Indoor and Built Environment

Indoor Built Environ 2011;20;1:36–46

Accepted: November 5, 2010

Building Pathology – Toxic Mould Remediation

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Key Words
Remediation · Toxic moulds · Damp building · Building pathology · Environmental management · Case studies

Abstract
The purpose of this paper is to provide examples of strategies and procedures for remediation of buildings affected by toxic moulds. Four case studies are included in the paper. Moisture and inadequate ventilation are the keys to proliferation of toxic moulds and dispersion of spores in air. Prevention should always be the main objectives for any environmental management plan or service maintenance of a building. The management and remediation plan should include an adequate control of moisture, damp and ventilation in the building. The most effective strategy for remediating mould problems is by source control, preventing or limiting the generation of moulds, and the other is to remove the sources. There should be a detailed study to identify the sources of mould problems. The remediation could involve mothballing of a building to rectify defects including leaks and removal of damp materials; venting of underfloor or wall cavities and to improve the general airflow in the building. Remediation may involve vacuuming to remove spores in air and mould from surfaces. Other techniques include heat treatment, steam cleaning, biocides treatment, fumigation and UV treatment.

Introduction

This paper is a continuation of a series of papers published by the authors relating to building pathology. The quality of indoor environment of a building can be affected by the emissions of volatile organic compounds (VOCs) [1] and the proliferation of toxic moulds [2], which could cause an adverse impact on occupants' health due to exposure. The health impacts caused by the emissions of VOCs and toxic moulds have already been discussed in the previous papers [1,2] which also included a discussion of the investigation procedures of sick buildings and the indoor air quality (IAQ) guidelines for assessing the acceptable levels in buildings. This paper focuses on the remediation of buildings affected by toxic moulds and also discusses issues regarding the control of moisture and prevention of water ingress that would cause dampness and deterioration of building environments.

Infestation of mould in the built environment has now become a growing industry particularly in America [3].

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Los Angeles, London, New Delhi and Singapore
DOI: 10.1177/1420326X10392056
Accessible online at http://ibe.sagepub.com
Figures 1–3 appear in colour online

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The issues relating to the proliferation of moulds in buildings are gaining increasing importance, particularly in the USA where there have been litigations against the developers, owners, management agents and landlords (www.apsnet.org/online/feature/stachybotrys/). Mould infestation in residential buildings is also an important concern in Korea [4], Hong Kong [5,6], UK [7,8] and other countries [9–12]. The issues of possible legal actions and insurance effects on chartered surveyors and building owners as well as the general concern of well-being of occupants have prompted development of guidelines by some authorities [13–22]. These concerns are reflected by the home insurance and home buyers: (http://homebuying.about.com/cs/mold/a/toxic_mold.htm, http://personalinsure.about.com/od/homeowners/a/aa101905a.htm).

The best strategy for remediating mould problems depends on the particular circumstances, including the severity of the problem, the number of affected persons, economic concerns and whether or not the building can be conveniently vacated for a time period to undertake remediation work. There are two general ways to reduce indoor air pollutants. The most effective way is by source control, preventing or limiting the generation of moulds, and the other is to remove the sources. There should be a detailed study to identify the sources of the mould problem, including a diagnosis of the mould symptoms, and this has been described in the previous paper [2].

Diagnosis and Identification of Mould Problems

IAQ management and management of bio-deterioration and health problems in buildings are complex issues that will require multi-disciplinary investigations and environmental monitoring [2]. Lack of maintenance, chronic neglect, insect infestation, flooding and deterioration of building materials caused by moisture; and building defects leading to water ingress, condensation and dampness in the building fabric will often produce proliferation of moulds that could be pathogenic to humans leading to sick buildings. Building pathology is the scientific study of abnormalities in the structures and functioning of the building envelope and its parts, which could lead to ill health of the occupants and a poor habitats for a living environment [2,23]. The inter-relationship of occupants' behaviour, building materials, construction (particularly air-tightness of building), building services and spatial arrangement of the occupants' environment can have a major effect on the proliferation of mould and these were previously discussed [2]. The particular health effects (symptoms) could also provide an indication of the type of mould infestation. Therefore, a careful survey (environmental conditions: relative humidity, damp, heating, lighting and ventilation levels and materials deterioration), including a questionnaire study (symptoms, records, history, uses, activities and building services) should be carried out prior to any environmental monitoring, analysis and assessment of moulds to determine causes of the sick building [2]. Identify the moisture sources, reservoirs and sinks which are important for the subsequent remediation of the problem [24,25].

Moulds thrive in damp buildings and these can have a strong link to respiratory diseases in relation to poor IAQ in homes. Mould will grow on any organic matters and these would include many building materials, furnishing and consumer products used in the house. Organic matters from humans, pets, pests as well as dusts (wood, paper, foam and human skins) are also important sources of nutrients for mould growth. The indoor temperatures between 15°C and 32°C are optimum for mould and an indoor relative humidity of about 65% would be ideal for mould to proliferate, especially in an environment with little ventilation or direct sunlight (e.g. wall and floor cavities). Careful step-by-step monitoring and inspection of the building would identify signs of rot, stains (mould and damp), moulds, algal growth, defective roofing, rising damp in basement, penetrating damp on walls, excessively high indoor humidity, roof and windows leaks, choked gutters, faulty drainpipes, rain downpipes, blocked drains and defective rendering. Inspect all timbers, beams and floorings, note symptoms such as warped or curled wall panelling, cracking or splitting in wall plastering and paint works. Strong mushroom and musty/earthy smell should be noted for signs of moulds. Identify the moisture zones (both actual and potential sources of dampness). The identification would then inform the remediation strategy later for rectifying problems.

Strategies for Control and Prevention

The key to develop a strategy to prevent and control mould growth is to limit moisture and sources of nutrients [25–27]. Moisture and inadequate ventilation are the keys to proliferation of toxic moulds and dispersion of mould spores in air. Prevention should always be the main objectives for any environmental management plan or service maintenance of a building. The management and remediation plan should include adequate control of moisture (e.g. condensation), damp (e.g. ingress of water due to leaks or failure in damp proofing) and also ventilation in the building. High temperatures above 40°C, for example, in the tropics and strong sunlight (UV irradiation) will limit fungal growth. 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 [28,29]. Moisture in the materials and in the indoor and outdoor environments should be monitored regularly [2].

The most practical way to control mould growth would be by controlling the moisture development in the building, reducing humidity and water ingress due to building defects and from leaks in piping, plumbing and sewage system. Therefore, assessing the moisture, managing and preventing moisture development would be the key to maintaining a healthy building in relation to mould growth. This is emphasised in the World Health Organization (WHO) guidelines for dampness and mould and for management and ventilation of buildings [30]. Methods for controlling moisture in new buildings including ventilation and heating are given in the WHO guide. Regular monitoring and maintenance of building services would also be important to ensure good practice is observed and to reduce defects.

There is a need to examine the waterproofing 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 [2]. Water condensation can occur within cavities of a building if vapour barriers and waterproofing 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) would encourage condensation to occur within the building envelope. This should be part of the survey of the building with a reported IAQ problem. The increasing requirement of building air-tightness and insulation of building components, particularly in the refurbishment of older buildings could lead to condensation risks. A Building Research Establishment (BRE) guide [31] to good practice building construction has provided technical advices regarding insulation of walls, floors and roofs and windows to avoid the risks of condensation forming in buildings. The thermal response of the roof, wall or floor is often affected by the positioning of the thermal insulation. High mass elements warm and cool slowly (slow response) and light weight elements, rapidly (rapid response). The report provides guidance to match the thermal response of the internal fabric with the type and pattern of heating to avoid the risk of surface condensation. Where the thermal response is slow, constant low output heating systems are more appropriate; quick acting intermittently used heating systems are better suited to constructions with a faster thermal response.

Domestic humidifiers and air conditioning systems are important sources of mould flora in buildings. Insufficient maintenance of HVAC systems, filters, pans and duct works will lead to development of mould growth. CISBE TM26 [32] and ASHRAE 62-1990 [33] provide the standard protocol for IAQ fresh air supply and maintenance of HVAC system for maintaining office ventilation ductwork to reduce microbial contamination in air distribution system and building environment.

Remediation Planning

The best strategy for remediating mould problems will depend on particular circumstances, including the severity of the problem, the number of affected persons, economic concerns and whether or not the building can be conveniently vacated for a time period to undertake remediation work. The most effective way is by source control, preventing or limiting the generation of moulds, and the other is to remove the sources. There are many considerations to take into account when devising strategies to control and deal with instances of possible mould. As well as the basic considerations such as the health and welfare of the occupants and the ongoing condition of the building, there are other factors that may become just as important, at various times in the project which should be included in the consideration:

- How far has the problem spread? What is the extent of the mould infestation in the building fabric?
- How to protect the people who will be carrying out the remediation?
- When can the remediation be safely carried out, without endangering anyone else's health or adversely affecting the function of the building?
- What are the criteria for monitoring and assessing the satisfactory completion of the remediation?

These are just some of the factors that need to be considered, for an appropriate strategy to be developed. A thorough risk assessment should be conducted to consider all these factors and appropriate control measures to prevent or control exposure, put in place. Fungal and insect problems in both modern and historic buildings are mainly the result of defects in buildings, lack of maintenance and gross neglect. Rectifying these defects and by ensuring proper maintenance can provide long-term sustainable, holistic solutions to these problems. In preparing a strategy to remediate a contaminated area, a risk assessment should be part of the process to consider requirements in a range of issues, such as:

- the remediation process and activities;
- the undertaking of remediation without spreading contamination outside the work area; and
- protection of the personnel undertaking the remediation and immediate occupants working and living in the remediation areas.

Risk assessment involves hazard identification, exposure assessment, dose response assessment and risk characterisation. The use of an enclosure or segregation of the work area may be sufficient to prevent occupants of the building and those not involved from being affected by the remediation process. In some circumstances, the immediate area and vicinity may need to be vacated to ensure that exposure cannot occur. The remediators themselves should also be protected; and respiratory protection (RPE, respiratory protection equipment) and appropriate skin and eye protection are vital parts of this. In selecting the type of RPE most suited to the activity, it is important to consider all factors such as the type and likely airborne concentration of the fungal spores, the practices employed and the time of exposure [34]. The chosen respirator may be a simple disposable dust mask of appropriate standard for minor works to a powered full-face respirator for larger extensive projects, depending on the particular requirements and the extent of the mould infestation. In extreme cases, the interface between the clean and the contaminated areas may require decontamination facilities and procedures so that the remediators do not spread mould as they enter and leave the work area.

The remediation could involve a range of techniques: wiping, cleaning, biocidal washing and coating, vacuuming of mould from surfaces and removing spores in the air, and in some cases UV treatment of indoor spaces [35,36], removal and replacement of materials etc. depending on the extend of the problem [37].

In order to safeguard operatives and prevent spread of airborne contamination to other parts of the property and the general atmosphere beyond, an "asbestos type" removal facility should be created. The exact detail of this aspect will depend on the requirements of the designated contractor, but the following general principles should be observed. An air-tight enclosure should be constructed to encompass the two most affected rooms (e.g. the main bedroom and dining room) and including a protected walkway with three-stage airlock to allow safe entry and egress of the enclosure. A suitably sized air mover fitted with high efficiency particulate air (HEPA) filtration should be fitted to ensure negative pressurisation within the enclosure. Decontamination facilities and procedures should be incorporated. Adequate messing and hygiene facilities should also be provided. The work should only be performed by trained professionals experienced in dealing with hazardous materials. Training should include familiarisation with the nature of the problem and the use of personal protective equipment (PPE) and all control measures. These should include wearing of PPE including full-face positive pressure respirator with HEPA filter suitable for organic vapours (A2 filter), impervious gloves and full skin protection to be worn. A disposable hooded coverall will assist in this latter respect. The working patterns adopted for the personnel carrying out this remediation work should reflect the arduous nature of the environment and the additional strain created by the use of the specified PPE. It is recommended that no more than 1 h at a time should be spent within the enclosure, with regular rest periods being taken in an uncontaminated area.

Contaminated waste, including used PPE, should be removed from site in sealed polythene bags or sheeting. All sealed bags and packages should be vacuumed using a type H vacuum cleaner fitted with a HEPA filter and cleaned externally with a damp cloth before removal from the enclosure. There are no special disposal requirements for the waste, although this aspect should be confirmed with the receiving authority. Following removal of retained items and waste materials, the work area should be cleaned using a type H vacuum cleaner fitted with a HEPA filter, followed by use of a damp cloth or mop with a detergent solution. All areas should be left dry and visibly free from contamination. On completion of remediation works, the enclosure surfaces should be cleaned and disposed of along with the waste materials. The remaining areas of the property should then be subjected to an environmental clean-up to remove all remaining traces of contamination that has spread throughout the house, prior to identification of the problem.

Having completed a remediation project, it is important to re-assess the cleanliness of the area and hence any possible ongoing exposure of the occupants. The use of air and surface sampling tests, with appropriate analysis will allow a judgement to be made. Ongoing monitoring of the situation is vital to confirm that any structural toxic mould repairs have been effective and that satisfactory drying out of the building is occurring. Of course it is possible that the mould may return, and this is an issue that may need further consideration in due course. The extent of ongoing monitoring depends on a considered judgement including the following factors.

- confidence in repairs carried out to prevent moisture ingress;
- general condition of building to withstand further deterioration;
- proximity of susceptible individuals that may be exposed;
- importance of items/structures likely to be affected; and
- costs/implications of a major recurrence.

In making the case for ongoing monitoring it is important to consider the implications of another similar instance of mould growth, taking into consideration the principle that early diagnosis leads to a much more cost-effective solution.

Remediation Techniques

Mothballing is preventative conservation and is the best way forward for cost-effective environmental management of deterioration of historical fabrics, contents, decorative finishes and fixtures. The key elements in mothballing of buildings are minimising further water ingress in the building and encouraging natural drying of saturated areas of buildings. A range of different types of techniques can be used, for example:

- rectifying defects in downpipes and guttering and clearing out valley and other blockages in the rainwater drainage systems;
- accelerating underfloor ventilation by lifting up one or two floor boards along the external elevations and set aside for reuse;
- encourage general ventilation in the building by opening up windows and internal doors, clear chimney flues, clear roof voids and clear the storage goods to encourage crossventilation; and
- removal of moisture saturated materials from the building for example floor coverings, debris and unwanted storage goods.

These actions will bring changes in the environmental conditions of the building and as a result microorganisms will struggle to grow and proliferate by denying them the optimum conditions for their survival, thereby reducing the risk of further infestation. Fungi in general have a very wide temperature tolerance range from 0°C to 60°C. Usually, a relative humidity in excess of 65% would be required for their growth. They sustain on simple food sources of simple sugar and other organic matter and these can generally be provided from organic dust deposits and particulate matters in the built environment. Air movement would provide sufficient oxygen. Controlling the availability of moisture is the only way to limit their growth in indoor environment. Water availability depends on its sources and movement, the occurrence of moisture reservoirs and sinks, heating, insulation, ventilation, external conditions, orientation of the building, materials and occupants [2]. These inter-relationships are complex and will need careful consideration when planning mediation.

Remediation may involve dry vacuuming of mould from surfaces, wiping with a damped cloth or simply disposal of the contaminated item, the preferred process varying according to various factors. The ease of cleaning of a contaminated surface will obviously depend on the adherence of the mould to that surface. This in turn is affected by the porosity of the surface, the "smoothness" of the surface on a molecular level and the presence of cracks, joints or other crevices in the contaminated surface. Hard surfaces such as glass, metals and glazed ceramic tiles can be decontaminated relatively easily, whereas porous surfaces such as bare masonry or timber represent the opposite extreme. Where surfaces cannot be adequately cleaned, disposal of the item may be the preferred option. The intrinsic value of an item may mean that incomplete decontamination may be an acceptable option in some cases. Various other techniques are available, for example, heat treatment, steam cleaning, biocides treatment, fumigation and UV treatment. The following provides a list of possible types of remediation treatment that might be appropriate for a project:

- filter the contaminants;
- ventilation;
- treat with liquid nitrogen to kill house dust mites;
- vacuum cleaning;
- cleaning;

- coating;
- biocide treatment;
- UV irradiation;
- air conditioning; and
- mothballing.

Environmental control and preventative maintenance are preferable to chemical means. Preventative maintenance should in most cases forestall the need for major interventions, and would reduce the cost of conservation of building. Since the internal environment of a building is a product of a number of influences, it is advisable to study these ecological factors, such as the temperature, humidity and air movement at the micro-environment levels and the response and performance of the building before undertaking any intervention involving any building work. Continuous monitoring of the internal environment can ensure the long-term health of the building materials and structure and also the occupants. In general, the clearance assessment of mould should be undertaken by a repeated inspection of the affected property immediately after remediation and then a further assessment by monitoring about 1 month after the re-occupation. Further monitoring and assessment may be required if mould growth recurred.

Case Studies

These principles and techniques have been successfully applied at many prestigious locations, both in the UK and abroad. Some of these include the Dover Castle, where historic artifacts in the museum, as well as the castle structure itself, have been remediated and preventative measures introduced to limit or prevent recurrence. At the National Library of Scotland, many important books and documents have been sympathetically decontaminated and preserved. The same approach has been just as successful in mundane buildings such as offices and private houses.

Following flood damage at the National Library of Scotland, one of the Strong Rooms on the "stack floor" became contaminated with mould infestation. Toxic mould had infested the cellulose-based linoleum and Gyproc plasterboard that made up the wall of the strong room adjacent to the smoke ducting. All of the collections had since been removed from the area and a survey had been conducted. Laboratory testing at Environmental Building Solutions Ltd. (EBS) in the UK, confirmed the presence of toxic mould (*Stachybotrys chartarum*). A protocol for toxic mould removal and a "plan of work" to remove the significant mould accumulation and reinstate the area back to dry shell was established. The risk of mould in the library was twofold: it presented an obvious health risk which was only getting greater; and also a risk of physical destruction to the valuable books and the fabric of the building. Operatives were required to wear specialist RPE providing organic and dust protection to an assigned protection factor (BS 4275:1997) of 40. Remediation protocols and methods to consider are as follows:

- containment of affected area in order to prevent any spread of mould spores during mitigation activities;
- containment of affected area;
- removal and disposal of contaminated materials;
- HEPA negative pressure air filtration; and
- HEPA vacuuming of affected area (structure and contents).

Case Study 1

At a site in Chatham, Kent, the basement in the shop premises had become infested with several species of mould, including wood rotting fungus, *Serpula lacrymans*, in load-bearing timbers supporting the ground floor. The infested areas were treated and remediated environmentally to assist the drying process and reduce the possibility of spread of organisms throughout the premises. The process was carried out with full enclosure and appropriate PPE for all personnel involved. All waste was disposed of, via authorised routes for microbiologically hazardous material.

The basement of the building was generally in very poor condition. There were visible signs of active wood rotting fungi and insects throughout the basement of the building. These include the following:

- true dry rot (*S. lacrymans*);
- wet rots (*Coniophora puteana, Asterostroma* spp.); and
- woodworm (*Anobium punctatum*).
- there was extensive mould infestation throughout the basement and the following active moulds were isolated:
- *Penicillium chrysogenum*;
- *Penicillium vermiculatum*;
- *Aspergillus niger*;
- *Aureobasidium pullulans*;
- *Cladosporium herbarum*;
- *Stachybotrys chartarum* (toxic mould); and
- yeasts.

Average levels (triplicate samples at three locations in the basement and the shop):

- before remediation 6780–7650 CFU m^{-3}
- after remediation 410–440 CFU m^{-3}.

Case Study 2

At the National Library of Scotland in Edinburgh, a substantial overnight water leak as a result of action by a negligent contractor contaminated a large number of rare volumes of books and manuscripts. The time of the event had led to a delay in its detection and it was found that water had penetrated several floors as it proceeded through and down the building. As well as damage to the documents, there was also significant damage to the fabric of the building and hence a threat to other as yet undamaged documents. There were several aims in remediating this situation. Care of the books and manuscripts was obviously a priority and these were removed to an unaffected area where careful low-temperature drying techniques were used. The fabric of the building was assessed initially for moisture penetration and a bespoke drying strategy using mechanical drying aids was developed to enable all affected areas to be remediated simultaneously and at optimum speeds. As the process continued the situation was continually monitored to spot any instances of mould formation and, all, an early response to be actioned. Following several months of carefully controlled treatment, the library building and documents were all restored to acceptable conditions.

The most dominant genera isolated on various floors were the following:

- *Penicillium*;
- *Cladosporium*; and
- *Aspergillus*.

Other dominant moulds, which were encountered in this study, were:

- *Alternaria alternata*;
- *Aspergillus versicolor*, *Aspergillus* spp. 1, *Aspergillus* spp. 2;
- *Aureobasidium pullulans*;
- *Cladosporium cladosporioides*, *C. herbarum*, *Cladosporium sphaerospermum*;
- *Penicillium glabrum*, *Penicillium expansum*, *P. chrysogenum*, *Penicillium* spp. 1, *Penicillium* spp. 2 and *Penicillium* spp. 3;
- *Stachybotrys chartarum*; and
- yeasts and 10 unidentified species.

Average levels (triplicate samples at the various locations on every floor in the library):

- before remediation 750–930 CFU m^{-3}
- after remediation 230–240 CFU m^{-3}.

Case Study 3

A couple had gone off on an extended holiday leaving their period house unattended. Unfortunately, during their absence, a central heating radiator in the first floor bedroom had developed a pin hole leak, allowing a jet of water to escape and spray water around the room. This had evidently gone on for some time because by the time it was detected, the whole of the room, the dining room beneath it and the basement beneath that had become wet and contaminated with a wild array of mould organisms including *S. chartarum*, which has been regarded as being a toxic mould. A substantial remediation programme was devised to remove all contaminated materials from affected areas of the house. Although in this case inhalation of airborne spores may be considered to be the prime hazard to those entering the affected areas, it should be borne in mind that in this situation, the mould growths will also release mycotoxins into the atmosphere, particularly in highly infested situations. Because of the extent of the mould growth in this case, this aspect was considered to be a significant risk and special measures had to be introduced to deal with the issue. As well as the usual negative pressure enclosure and personal protection, additional measures including respirators to protect against emissions of VOCs were utilised. After a long remediation process, with stage-by-stage contamination checks to confirm that the mould had been banished, followed by a reinstatement programme, the rooms were restored to their original glory (Figures 1–3).

The most dominant genera, which were encountered in this study, were the following:

- *Aspergillus* spp.;
- *Cladosporium* spp.;
- *Chaetomium*;
- *Mucor* spp.;
- *Rhizopus* spp.;
- *Penicillium* spp.;
- *Stachybotrys chartarum*;
- *Trichoderma viride*; and
- yeasts.

Fig. 1. Mould growth on the dining room walls of the infested property.

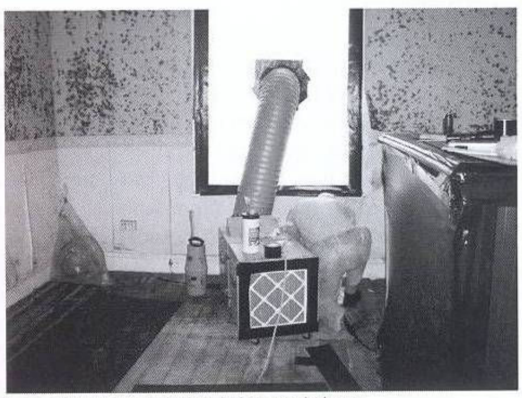

Fig. 2. Mould remediation being carried out.

The most dominant species isolated in this study were the following:

- *Alternaria alternata*;
- *Aspergillus versicolor*, *A. niger*, *Aspergillus* spp. 1;
- *Aureobasidium pullulans*;
- *Cladosporium cladosporioides*, *C. herbarum*;
- *Chaetomium globosum*;
- *Eurotium chevalieri*;
- *Fusarium* spp.;
- *Mucor* spp.;
- *Penicillium aurantiogriseum*, *Penicillium brevicompactum*, *P. expansum*, *P. chrysogenum*;
- *Paecilomyces variotii*;
- *Rhizopus* spp.;
- *Trichoderma viride*, *T. harzianum*;
- *Ulocladium chartarum*;
- *Ulocladium atrum*;

Fig. 3. Mortar sampling to determine the extent of residual moisture in the building fabric.

- yeasts; and
- Sixteen unidentified species.

Average levels (triplicate samples in the bedroom, dining room and basement):

- before remediation: 765–17,700 CFU m^{-3}
- after remediation: 310–430 CFU m^{-3}.

Case Study 4

Toll Bar in Doncaster was one of the areas, most badly affected by flooding in South Yorkshire in June 2007. Several hundred properties had been flooded to an internal depth believed to be up to a metre. The flood waters took several days to recede, resulting in devastating effects. Much of the internal plaster and timber-studded walls of the properties had been removed at the ground floor level, allowing more efficient drying of the structure to occur. Following a long period of the water receding and buildings drying out, the local council undertook a mammoth programme to refurbish the affected homes. Although all the internal fittings of the houses were stripped out for replacement, because of the length of time that the building fabric had been wet, several properties had developed a widespread incidence of mould growth. EBS undertook a scientific survey of 13 of the worst affected houses, some 6 months after the event.

The findings showed a wide range of mould species but none of those could be regarded as being toxic. Following this confirmation, the refurbishment programme progressed to completion, with the residents finally getting back into their homes, some of them after over a year in temporary accommodation such as caravans.

The remediators themselves were protected with RPE and appropriate skin and eye protection are vital parts of this. In selecting the type of RPE most suited to the activity, it was important to consider all factors such as the type and likely airborne concentration of the contaminants (fungal spores and VOCs), the practices employed and the periods of exposure. The chosen respirator in this case should be a powered full-face respirator, because of the extensive remediation involved and the physical nature of the work. The interface between the clean and the contaminated areas will require decontamination facilities and procedures so that the remediators do not spread mould as they were entering and exiting the work area.

The most dominant genera, which were encountered in this study, were the following:

- *Aspergillus niger*;
- *Cladosporium* spp.;
- *Penicillium* spp.; and
- yeasts.

The most dominant species isolated in this study were the following:

- *Alternaria alternata*;
- *Aspergillus niger, A. versicolor*;
- *Aureobasidium pullulans*;
- *Cladosporium cladosporioides, C. herbarum*;
- *Chaetomium globosum*;
- *Penicillium aurantiogriseum, P. brevicompactum, P. chrysogenum;*
- *Trichoderma viride*;
- yeasts; and
- Five unidentified species.

Average levels (triplicate samples in the various rooms in 13 houses):

- before remediation 970–1320 CFU m^{-3}
- average level after remediation 220–230 CFU m^{-3}.

This investigation yielded fungal concentrations at various sampling locations, and replicates ranging from 970 to 1320 CFU m^{-3}, indicating that there were significant reservoirs of mould contamination in the indoor environment of a house at Langar Close, Toll Bar, Bentley, Doncaster. This was taken into the consideration during the planning and undertaking of the remediation of all the properties affected.

Final Clearance Criteria

A general guideline for assessing the acceptable indoor level of mycological indoor samples for investigation of IAQ problem associated with moulds has been suggested [2] based on the survey of 180 homes in Avon in the UK by BRE [38]. A geometric mean count of 234.9 CFU m^{-3} would be the baseline number for assessment of homes in the UK. In Canada, the Ministry of National Health and Welfare [39] 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 m^{-3} if only one species is present, and 150 CFU m^{-3} if a mixture. A suggested "guideline" for threshold levels of fungi in indoor air [2,23] was used to determine the relative safe level after remediation and mould abatement projects. However, the final clearance should also include survey inspection of the properties, about 1 month after remediation work has been completed. The survey should show no visible mould contamination on walls, the air samples should contain no pathogenic (e.g. *Aspergillus fumigatus*) and toxin-producing species (e.g. *S. chartarum*) and there should be fewer fungi in air indoors compared to outdoors (approximately one-third of the number inside compared to outside).

In all the cases reported above, the average levels found in the properties after remediation work were within the low (200 CFU m^{-3}) to intermediate (1000 CFU m^{-3}) and were within the 1 : 3 indoor to outdoor (I/O) ratio. The analyses of the air samplings showed that the pathogenic and toxic moulds were successfully removed by the remediation work. No further mould infestation has been reported by the owners or the properties managers since the remediation had been completed. The recommendations suggested by Quezada and Lange [40] were observed in the case studies reported. The final clearance criteria [40] after mould remediation included the following protocol:

- At least five to seven air samples (in triplicates) per property should be collected and determined after a visual inspection following remediation. Outdoor air samples (at least 3 m away from building) should also be collected. The analysis of moulds should help to determine whether the toxic and pathogenic moulds still persisting in the property.
- Non-parametric statistic testing [41,42] should be carried out to determine whether the airborne fungal spore concentrations are still within the accepted level as comparison to outdoors.

- An I/O ratio of fungi count should be approximately less than 1.
- The inside samples would be considered acceptable if the inside samples were statistically lower than that of the outside or if no statistically difference exists at 5% level or less.
- The indoor mould spore concentrations in the building after remediation can be predicted using mathematical model based on the mechanism of spores transportation due to mechanical ventilation system [43].

Conclusion

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. The management and remediation plan should include an adequate control of moisture, damp and ventilation in the building. The most effective way is by source control, preventing or limiting the generation of moulds, and the other is to remove the sources. Preventative maintenance should in most cases forestall the need for major interventions, and would reduce the cost of conservation of building. Since the internal environment of a building is a product of a number of influences, it is advisable to study these ecological factors, such as the temperature, humidity and air movement at the micro-environment levels and the response and performance of the building before undertaking any intervention involving any building work. Continuous monitoring of the internal environment can ensure the long-term health of the building materials and structure and also the occupants.

This paper has provided a guide to prevention, control and remediation of toxic mould infestation by discussing the factors involved and these are illustrated by the case studies.

Acknowledgment

This research was supported by the Basic Science Research Program through the National Research Foundation (NRF) of Korea, funded by the Ministry of Education, Science and Technology (No. 2010-0001860).

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