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Building Pathology, Investigation of Sick Buildings –Toxic Moulds

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Abstract
This paper considers the requirements for investigation of sick buildings including some guidelines for assessment of exposure risks with a particular focus on dampness, proliferation of moulds, and dispersion of fungal spores in indoor environments. Building pathology, indoors air quality management and management of bio-deterioration, and health problems in buildings are complex issues requiring multi-disciplinary investigations and environmental monitoring. Lack of maintenance, chronic neglect, and building defects leading to water ingress, condensation, and dampness in the building fabric will often produce proliferation of pathogenic toxic moulds, and other microbial and biological effects that could cause allergic response in sensitive people and generally lead to ''sick buildings.'' A general guide has been provided by this paper for environmental assessment of toxic moulds in indoor environments, including a suggested guideline for assessing the threshold levels for fungal spores in indoor air.

Introduction

Buildings, work as spatial environmental ecosystems and provide ecological niches and pockets of microclimates in their built environment, which allow the development of building pathology and must be understood as a whole [1]. Building pathology is the scientific study of abnormalities in the structure and functioning of the building envelope and its parts, that could lead to ill-health of the occupants and a poor habitat in which to live [1,2]. This paper examines the interrelationship of building materials, construction, building services, and spatial arrangement with their environments, occupants, contents, and activities. These interrelationships are complex and can influence the health of the building fabric and well-being of occupants.

The purpose of this paper is to provide an introduction to building pathology and a review of the methods for investigating sick buildings, with a particular focus on toxic moulds. The investigation of sick buildings relating

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to the emissions of volatile organic compounds (VOCs) and formaldehyde (HCHO) has been reviewed in a related paper [3].

Building Pathology and Sick Buildings

The most common health problems arising from exposure to airborne fungi and bacteria are: asthma, rhinitis, and eczema or the less common but extremely dangerous extrinsic allergic alveolitis (hypersensitivity pneumonitis) and allergic bronchopulmonary aspergillosis [4], resulting from exposure to high concentrations of airborne fungal spores such as, *Cladosporium* and the dry rot fungus (*Serpula lacrymans*), indoors. Fungal species: *Alternaria*, *Aspergillus*, *Cladosporium*, and *Penicillium* are known to cause respiratory allergic conditions in humans [5].

In the UK, asthma is very common, affecting some three million people (5% of the adult population) and in children – this is the most prevalent chronic illness [6]. The main fungus of concern is the *Stachybotrys chartarum*, which is a black mould that grows on moisture-saturated building materials with high cellulose content including timber, wall liner (plasterboard), and ceiling tiles [7]. Exposure to high levels of this fungus may cause cold-like symptoms, rashes, and aggravation of asthma. There have been reports in the US, linking the presence of this fungus to the pulmonary hemosiderosis (lung disease – bleeding) [8]. Also reported was the organic dust toxic syndrome (flu-like symptoms) after exposure to mould-infested rooms. Other type, e.g., Aspergillosis, is related to moulds growing on bats/birds droppings [9]. There are a number of instances where hypersensitivity pneumonitis may be caused by exposure to high concentrations of spores in the offices or domestic environments [10]. These include *Cladosporium cladosporioides*, *Penicillium chrysogenum*, and *Penicillium cyclopium*.

In the USA, architects, developers, managing agents, and landlords have been subjected to litigation due to occupants suffering from mould exposure as a result of water-damaged buildings (http://www.apsnet.org/online/feature/stachybotrys/). The issue of possible legal and insurance effects on chartered surveyors and on building owners as well as the general concern of well-being of occupants has increased the need for research on the toxic moulds in buildings (http://www.homeinspectors.co.uk/docs/Toxic%20mould%20report.pdf).

Buildings, particularly new homes, are increasingly being built to a higher standard of air-tightness to meet the requirements for energy conservation [3]. The increased air-tightness of buildings can reduce airflow and could allow moisture build up in indoor environments, particularly in the insulated cavity walls and lofts leading to a proliferation of moulds, the so-called hidden toxic mould and their airborne spores can produce toxins and cause allergic health effects to occupants, particularly in domestic homes [11–19]. The volatile metabolites, microbial volatile organic compounds, from moulds typically characterized by their musty smell in damp and old buildings can also affect indoor air quality (IAQ) and the health of occupants [2,20].

Investigation of Sick Buildings

The investigation of sick buildings for toxic mould would involve investigation of the total performance of the building envelope through multi-disciplinary scientific survey of the causes and symptoms of failures and will require examination of the reported symptoms, building services, biodeterioration of building materials, examination of microbial proliferation, and human activities. The investigation of sick building complaint would usually involve undertaking the following:

(1) Questionnaire survey to establish:

- the symptoms (complaint diary/record);
- the history: building design, refurbishment, and operations;
- conditions and uses of the building including opening of windows or vents;
- the materials used and activities undertaken by the occupants;
- heating, building services, and ventilation (HVAC management records);
- lighting (natural and artificial) levels;
- how the occupant feel about the building environment.

(2) Conduct a walk-through survey of the building, noting:

- Visual inspection of building conditions, environments, and deterioration of materials (e.g., wood rots) and defects;
- Damp patches, leaks, cracks, and disfigurations;
- Signs of moulds, mould stains, and smell.

(3) Measure temperature, humidity, airflow, and ventilation (air exchange rate).

(4) Undertake monitoring and measurements of microbial particles, moulds, and house dust mites.

(5) Undertake assessment of analytical data and evaluate exposure risks based on the recommended guidelines provided by relevant authorities.
(6) Recommend remediation or actions to reduce exposure risks of occupants to indoor contaminants.

Assessment of the Likely Causes

Generally, new building interiors and finishes, such as in homes and offices, would produce a higher chemical pollution load than biological loads, this is due to emissions of VOCs and formaldehyde from building and interior fitting materials, furnishing, and other building fabrics [3]. However, in exceptional circumstances, such as in poorly maintained HVAC systems where microbial flora can proliferate and be delivered to indoor areas to become a significant exposure risk to occupants. Filters fitted in the HVAC systems can minimise this potential risk.

The major sources of toxic mould occur in buildings (even in new build) e.g., on damp Gyproc plaster walls (Figure 1), in hidden cavities and voids in homes, particularly in air-tight, warm environments.

There is a strong link between dampness in buildings and mould growth and associated respiratory diseases in relation to IAQ in homes [2,11]. Proliferation of toxic moulds could also arise due to bad building practices (e.g., insufficient ventilation and misconnection of drains and sewerage pipes) and bad or insufficient maintenance, leading to high levels moisture and proliferation of toxic moulds in indoor environments [20]. Nutrients to support mould growth are ubiquitous in the building environment.

Fig. 1. Toxic mould on Gyproc plasterboard.

Mould will grow on any organic building material such as timber, plasterboard, paper, coatings, adhesives, resins, furnishings, etc. as well as organic matters produced by pests and humans in the house. The dusts in office buildings consist primarily of paper dusts, wood dusts, skin cells, and other organic particular matters; and these would support mould growth. The indoor environmental temperatures, of about 15 to 32°C in most countries in Europe, Northern America, Korea, and Northern China, are ideal for mould growth. In sub-tropical regions of China, where the indoor conditions are usually damp and warm and in areas where there is little ventilation or natural light penetration, proliferation of mould and dispersion of fungal spores could be a serious risk to health of people. A relative humidity above 65% would encourage mould growth in the built environment. The practical way to control mould growth would be by control of moisture in the building environments. Therefore, assessment of moisture in the building materials and in the building's environment would be crucial to any investigation of sick buildings with a particular consideration of toxic moulds.

Deterioration of building materials in old houses and historical buildings are attributed to the changes in the building environment through neglect, building defects, insufficient ventilation, build up of humidity, and inadequate building maintenance leading to water ingress, condensation, decay of materials, dampness of building fabrics, biological, and mould growth [1]. Insufficient exposure to the natural sunlight can also be a factor for mould growth. Careful inspection of signs, for example, severe salt efflorescence, moisture, mould stain, blistering of finishes, and timber decay would indicate symptoms of deterioration leading to health complaints. The causes of deterioration are influenced by the internal building environment, which has a varied microclimate depending upon the building envelope of the internal building fabric [21] and to control these changes will require careful management [22,23].

Moisture-induced degradation could deteriorate thermal resistance, strength, and stiffness of materials and corrosion of building components (e.g., mortar and steel reinforcement); It would also result in insect infestation, supporting the growth of mites, cockroaches, and other pests [22,24]. Infestation of house dust mites leaves deposits of their fecal materials, particularly in soft furnishings and this could pose a risk to health of occupants, suffering allergic reactions and asthma [25]. These are important signs of sick buildings.

Domestic humidifiers and air-conditioning systems in buildings can be important sources of microbial flora, e.g., in office buildings. Large concentrations of biological agents mostly resulting from bad management of the HVAC systems, lead to insufficient fresh air intake allowing for the build up of indoor contaminants, condensation or water accumulation in pans under cooling coils, humidifiers, and dust accumulation in air filters [26,27]. Inspection of the humidifier and air-conditioning unit would be an important part of an IAQ investigation. The CIBSE TM26, Hygienic Maintenance of Office Ventilation Ductwork [28] provides the building managers with guidelines regarding the importance of ductwork maintenance, protocol for maintaining ductwork systems in a safe, and effective state and the microbial contamination in air distribution systems and buildings. ASHRAE standard 62-1990 [29] recommends fresh air intake of 20 cfm per person. The standard provides guidelines related to chemical, physical, and biological contamination as well as moisture and temperature that can affect human health and perceived air quality. Also included are: construction and finishing materials, start-up, operation, and maintenance of HVAC systems. The IAQ assessment of the sick office building should incorporate the guidelines provided by the CIBSE TM26 and ASHRAE standard, "Ventilation for Acceptable Indoor Air Quality":

(1) New and renovated buildings should satisfy the heating and air-conditioning system design procedures as given by the TM26 guideline and ASHRAE standard.
(2) Check routine maintenance operations and failures, such as the regular changing of air filters.
(3) Building maintenance should include a record of all inspections and services for the life of heating and air-conditioning systems.

Environmental Monitoring of Moisture, Dampness, and Moulds

The WHO has produced IAQ guidelines for dampness and mould [11] and for management of buildings by controlling moisture, dampness, and provision of adequate ventilation. The WHO document emphasises the need to prevent moisture and mould forming on building surfaces and if there is evidence of mould, moisture, and dampness, immediate remediation should be undertaken to minimise occupants' risk of exposure to the microbial flora, airborne spores, and volatile toxins.

The investigation of mould infestation in buildings would involve a careful stage-by-stage survey to assess moisture and dampness in the building [1]; and to inspect materials for signs of moulds and deterioration. Environmental monitoring includes a study of the ventilation provision, measurements of temperatures, and relative humidity in the houses. The houses can either be occupied or unoccupied during the monitoring. Moisture in building materials can be measured with direct reading instruments using moisture meters, or by sealing a vessel over the surface and measuring the equilibrium relative humidity. Moisture surveys of buildings typically start with a qualitative sweep with a pinless type meter to determine patterns of moisture intrusion followed by a more precise measurement with a pin-type meter. Wherever possible, mortar from the affected areas should be taken to determine the salt and residual moisture content.

Moisture and inadequate ventilation are the keys to bio-deterioration and proliferation of moulds and mould spores in air. Once infestation has started, it will continue to propagate, if the condition is favourable until eventually the material can no longer sustain the fungal loads. Fungi differ in their optimum temperature for growth but for most, the range would be about 20–30°C. High temperatures above 40°C, e.g., in the tropics and strong sunlight will kill fungi. The water content in materials can support mould growth and in timber, a moisture content of 20–30% would be ideal for dry rot and other infestation [30,31]. Moisture will need to be monitored regularly, for:

- Indoor temperature, relative humidity, and dew point of the environment and also outsides;
- Surface moisture and moisture content of materials using moisture probes;
- Penetrating damp/rising damp;
- Moisture profiles in large dimension timbers and across masonry;
- Salt content of masonry;
- Condensation;
- Building disaster;
- Construction moisture;
- Building defects.

Moisture can move through building envelopes as liquid, vapour, or be carried as humid air infiltration. Materials such as sheet plastics, foam liners, bituminous or asphaltic coatings, and foil are vapour barriers and would reduce water permeation into buildings [32]. There is a need to examine the water proof membrane or other damp-proof course and vapour barriers in the house. These should be carefully located within an envelope and foundation of the building to prevent water ingress. Water condensation can occur within cavities of a building if vapour barriers and water proofing are improperly installed or not fitted to the house. However, sufficient moisture could occur inside the wall of a modern house to support mould growth due to diffusion of water vapour. A vapour barrier fitted to the inside of the wall would reduce the problem. In a warm humid climate the vapour barrier, however, would need to be fitted on the outside of the wall to prevent water ingress. In general, a vapour barrier should be fitted on the warm side of the insulation layer. If fitted on the cold side of the insulation (outside in cold climates, inside in hot humid climates) it would encourage condensation to occur within the building envelope. This should be part of the survey of the building with a reported IAQ problem.

Moulds and fungal spores could occur in hidden cavities and underneath the interior wall surfaces or in cavity walls in historical buildings. The diagnosis of the problem will involve regular inspection and survey using a variety of techniques and nondestructive monitoring. Nondestructive techniques including fiber optic inspection, ultrasonic, and infrared techniques would be needed for a survey without causing too many damages to the structure of the building. Simulation models [33] can be employed to determine the existence of moisture in the building but this will need validation by environmental monitoring.

An assessment of a problem building will involve a careful systematic inspection or survey of the building. The first step would be to identify the objectives of the survey, involving interviewing the owners/occupiers to identify the problem and the likely location of the problem. Also there is a need to inspect records, history, and plans of the buildings if these are available.

The second step would be to undertake a primary inspection of the house to look for signs of rot, mould and damp stains, algal growth, choked or overflowed gutters, defective roof coverings, leakages, faulty drainpipes, rain downpipes, and defective rendering. Inspect all timbers, beams and floorings; note symptoms such as warped or curled wall paneling, cracking or splitting in wall plastering and paint works. Strong mushroom and musty smell should note for signs of moulds. Other things to be noted are springing lintels or floors and fruiting bodies (Figure 2, fruiting body of dry rot in a badly neglected building) with a layer of red-dust like spores (Figure 3, dry rot spores covering the floor and other surfaces in a lavatory). Identify the moisture sources, moisture reservoirs, and moisture sinks (both actual and potential sources of dampness).

Once the problem area or the risk location has been identified, a follow-up inspection involving lifting of floorboards and wall panels will be required to locate

Fig. 2. Dry rot fruiting body and spores.

Fig. 3. Dry rot spores covering the surfaces.

the hidden mould. Nondestructive technique such as the use of fiber-optic endoscope would minimise damages in the first instance but more intrusive access to the problem will inevitably be carried out. Solum levels of sub-floor voids that are below the outside ground level are potentially vulnerable to flooding and difficult to ventilate properly. If the finish of a suspended timber floor is at or near the outside ground level then this would be above the solum level and this should be checked. Defects should be identified, which could lead to dampness; timbers and hidden timbers should be inspected to pin point the risks. Only by exposing the concealed timber structures in cavities or sub-floor, in ceiling or loft, would enable an examination of the timber conditions in certainty. However, sometimes the conditions of the concealed timbers could be deduced by examining the conditions and moisture content in the adjacent structures.

The monitoring of the range and sizes of fungal species could assist in the diagnosis of health symptoms [34].

For assessment of occupants' exposure risks to mould, environmental monitoring involving sampling of mould spores, both airborne and on surfaces, would be needed. There are a number of standard methods for sampling airborne spores and these are sampled by drawing air onto Agar growth medium for onsite spot sampling. The following are the International Standards (ISO) for air sampling of moulds:

- For a survey to cover a longer duration, mycological sampling of indoor air can be sampled by a filtration method as described by *ISO 16000-16:2008:* Indoor air – Part 16: Detection and enumeration of moulds – Sampling by filtration. Disposable sterile aerosol monitor cassette containing a 37 mm diameter 0.8 μm polycarbonate membrane filter (nucleopore) would be used for pumped sampling at about 4 L per minute for 4–6 h.
- *ISO 16000-17:2008*: Indoor air – Part 17: Detection and enumeration of moulds – Culture-based method – describes a dichloran glycerol selective agar (DG18 Agar) solid differential and low water activity medium, for the determination of xerophilic fungi in low moisture food and in indoor air.
- A Burkard agar plate impactor type sampler (*ISO DIS 16000-18:* Indoor air – Part 18: Detection and enumeration of moulds – Sampling by impaction); pumped sampling of about 20 L/min to obtain representative sample of indoor air. The agar medium used could be a 'general purpose' nonselective medium using malt extract agar (MEA) incorporating chloramphenicol to inhibit bacterial growth, but growth of all genera of fungi likely to be present in the indoor environment.

Surface samples can be taken directly from interior surfaces using the contact plate technique (Figure 4). Contact plates are a specialised type of agar plate used for taking direct mycological samples from surfaces. They are used by firmly pressing the plate against the surface and holding for 5 s. The agar medium used for contact plates should be the same as in the air sampling of spores, so as to allow direct comparison between the air and surface results.

The choice of samplers will require a careful consideration for the purpose of the investigation, information required, characteristics of the biological pollutants in the environment concerned, the sampling and trapping efficiency of the samplers to be used. For analysis, the agar plates are returned to the laboratories for incubation for 5 days at 25 ± 2°C. The fungal colonies should be enumerated and speciated, at least to genus level. Results were expressed as colony forming units (cfu) per volume of air (for air samples) or per sampled surface area (for surface samples).

Fig. 4. Contact sampling of molds on walls.

Other methods include sampling airborne allergens, airborne mycotoxins and volatile metabolites (e.g., 3-methylbutanal, octen-e-one, octan-3-one, octan-3-ol, 2-octen-1-ol, 1-octen-3-ol, 1,10-dimethyl-trans-9-decalol (geosmin), and endotoxins. The characteristic 'musty', 'mouldy,' or 'earthy' odors are associated with the presence of 2-methyl isoborneol and 2-methoxy-3-isopropylpyrazine and these could provide a good indicator of mould proliferation [4,20].

Guidelines for Assessing Environmental Risks

As the relation between dampness, microbial exposure, and health effects cannot be quantified precisely, no quantitative health-based guideline values or thresholds have been recommended by the WHO for acceptable levels of contamination with microorganisms [11]. The assessment will be based on the mix of species present, the nature of exposure, and the constitution of the personnel at risk. The presence of pathogenic species e.g., *Aspergillus fumigatus* and toxigenic species e.g., *Stachybotrys chartarum* would be an important indicator of health risks. Also of concern would be a sample containing predominantly allergenic species such as (some) *Penicillium* species. *Penicillium* species are important in the indoor environments, as they are often present in higher numbers in comparison to the local outdoor environment and probably the most frequently occurring indoor species. In a survey carried out by BRE of 180 homes in the Avon area in the UK between 1990 and 1992, *Penicillium* species were present in over 90% of intensively studied homes.

In terms of determining safe and disease causing levels of microorganisms in the indoor environment, BRE survey

Table 1. Suggested threshold levels for fungal spores in indoor air

Category	Fungi $cfu \cdot m^{-3}$
Very low	Less than 50
Low	Less than 200
Intermediate	Less than 1000
High	Less than 10,000
Very high	More

of 180 homes in the Avon area (1996) in the UK [35], reported an overall geometric mean count of 234.9 $cfu \cdot m^{-3}$ and this would provide a baseline for assessment of homes in the UK. In Canada, the Ministry of National Health and Welfare [36] has indicated in their technical guide to IAQ that unacceptable levels of air spora in the office environment may be as low as 50 $cfu \cdot m^{-3}$ if only one species is present, and 150 $cfu \cdot m^{-3}$ if a mixture of species is present.

A general 'guideline' for interpretation of results of mycological indoor samples for investigation of IAQ problem associated with moulds has been suggested:

- Visible fungal contamination of walls/surfaces/appliances should be absent.
- No known pathogenic species (e.g., *Aspergillus fumigatus*) should be present in the air or on surfaces.
- No known toxin-producing species (e.g., *Stachybotrys chartarum*) should be present in the air or on surfaces.
- There should be fewer fungi in air indoors compared to outdoors (approximately one-third of the number inside compared to outside). Actual numbers will vary considerably with seasons, weather, etc.
- Samples should show a mixture of species, often similar to the mixture of species found in accompanying outdoor samples. These species will often be representing organisms that are found on plant surfaces and in soil (e.g., *Cladosporium*, *Alternaria* species).
- Indoor samples that predominantly show one species, which is not reflected in accompanying outdoor samples; this would indicate an indoor source.

A suggested 'guideline' for threshold levels of fungi in indoor air [2,28] is shown in Table 1.

Conclusions

Health and safety issues relating to proliferation of toxic moulds should be an important consideration for architects, developers, building owners, managers, and agents.

The lack of maintenance, chronic neglect, and building defects leading to water ingress, condensation, and dampness in the building fabrics would lead to proliferation of toxic moulds and could cause complaints of sick buildings by occupants. The major sources of toxic mould occur in buildings on damp walls, in hidden cavities and voids particularly in warm, airtight buildings. Poorly maintained HVAC systems, insufficient ventilation, and bad building practices can also lead to microbial proliferation.

Indoor air quality management and management of biodeterioration and health problems in buildings are complex issues requiring multi-disciplinary investigations. The investigation of sick buildings would involve stage-by-stage surveys to assess moisture, dampness, and mould growth in buildings. The survey should also involve a questionnaire study of the occupant complaints (symptoms), records, history, and uses of the buildings as well as carrying out a general inspection of the condition of the buildings.

A general guide for an assessment of environmental risk relating to the proliferation of moulds in indoor environments has also been provided in this paper, which includes a suggested guideline for assessing the threshold levels for fungal spores in indoor air.

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