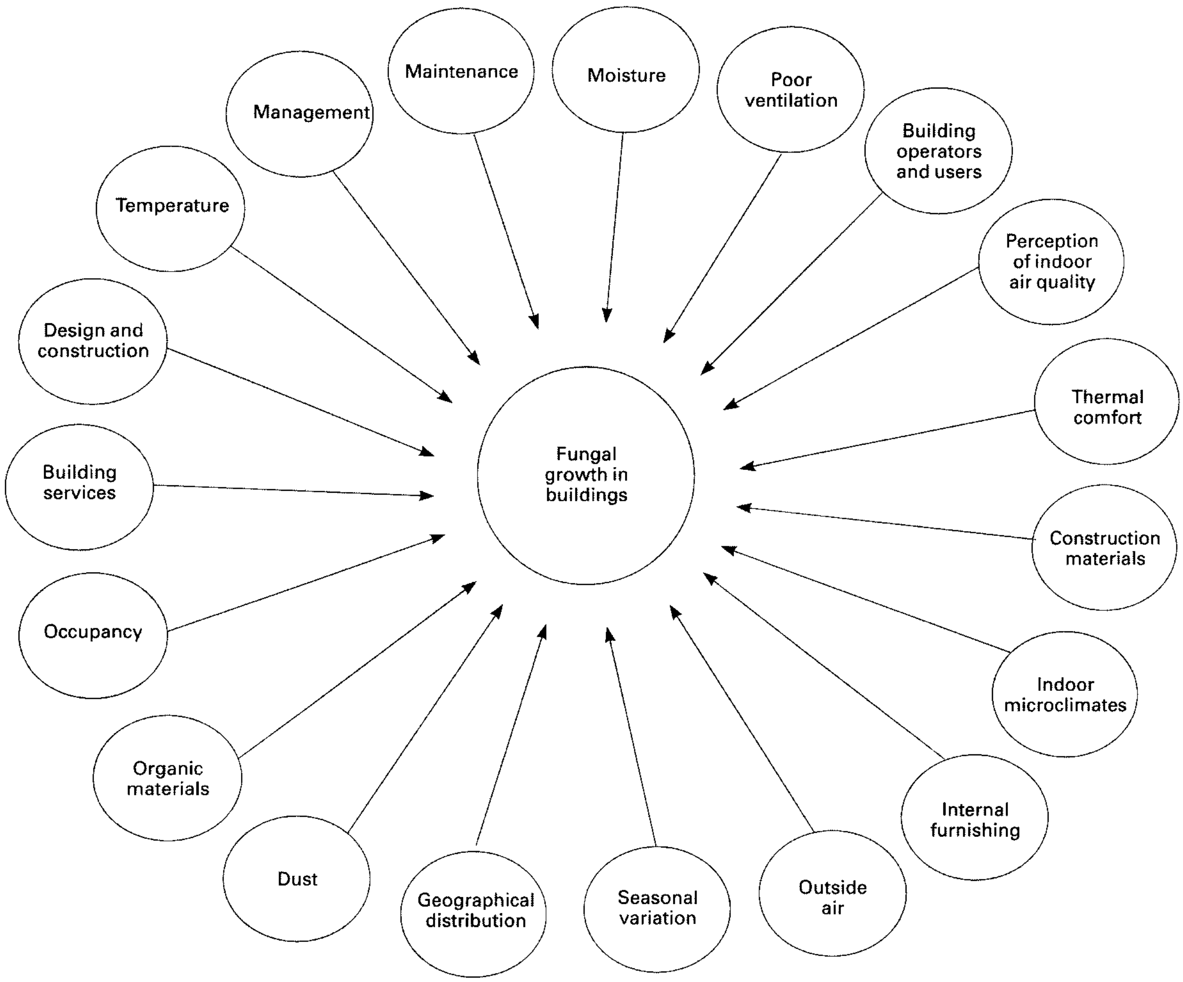

Fig. 1. Factors affecting fungal growth in buildings.

caused by Sap stain which has occurred in the log may still be detectable after the drying and conversion of the timber, but this will affect only the aesthetic value of the wood. Damage of the coatings will occur only through the growth of blue stain in service.

Ecological and Environmental Factors

Ecological Factors Affecting Timber Decay

The main factors which affect fungal ecology, and so affect the decay of timber, are temperature, water, humidity and ventilation [23] (fig. 1).

Fungi differ in their optimum temperature requirements, but for most the range is from about 20 to 30°C. The optimum temperature for dry rot growth in buildings is about 23°C, maximum temperatures are about 25°C, and the fungus is rapidly killed above 40°C. Timber moisture contents in buildings in the 20–30% range are ideal for dry rot attack and other infestations.

Water in buildings, and so the potential for increased humidity, can have many origins. The following factors are the most important contributors to moisture in buildings: penetrating damp/rising damp, condensation, building disaster, construction moisture and building defects.

Environmental and Other Factors

The following parameters are considered the most hazardous to the integrity of wood: Relative humidity, UV light, air temperature, dust, pollution, pests, handling, visitors, fire and water, air movement and cultural/organisational/management factors.

Inspection Methodology

A careful, systematic methodology is required when carrying out a building survey. One of the objectives is to assess the likely location or danger of dry rot. Unless the property is new or relatively modern, it may be safe to start with the assumption that dry rot is probably present until proven otherwise. The aim in any inspection of a building for dry rot is to identify infected or vulnerable areas and to provide a logical assessment of the risks. This is usually best achieved if the same methodical approach used for a typical building survey is adopted, as summarised:

Stage 1 – Desk Top Study. Inspect records, drawings, relevant correspondence, previous treatment contract documents relating to the property; consult owners/previous occupiers about problems with and alterations to the building; all of these sources may reveal valuable information about the building and may confirm or suggest previous outbreaks.

Stage 2 – Primary Inspection. Externally: Top down – look for typical indicators of rot, such as algae growth on walls, damp stains on walls, choked/overflowing gutters, defective roof coverings, leaking/faulty rainwater downpipes, defective pointing/rendering. Internally: Top down – all visible timbers should be inspected; note symptoms such as warped or curled wall panelling boards, splitting and cracking of painted woodwork, strong mushroom smell in the vicinity of an outbreak, springing lintels or floors and, of course, fruiting bodies with a layer of red dust-like spores.

Stage 3 – Secondary Inspection. Once the 'at risk' areas have been identified, it is advisable for the surveyor to recommend further investigations which may involve an element of 'opening-up', uplifting floorboards and removing sections of timber panelling. The use of a fibre-optic endoscope will help to minimise such work (see below). Solum levels of subfloor voids that are below the outside ground level are potentially troublesome areas because they are prone to flooding and are difficult to ventilate adequately. If the finish of a suspended timber floor is at or near the outside ground level, then the latter will be above the solum level, and this should be checked.

There are six main objectives in carrying out the above three-stage investigation:

(1) Building context: Establish the client's instructions and the purpose of the investigation. Ascertain the age of the property, form of construction and orientation. A knowledge of its location and recent history, especially as regards the level of maintenance and occurrence of adaptations (if any), may also be revealing.

(2) Moisture zones: Identify actual or potential sources of dampness [24].

(3) Timbers affected: Forecast the probable presence of hidden timbers within the building.

(4) Dampness defects: Identify and diagnose defects that can cause dampness.

(5) Risk factors: Pin-point vulnerable areas such as floor/roof/wall voids, look for external and internal indicators such as dampness; if there has been a previous infection, there is a higher risk of a further outbreak.

(6) Reporting: Accurate and impartial reporting of the nature and extent of decay.

Investigating dry rot is rarely a non-destructive exercise. Some damage to plasterwork and decorations may be unavoidable, particularly where built-in timbers are likely behind wall/ceiling finishes. Nevertheless, the small investment in such exploratory work initially may obviate the need for more expensive repairs later. An endoscope to inspect void areas in roof spaces and subfloor areas and behind wall panelling is a useful tool for the surveyor. It can be used through holes not more than 10 mm in diameter. The surveyor can also test the soundness of timber by using a sharp instrument such as a bradawl or pointed screwdriver to probe the wood. In the case of a built-in end of a bressummer or other joist, a 5- to 8-mm diameter wood bit can be drilled at a 45° angle into the bearing end of the member along its neutral axis or from below if access to the side is difficult. Decay is usually present if the drill penetrates the timber too easily and this can be confirmed by examining the wood residue from the drill bit for signs of rot.

In any event, it is very important to identify the extent of any suspected or obvious outbreak. This can be achieved with the aid of simple schematic plan/s and cross-section/s of the building to record and prioritise key findings. The sketches can highlight defects likely to lead to dampness, likely moisture ingress points and their areas of spread, and high moisture contents of masonry and timbers likely to be at risk. The surveyor should consider the consequences of moisture-causing faults such as missing/defective roof coverings, faulty abutment/chimney flashings, springing floors and lintels, and high outside ground levels and state them clearly in his report. Such implications are ascertainable even if any timber decay is not obvious and so further investigations may have to be recommended.

Diagnosis of Decay. The following techniques are used to diagnose the decay: physiochemical and morphological characteristics of decay, cultural characteristics of decay, genetic fingerprinting and trained animals.

Special Search Techniques. The condition of concealed timbers and cavities may be deduced from the general condition and moisture content of the adjacent structure. Only demolition or exposure work can enable the condition of timber to be determined with certainty, and this destroys what it is intended to preserve. A non-destructive approach is therefore required, and, to help reduce uncertainty, instrumentation and test equipment can be useful at this stage. However, it is important to remember that all tests and instruments are only aids to the surveyor and must be interpreted with experience and care. A slavish reliance on any techniques, and failure to take into account its limitations, is a recipe for disaster. A non-destructive inspection includes the use of trained animals, fibre-optic inspection, ultrasonics and infrared techniques.

Fibre-Optic Inspection of Decay Fungi. The correct identification of fungal material is important, as not all fungi are equally destructive. By employing the use of high-power fibre-optic instruments, the type and extent of fungal decay in concealed cavities can be assessed. High-intensity light is produced by the light source, is transmitted and illuminates the infested area under inspection through a liquid light guide and a rigid fibre-optic eyepiece. The image can then be photographed using a 35-mm SLR camera, attached to the eyepiece.

Canine Detection. Canine detection helps to discover the location of dry rot and whether or not it is actively growing. 'Rothounds' sniff out dry rot fungus in much the same way as dogs can sniff out drugs or explosives, uncover avalanche victims and hunt for truffles. Obtaining fresh dry rot samples to train dogs is a tedious process because it is difficult to duplicate the subtle conditions required to grow the fungus outside its normal habitat. Removing pieces of dry rot from infested areas does not work, for the fungus soon dies and the scent is lost, thus becoming ineffective for training purposes. On the other hand, *S. lacrymans* produces specific secondary metabolites during its active growth period, and dogs can be trained to detect these metabolites. Currently three varieties of dog have been trained for this purpose, a Springer Spaniel cross, a Border Collie cross and a Labrador.

Preliminary Inspection and Investigations. The basis of any investigation is an understanding of building structures and defects and how these may interact to produce the ecological niches in which various decay organisms can thrive. With experience, an initial visual inspection can give a good indication of areas that will need further study. A check-list for this preliminary investigation includes building defects, significant timber structures and concealed cavities. Obviously, it is important to be familiar with the ecology and signs of significant decay organisms.

Moisture Contents

Timber Moisture Contents. Timber moisture content at the surface may be estimated by the use of a resistance-type moisture meter, fitted with insulated needle probes. This will fluctuate depending on relative humidity and temperature. A rafter may have a surface moisture content of 16% in the summer which might rise to over 20% in winter. This would not necessarily indicate increased water content from a fault in the roof, but might be water absorbed through a drop in temperature. The core of the timber will remain relatively dry, and a hammer probe with insulated electrodes is recommended for measuring the subsurface moisture content.

Masonry Moisture Contents. The estimation of surface moisture content in plaster and mortar is of limited value except for comparison. A surface capacitance meter may be used on plastered walls and panelling to detect areas requiring further investigation. Absolute readings should be made by means of a carbide-type pressure meter or by the oven drying method. Moisture-reading contours on the surface and in the thickness of the wall help to define the source and type of moisture giving rise to decay.

Detailed Investigation. The findings from the initial investigations are followed up by more detailed study. The aim is to determine the distribution and extent of all significant decay organisms in the building, the distribution of all micro-environments predisposing to timber decay and the building defects that cause them. The distribution of moisture and its movement through the structure is particularly important. The extent of significant timber decay should also be determined. Active decay organisms may not yet have caused significant timber decay. Conversely, there may be significant decay even when the decay organisms that caused it have been dead for many years. Key factors to be noted are species and viability of decay organisms, moisture content of materials, ambient relative humidity and ventilation. Timber species and previous chemical treatments may also be significant.

Table 2. Primary detection methods

Detection methods	Types	Examples
Human senses	visual	warping or cuboidal cracking in wood, sporophores
	aural	hollow sound when tapped
	olfactory	musty/mushroom smell
	touch	spongy, friable when felt or probed
	taste	acrid
Non-human senses	sniffer dogs	specially trained hounds to locate dry rot outbreaks
Artificial detection	moisture meter	necessary to confirm damp areas
	hand mirror and torch	to help inspect awkward voids
	ultrasonic hammer	can help to indicate the soundness of large joists
	endoscopes	to inspect inaccessible areas
	genetic[1]	DNA analysis of rot samples

[1] Research in this area is being undertaken by biologists Dr. N. White and Dr. J. Palfreyman, University of Abertay, Dundee, UK.

Table 3. Timbers vulnerable to dry rot

Location	Common timbers affected
Walls	safe lintels
	door standards
	bonding timbers
	strapping and boarding of dado panelling
	lathing behind plaster
	skirting grounds and skirtings
Roofs	rafter feet and ends of ceiling ties, particularly behind 'beam filling'
	ceiling ties built into wallheads
	wallplates
Floors	joists built into masonry
	bressummers (large support beams)
	wallplates
	floorboards
	skirting grounds and skirtings

It is important that the results of the investigation are coordinated with the building structure, bearing in mind the characteristics of particular periods and methods of building. They should also be carefully recorded and quantified where possible. This allows analysis of the results by other experts, reduces the 'grey' area in which differences of opinion can arise and forms a basis on which future investigations can build. This recording of data is especially important in the current legal climate, and photography can be especially valuable. A detailed investigation of this sort might take about 5 man-hours for a typical 3-bedroomed house.

Detection of Dry Rot

The correct and early diagnosis of dry rot requires an understanding of the pathology of the fungus as well as a sound knowledge of building construction. Determining the presence of hidden or built-in timbers is crucial to a full and accurate detection of the fungus. There are a number of techniques that the surveyor can use to help in arriving at a correct diagnosis, and these are listed in table 2.

Although dry rot primarily attacks softwoods, it can also infect hardwoods such as oak. There are various timbers within a building which are susceptible to dry rot to which the surveyor should give particular attention (table 3).

Dry rot in its early stages is difficult to distinguish from other wood rots without the benefit of laboratory analysis. This involves growing samples of the fungi on an artificial medium under controlled conditions. Various media based on oatmeal, wheat flour and malt extract can be used as a nutrient to encourage fruiting of the fungus.

In its terminal stages when the fruiting bodies or sporophores have developed brown spore dust, dry rot is relatively easy to distinguish from wet rot. The former, however, can spread to other timbers, even through masonry materials, whereas the latter is always restricted to the locus of the moisture source. This ability to spread is one of the distinguishing and most menacing features of *S. lacrymans.*

Other techniques used included microscopy, laboratory culture and identification of fungi and insects, hot-wire anemometry and electronic RH measurement (fig. 2). More exotic techniques may sometimes be useful, such as pheromone insect traps, infrared thermography, shortwave radar, automatic weather stations, ultrasonic detection of timber-boring insects and total building monitoring using specialist data loggers. It is important to remember that any technique must be carefully justified because the value of the information from techniques not routinely used or properly calibrated can be very limited.

Ecological Factors Influencing Biodeterioration

When considering any form of biodeterioration, there are 3 factors of concern: the material, the environment and the organism. Ecology as a branch of science is usually confined to a very close analysis of the interaction of organisms with one another and with their environment. The environment in which any organism lives will contribute physical, chemical and biological factors which will have a bearing on the settlement, growth and development of an organism.

The fundamental role of ecology is concerned with predicting the susceptibility of a given material to attack by various organisms, depending on prevailing environmental conditions. Macro-environmental parameters such as average temperature, humidity or hours of light have little significance in determining the activities of decay. Indeed, it is the details of micro-environments and their relationships to organisms which need to be examined.

Micro-environments must be surveyed in order to obtain a better understanding of the activities of decay. This includes a whole series of micro-environments, on and within the materials, such as the micronutrient level of the materials, the microclimates of the materials, population density, frequency of distribution of propagules and relative frequency of biodeteriogens to other organisms. For example, with a piece of exposed structural timber in a particular situation, climatic information concerning average temperatures and humidities will have little meaning. It is difficult to establish the precise effect that insulation has on a piece of wood. It could change the surface and internal environment to such an extent as to have little superficial correlation with general air conditions; yet it is precisely these micro-climates on and inside the timber which are of the greatest significance in determining the organisms which will be present and able to grow.

Water accounts for between 80 and 90% of the weight of a micro-organism. A microbial metabolism requires an aqueous environment, therefore water must be in the environment if the organism is to grow and reproduce. Wood-rotting fungi are unable to colonise wood which has a moisture content below 20%. Microbial biodeterioration of timber in buildings can occur only if the material has a moisture content in the range of 20–30%, although some moulds can develop under drier conditions below this range.

Ecological Succession

Most of the work on ecological succession and microbial associations in biodeterioration has been carried out on standing trees, submerged wood and on wood in ground contact or else on the degradation of crop residues. Little work has been done on the biodeterioration of building materials.

Fig. 2. The author using a hammer probe to measure the deep moisture content of timber.

When a material is exposed to the air, a large number of spores from a range of species will settle on the surface, and if it is moist, they are likely to germinate. If the material is in contact with soil, the surface will be colonised initially by both the mycelium already actively growing in the soil and the germination of previously dormant spores.

There are various factors which affect the pattern of the colonisation of substrates. Many substrates are first colonised by what are known as sugar fungi, capable of growing and sporulating rapidly on simple, soluble sugars and nitrogen sources. Later colonisers are able to utilise more highly polymerised compounds such as hemicellulose and cellulose by secreting extracellular enzymes. The latter are frequently associated with secondary fungi which utilise some of the enzymatically produced sugars. Thus, it is often difficult to isolate cellulose/lignin decomposers on standard laboratory media containing simple sugars, as they are usually associated with faster-growing sugar fungi that grow, sporulate and smother the polymer decomposers before the latter have a chance to develop any substantial mycelium.

The availability of nutrients to potential colonisers will vary from the initial state to after attack has commenced. Thus one micro-organism may have an initial selective advantage as far as the available nutrients are concerned, but may then be replaced or added to by other species, giving rise to an ecological succession.

Among microbes, 6 ecological niches or physiological groups can be differentiated which are as follows: bacteria, primary moulds, stainers, soft rots, wood-rotting basidiomycetes and secondary moulds. There is an ecological sequence of colonisation by micro-organisms starting with bacteria, moulds, stainers and climaxing in the final decay by basidiomycetes. Several of these early colonisers have been shown to increase the absorbency of the timber from the joint in a manner similar to the ponding effect.

Remedial Treatment

Remedial Treatment of Dry Rot

- Establish the size and significance of the attack. In particular, if structural timbers are affected, carry out or arrange for a full structural survey to determine whether structural repairs are necessary and, if they are, take appropriate steps to secure structural integrity.
- Locate and eliminate sources of moisture.
- Promote rapid drying of the structure.
- Remove all rotted wood cutting away approximately 300–450 mm beyond the last indications of the fungus.
- Prevent further spread of the fungus within brickwork and plaster by using preservatives.
- Use preservative-treated replacement timbers.
- Treat remaining sound timbers which are at risk with preservative (minimum two full brush coats).
- Introduce support measures (such as ventilation pathways between sound timber and wet brickwork, or, where ventilation is not possible, provide a barrier such as a damp-proof membrane or joist hangers between timber and wet brickwork).
- Do not retain dry-rot-infected timber without seeking expert advice. There is always some risk in retaining infected wood which can be minimised by preservative treatment and subsequent reinspection.

Chemical Control of Biodeterioration

A great variety of toxic chemicals are available on the market for use as wood preservatives. The ideal wood preservative should possess the following characteristics: (1) A high toxicity towards wood-destroying organisms; (2) permanency in treated wood, that is, low volatility and a high resistance to leaching; (3) ability to penetrate deeply into the wood; (4) non-corrosive to metals and non-injurious to the wood itself, and (5) reasonably safe to handle and without injurious effects on operatives and occupants.

Wood preservatives are regulated in the UK under the Control of Pesticides Regulations 1986.

Biological Control of Biodeterioration

Microbial interactions and biological control methods have received much attention during recent years as an alternative to existing chemical control methods, which cause extensive environmental degradation, pose potential hazards to wildlife and are of grave concern to public health authorities. Biological control involves the use of one biological agent to suppress another. There are many successful examples of the biological control of wood decay fungi, for instance use of *Trichoderma* spp. against various wood-rotting fungi such as *Polyporus adustus, Polystictus hirsutus, Polystictus versicolor, Stereum purpureum* and *Scytalidium lignicola* against *L. lepideus.* It has been demonstrated that pure cultures of *Bacillus subtilis* inhibit the growth of various wood-staining fungi such as *Alternaria tenuis, Trichoderma reesei* and *A. pullulans* in vitro. The role of immunising commensal fungi both as preventive and curative treatments in reducing the incidence of *L. lepideus* has been described.

Competition occurs when there is a demand by two or more micro-organisms for the same resource in excess of immediate supply. Resources include space as well as nutrients. *Trichoderma* spp. are common saprophytes of wood, and they have the ability to utilise simple sugars, and although they can decompose cellulose, their ability to utilise structural polysaccharides of wood is very limited. It has been observed that *Trichoderma* spp. inhibit the attack of wood-destroying fungi by removing some structural carbohydrates from the wood which are necessary for the rapid colonisation and initiation of decay by wood-destroying fungi. *Trichoderma* spp. also inhibit the development of other pathogenic fungi by the production of antibiotics and hyper-parasitic activity.

Once the thorough investigation of the ecological succession, the availability of micro-nutrients and the conditions of micro-environments in and around the material have been established, the use of potentially hazardous chemicals in certain situations can be avoided. Hence, the risk of reinfestation is slight. Unfortunately, this knowledge has lagged behind in recognition, and hasty control measures have been instituted without the full knowledge of ecological aspects. The reliance on one method of control in a situation not fully understood can result in an even worse situation.

In view of these concepts, the prevention of biodeterioration may be achieved by biological control methods. This involves placing a micro-organism into a material which does not affect the properties, but which successfully prevents invasion by species capable of damage.

Environmental Control of Biodeterioration [25–30]

When considering the prevention of any form of biodeterioration, there are 3 factors which can be taken into account: the material, the environment and the organism. The removal or alteration of any one of these can prevent the growth of decay organisms.

The control of the environment of a susceptible material, instead of the application of biocides, is the oldest and still the most widely used method of preventing biological deterioration. Traditionally, the control of physical conditions has been by far the most important method of preventing biodeterioration. For example, in the use of timber in construction, the object has been to prevent its moisture content rising to levels at which wood-rotting fungi can thrive.

The environment of a material is complex and dynamic; all organisms live in a biological equilibrium, and for an organism to succeed, it must be in balance within fine limits with the environment. If this balance can be disturbed to render it more hostile to the organism, less growth, and therefore less damage, will occur. The levels of moisture content and temperature necessary for the safe limits of biodeterioration are often decided much more on practical experience than on theoretical calculations and a knowledge of the physiology of the micro-organism concerned. However, when a situation arises such as the need to prevent the biodeterioration of materials in buildings, it is absolutely necessary to predict the following:

(1) How particular temperature and moisture conditions may arise and be controlled in the micro-environment of the substrate.

(2) The effects of the interaction of physical conditions both between themselves and with other factors on the growth and activity of decay organisms.

(3) The interrelationship of building structures and materials with their environments, occupants and contents.

The basic principle in the control of fungal growth is to render the micro-environment in or around the material in buildings as hostile as possible to the settlement, germination and spread of micro-organisms. This can be achieved in various ways:

(1) To prevent or limit the growth and proliferation of the biological agents by means of toxic chemicals.

(2) To ensure that the material to be protected is kept, or keeps itself, in such physical condition that growth of biological agents is severely limited or prevented entirely.

The second approach will be discussed in more detail as, traditionally, the control of physical conditions has been the most important method of preventing bio-deterioration. The application of the general principles of the control of physical conditions and the reactions of micro-organisms to these conditions often result in the most effective and economical prevention of deterioration.

Water activity (a_w) is the most valid measure of physiological drought in all types of substrate. The a_w of a material is the ratio of the vapour pressure of water over the substance to the vapour pressure over pure water at the same temperature. Dryness is effective in the control of decay as the chemical potential of water in a dry material is reduced to the level at which micro-organisms are unable to obtain sufficient water for growth or normal metabolism. For any material, there is a relationship between its moisture content and the activity of its water. In relative humidity terms this is often referred to as the 'equilibrium relative humidity' of the substance at a particular moisture content. Changes in temperature affect the vapour pressure over the substance and over water, approximately proportionally; a_w (or relative humidity) over the substance does not change very greatly with a change in temperature. The changes which do occur are usually in the direction of increasing a_w with increasing temperature at a constant moisture content. The limits or optima of temperature and moisture are stable characteristics of microbial species or of definite subspecific groups. Within each group, the limits vary from an average, which is characteristic of the group, to only a limited and statistically definable extent. The strains of particular species may differ in their moisture and temperature requirements.

As 'dryness' rather than low a_w is commonly understood to be the controlling factor in the growth of micro-organisms, it is usual to speak of a 'safe' moisture content for any material, for example softwood in buildings, as at or below 16% moisture content. In practice, these low levels are found to be safe, and attack by fungi and other micro-organisms does not occur. In so far as a_w can be inferred from moisture content, the latter is a perfectly valid measure of 'safeness' or resistance to microbiologi-

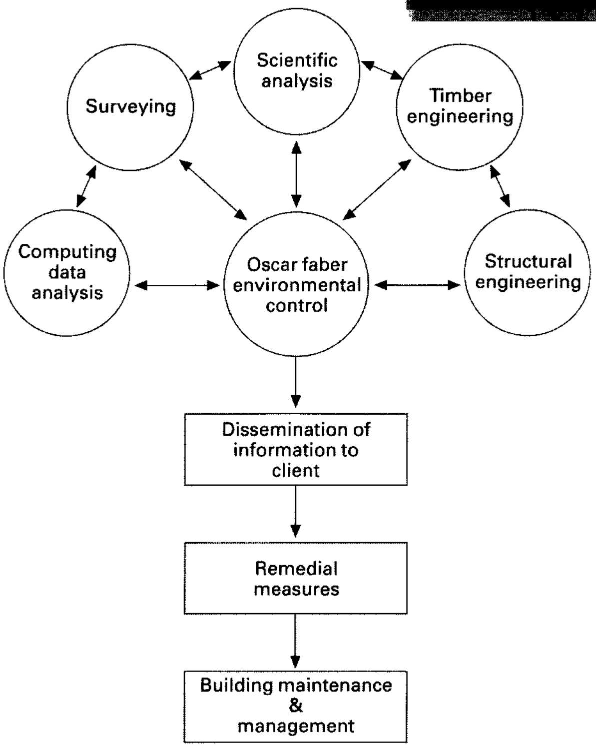

Fig. 3. Environmental control of timber decay.

cal attack. Growth of micro-organisms is possible at a lower water level on substrates of a higher nutritional status. Understanding the mechanism linking nutrition and tolerance of low a_w might well lead to more effective control of biodeterioration. Some enzyme reactions continue at a_w well below the levels which permit microbial growth [1]. This suggests that the ultimate limit for growth at between 0.6 and 0.7 a_w is due to the distortion of the helical structure of the DNA molecule due to dehydration.

The Greener Approach

Environmental control relies on controlling the cause of the problem by controlling the environment [31–40] (fig. 3):

(1) Locate and eliminate sources of moisture.

(2) Promote rapid drying.

(3) Determine the full extent of the outbreak.

(4) Remove the rotten wood.

(5) Determine structural strength of timber and fabric construction.

(6) Institute good building practice: (a) ventilation; (b) damp proof membrane; (c) isolation.

This method of control is complex and requires a multidisciplinary team of scientists, engineers and surveyors and computing skills.

The Green Approach Standards

In cases of actual or suspected problems of wood rot or wood-boring insects in buildings, the following standards should be met by any remedial works:

(1) Investigation should be carried out by an independent specialist consultant, architect or surveyor to establish the cause and extent of the damp and timber decay, including the potential risk to the health of occupants, before specification or remedial work. This investigation should include:

(a) the inspection of all accessible timbers to determine whether they are subject to, or at risk from, fungal decay or insect attack;

(b) the determination as to whether any wood-rotting fungi or wood-decaying insects found are active, and whether their activity is significant in each particular case.

(2) Specification of remedial work should be prepared by an independent consultant as in 1a, b. Such specification should provide for:

(a) the maximum conservation of materials;

(b) the future health of the building and its occupants;

(c) the minimal use of new materials;

(d) the avoidance of chemical pesticide use where possible;

(e) the use of materials and techniques with minimum adverse environmental impact;

(f) the minimum cost of the whole project including the costs of the proposed works, the disturbance of occupancy, future maintenance costs, and the cost of safe disposal of all waste materials.

(3) Remedial building works should be carried out as specified above to control the timber decay, to prevent further decay and to correct any significant building defects resulting in conditions of high moisture content or poor ventilation of timber. These should provide for:

(a) the reduction of the subsurface moisture content of all timber below 16–18%;

(b) the isolation of timber from contact with damp masonry by air space or damp-proof membrane;

(c) the provision of free air movement around timber in walls, roofs and suspended floors;

(d) humidities in voids not exceeding an average relative humidity of 65%;

(e) the removal of active fungal material and any timber affected to the extent that its function is compromised or adjacent structures put at risk; in the case of insect infestation, measures to avoid contamination;

(f) the prevention of, or protection of timber from, sources of water likely to cause wetting such as overflowing gutters, leaking plumbing, condensation and rising or penetrating damp;

(g) the removal of all rubbish of builders from voids and cavities and vacuum cleaning to remove dust.

(4) The use of chemical pesticides should be avoided wherever possible. Where their use is essential the following requirements should be observed:

(a) the minimum use of fungicides consistent with the probability of reinfestation in the light of 3a–g;

(b) the limitation of insecticidal treatment to the locations of significant active insect attack in the light of 3a–g;

(c) specific agents to be used on specific organisms only; 'combined', 'general' or 'precautionary' treatments are not to be used;

(d) fungicides and insecticides must be currently fully approved under the Control of Pesticides Regulations 1986; pesticides with special dispensation or licence as of right are not to be used; as a guide, products with serial numbers greater than 3,000 have gone through the full HSE approval procedure;

(e) pesticides should be applied in accordance with the manufacturer's instructions and within any regulations, codes of practice guidelines or recommendations currently recommended by the BWPA, HSE, NCC or other competent authority;

(f) the contractor applying the pesticide must certify that the treatment will not damage the health of the occupants and of the structure or wildlife in and around it;

(g) the contractor must certify that the disposal of surplus pesticide, pesticide containers and treated waste materials is safe, non-polluting, and in accordance with all current central or local government regulations and guidelines.

Environmental Monitoring [41, 42]

Environmental monitoring includes the data logging of temperature, humidity, moisture content and other parameters in building materials, including internal and external environmental conditions, using on-site sensors and an automatic weather station. These systems are as follows.

Remote Sensing of Moisture Content in Timber. The remote sensing of moisture content in timber and monitoring the drying of buildings provide simple and economical methods of avoiding serious timber decay. These systems accurately determine the source and distribution of moisture within the building fabric, and detect water penetration in critical areas or monitor drying following building failure, fire or flood. Data from these investigations is used to determine a policy and control the drying out of the building fabric to reduce the risk of future decay after refurbishment.

Remote Sensing of Moisture Content in Masonry. Remote sensing systems can be installed in the damp masonry or area likely to be at risk from water penetration, and the data obtained can be used to determine the state of drying down and to take profiles of moisture across a thick wall which may take many months to dry out. Permanently installed systems can act as a warning for future water penetration.

These systems can be simple or complex and are tailor-made to suit a particular building. In complex remote sensing systems, the resulting data can be transferred to the computer or via a model to a central building management system.

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