2022 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
University of Calabria, Italy, October 19-21, 2022

# Biodeterioration in historic buildings. Indoor environmental conditions and risk of fungal growth

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***Abstract* – Conservation of historic and cultural heritage poses great challenges, as the causes threatening the integrity of structures are becoming more frequent, including inadequate maintenance, the occurrence of exceptional events (such as floods and fires), as well as the exposure to increasing levels of air pollution. Furthermore, even during normal operation and in controlled indoor environments, the conditions can become favourable for the colonisation and development of harmful agents. The fungal contamination and growth on indoor building materials can alter the surfaces and deteriorate the building elements. In the present work, a preliminary investigation is conducted aimed at analysing the critical conditions for the proliferation and growth of different fungal genera or species, on commonly encountered materials in historic buildings. The study is carried out considering the climatic conditions of two locations, typical of northern and southern Europe, respectively. Possible solutions are suggested to limit the proliferation of microbiological contamination and growth and to prevent degradation phenomena of cultural heritage.**

## I. INTRODUCTION

Biodeterioration in buildings occurs due to various agents and mechanisms, and the effects caused on colonised materials are different. Generally, mould and moisture related problems are reported in literature among the factors that generate building pathologies. Indoor dampness and excess moisture are indicators of fungal growth and an important risk factor for public health. Contamination and growth of moulds in indoor environments result in exposure of the occupants to toxins, spores, cell fragments and Microbial Volatile Organic Compounds (MVOCs), degrading the indoor air quality and leading to adverse health effects and symptoms. Sources of water in buildings are quite diverse, including natural, ambiental factors, as well as anthropogenic. So, dampness can be the result of water penetration in the construction or in the building due to rising moisture from the ground, excessive rain, melting snow, flooding, or leaks of plumbing. On the other hand, it can originate from normal, everyday activities of the occupants i.e., cooking, bathing, drying of clothes, cleaning and even breathing [1].

A systemic approach to the problems of humidity in buildings was adopted by Pietrzyk [2], providing a tool able to address the probabilistic risk/reliability analysis of building performance with respect to mould safety. As stated by Andersen et al. [3], both nature and culture influence the fungal composition indoors, as they determine the ways and habits of opening windows and, consequently, the permeability and exchanges between internal and external environments. Cases of pre-contamination of building materials have also been detected, as observed for example by Andersen et al. [4] for gypsum wallboard, which suggest that some species of fungi are already incorporated in the materials from the fabrication stage.

Construction practices, in addition to the building's condition and characteristics play an important role for the creation and accumulation of moisture. For example, air tightness and high insulation level of newly constructed buildings obstruct the free movement of air, leading to increased dampness. A study was developed by De Castro Silveira et al. [5] in order to understand the influence of

the use of thermal insulation and the solar orientation of the walls in the mould growth in naturally ventilated residences. The periods of occurrence of ideal conditions for formation and growth of moulds were evaluated based on simulations. Coupled heat and moisture transfer was instead adopted in [6] to evaluate the influence of humidity on the thermal transmittance. When it comes to historical buildings, placing internal insulation can result in decrease of the material's surface temperature, moisture accumulation in the construction, while also affecting its ability to dry out [7]. The study conducted by Guerra et al. [8] on a historic building located in Porto Alegre (Brazil) led to the isolation of 60 colonies of fungi that attack mortar coating. The investigation carried out by [9] on the limestone walls of the old cathedral of Coimbra (Portugal) proved that the mycobiota associated with different biodeterioration types are taxonomically distinct. The parallel use of traditional cultivation methodologies and modern Next Generation Sequencing techniques (NGS) is recommended to obtain the complete profile of these colonizers. Ponizovskaya et al. [10] used both literature data and the results of a wide-scale experimental campaign involving fourteen objects (monuments and museums) to characterise the main community groups of culturable micromycetes of mineral building materials, i.e. limestone and plaster, in interiors of cultural heritage, trying to explore their role and participation in the biodeterioration process. A distributed measurement system is proposed by Lamonaca et al. [11] to monitor the environment of a museum, allowing to count the Colony Forming Units and evaluate the pollution by fungal spores.

The aim of the present research is to investigate biodeterioration in cultural heritage by analysing the microbial flora that can attack building materials commonly found in historic buildings. The occurrence of critical conditions for fungal growth is assessed with reference to the typical climate of two localities, representative of northern and southern Europe. Finally, possible mitigation strategies are suggested in order to prevent degradation phenomena.

## II. MATERIALS AND METHODS

### A. *Origin and parameters affecting fungal growth*

Fungal growth is the outcome of a complex and multivariate process. It is dependent on many different and often interdependent factors, making it very difficult to predict its appearance. The main parameters affecting the development of mould are the hygrothermal conditions dictating the moisture availability, the properties of the material serving as substrate and the availability of required nutrients. In general, microfungi are very resilient organisms and can survive under unfavourable conditions for a long time until the appropriate circumstances arise, and spores can germinate on the surface of materials.

The affinity of different fungal genera for specific materials is dependent on the materials' characteristics, as well as the environmental conditions in relation to temperature and humidity. For fungi to grow, a nutrient source is necessary. This can be in the form of simple carbohydrates, which means that even accumulated dust can serve as nutrient. Organic materials are, therefore, at high contamination risk. Nevertheless, moulds could practically colonise almost any material. Other relevant characteristics of materials are porosity, moisture absorbing potential, alkalinity and presence of additives on the surface. Finally, persistent or prolonged dampness and condensation are critical indicators for microbial contamination. So, when investigating the risk of fungal contamination on a construction, the analysis can start by assessing the condensation probability on the surfaces. Water availability is normally described in terms of water activity (aw), which refers to the amount of unbound water that the microorganisms can use. Depending on the species and their preferred level of water activity, fungi are often divided into three categories: xerophilic, mesophilic, hydrophilic. Another way to divide fungi is based on the order they will appear on a material as the amount of water gradually increases: primary, secondary and tertiary colonisers. Based on previous research, we know that the favourable range for growth of fungi is approximately at 75-100% Relative Humidity (RH), even though there are certain species that can grow at even drier conditions [12,13]. Other studies have suggested more generalised growth conditions with the temperature ranging between 0-50 $^{o}$C and RH of at least 80% [14], while keeping in mind that for lower temperature than the optimal for the specific filamentous fungi, higher RH is necessary for fungal growth to be developed.

Several studies have focused on identifying some of the most encountered fungal groups of indoor environments [15,16] and determining the required hygrothermal conditions by different fungal species. Some of the most reported fungal genera are: *Penicillium*, *Aspergillus*, *Stachybotrys*, *Cladosporium*, *Paecilomyces*, *Trichoderma* [17-19]; while on a species level are: *Aspergillus fumigatus*, *Aspergillus melleus*, *Aspergillus niger*, *Aspergillus versicolor*, *Cladosporium herbarum*, *Penicillium brevicompactum*, *Purpureocillium lilacinum* [20], *Stachybotrys chartarum* [17]. An investigation on the effect of indoor conditions to the growth of *Aspergillus niger* and *Cladosporium sphaerospermum* suggests that the temperature range of 25-30 $^{o}$C favours the colony diameter, while maximum growth is achieved at RH of 75% and 100% for *Aspergillus niger* and *Cladosporium sphaerospermum* respectively [21]. Menetrez et al. concluded that *Stachybotrys chartarum* will attain visible growth only on wetted materials when RH is below total saturation or even with high relative humidity levels [22]. When researching the mass occurrence of *Penicillium corylophilum* in crawl spaces, Bok et al. concluded that the RH level had to be maintained at 80-100% for several consecutive months [23].

### B. Common construction materials in historic buildings and associated fungal species

The analysis was performed for some commonly used materials in historical buildings: brick masonry, limestone and plaster finish (Fig. 1).


*Fig. 1. Analysed building materials for historic buildings: brick masonry (a), limestone (b), plaster (c).*

Previous research has shown that it is very important to know what to look for when performing an investigation in relation to fungal contamination [24]. A summary of associated mycobiota of the examined materials is, therefore, presented. These connections have been drawn from analysing existing literature and studies that have investigated the associations between fungi and building materials. Due to the complexity of the topic, there are a few things that need to be taken into consideration when evaluating previous research on fungal growth. Firstly, the conditions of each study need to be considered. Results vary greatly based on the chosen methods and decisions made. For example, naturally infested materials might have different mycobiota than inoculated materials in the laboratory. Growing conditions, duration and duration cycles of exposure stages, detection methods, assessment criteria etc. affect the results greatly. Secondly, filamentous fungi, like most organisms, can be considerably different in various countries and climatic regions. Nevertheless, for the purpose of this study, the most frequently reported fungal genera or species have been gathered, with the hope to create a short database for future reference. By identifying the main agents on specific building materials, better preservation strategies can be selected. The identified fungi genus and species are listed in Table 1.

*Table 1. Fungi affecting building materials.*

| **Fungi Genus** | **Fungi Species** | **REF.** |
|---|---|---|
| **PLASTER** | | |
| *Acremonium spp.* | | [10,25,26] |
| *Alternaria spp.* | | [25,27,28] |
| *Aspergillus* | *niger* | [27] |
| *Aspergillus* | *sydowii* | [29] |
| *Aspergillus* | *versicolor* | [29] |
| *Cladosporium* | *allicinum* | [3] |
| *Cladosporium* | *cladosporioides* | [27] |
| *Cladosporium* | *sphaerospermum complex* | [3] |
| *Geosmithia sp.* | | [28] |
| *Lecanicillium* | *kalimantanense* | [10] |
| *Mucor* | *globosus* | [27] |
| *Parengyodontium* | *album* | [10] |
| *Penicillium sp.* | | [25] |
| *Penicillium* | *brevicompactum* | [27] |
| *Penicillium* | *chrysogenum* | [10,29] |
| *Penicillium* | *corylophilum* | [29] |
| *Penicillium* | *palitans* | [29] |
| *Penicillium* | *sumatrense* | [28] |
| *Purpureocillium* | *lilacinum* | [10] |
| *Sarocladium* | *kiliense* | [10] |
| *Sporothrix sp.* | | [25] |
| *Wallemia spp.* | | [3] |
| **BRICK WALL** | | |
| *Acremonium* | *strictum* | [30] |
| *Aspergillus* | *fumigatus* | [30] |
| *Aspergillus* | *sydowii* | [29] |
| *Aspergillus* | *versicolor* | [29] |
| *Cladosporium* | *cladosporioides* | [30] |
| *Penicillium* | *chrysogenum* | [29] |
| *Penicillium* | *corylophilum* | [29] |
| *Penicillium* | *palitans* | [29] |
| *Wallemia spp.* | | [3] |
| **LIMESTONE** | | |
| *Acremonium spp.* | | [10,26] |
| *Aeminium* | *ludgeri* | [31] |
| *Aspergillus* | *glaucus* | [31] |
| *Aspergillus* | *sydowii* | [29] |
| *Aspergillus* | *versicolor* | [9,29] |
| *Aspergillus* | *westerdijkiae* | [31] |
| *Cladosporium* | *cladosporioides* | [9] |
| *Cladosporium* | *langeronii* | [10] |
| *Cladosporium* | *sphaerospermum* | [9] |
| *Cladosporium* | *tenuissimum* | [9] |
| *Epicoccum* | *nigrum* | [9] |
| *Lecanicillium* | *kalimantanense* | [10] |
| *Parengyodontium* | *album* | [9] |
| *Penicillium* | *brevicompactum* | [9,31] |
| *Penicillium* | *chrysogenum* | [28,29,31] |
| *Penicillium* | *corylophilum* | [29] |
| *Penicillium* | *crustosum* | [9] |
| *Penicillium* | *glabrum* | [9,28] |
| *Penicillium* | *palitans* | [29] |
| *Pseudogymnoascus* | *pannorum* | [10] |
| *Sarocladium* | *kiliense* | [10] |
| *Stachybotrys* | *chartarum* | [28] |
| *Talaromyces spp.* | | [9] |
| *Verticillium* | *zaregamsianum* | [10] |

### C. Simulation assumptions

Dynamic simulations were performed using the DesignBuilder software [32] in order to evaluate the occurrence of internal conditions favourable to the proliferation of fungi. A test model was created consisting of a block with dimensions 6mx6m, with external walls 30 cm thick, made with the materials previously identified and assessing the risk of local condensation that would favour the appearance of the fungi presented in Table 1. The thermo-physical properties of construction materials are described in Table 2 while thermal transmittance values U ($W/m^2$) obtained for the three types of walls are reported in Table 3. The south wall includes a windowed area with a 25% WWR.

*Table 2. Properties of the analysed building materials.*

| Material | Conductivity (W/mK) | Specific Heat (J/KgK) | Density ($Kg/m^3$) | Vapour factor (-) |
|---|---|---|---|---|
| Brick | 0.84 | 800 | 1700 | 150 |
| Limestone | 1.40 | 1000 | 2000 | 50 |
| Plaster | 0.35 | 840 | 950 | 150 |

*Table 3. U-values (W/m²K) of the analysed external walls.*

| | U (W/m²K) |
|---|---|
| Brick masonry wall | 1.90 |
| Limestone masonry wall | 2.60 |
| Masonry wall with internal plaster | 1.78 |

The model was simulated according to two hypotheses. In the first case, an occupancy schedule from 8.00 to 18.00 was assumed and the building was equipped with a heating and cooling system, operating in the same time interval. The set point temperature is fixed at 20 °C for heating and 26 °C for cooling. In the second case, the simulation was conducted in free floating, assuming that the building is not occupied and not equipped with heating and cooling systems. In fact, historical buildings that are part of the cultural heritage often do not have the structural and functional characteristics to be regularly used, but are kept as archaeological assets, not permanently occupied. In these cases, their conservation is even more difficult, as the environmental conditions that can protect the construction elements and materials are not maintained inside. An infiltration rate of 0.5 ach is considered in both cases. Regarding the external conditions, the model was simulated in two locations representative of the climatic conditions of northern and southern Europe, Helsinki ($T_{max}$=28.6 °C; $T_{min}$=-21.4 °C) and Rome ($T_{max}$= 31.1 °C; $T_{min}$=-4.1 °C), respectively. Table 4 summarises the case studies analysed and the related codes. The simulation was conducted on an hourly basis.

*Table 4. Case study definition.*

| Case study | Material | | | Location | | Heat./Cool. system | |
|---|---|---|---|---|---|---|---|
| | Brick | Limestone | Plaster | Rome | Helsinki | Yes | No |
| CS1 | v | | | v | | v | |
| CS2 | v | | | v | | | v |
| CS3 | v | | | | v | v | |
| CS4 | v | | | | v | | v |
| CS5 | | v | | v | | v | |
| CS6 | | v | | v | | | v |
| CS7 | | v | | | v | v | |
| CS8 | | v | | | v | | v |
| CS9 | | | v | v | | v | |
| CS10 | | | v | v | | | v |
| CS11 | | | v | | v | v | |
| CS12 | | | v | | v | | v |

## III. RESULTS AND DISCUSSION

Simulation results were analysed in terms of internal conditions, characterised by zone temperature and relative humidity, and the risk of condensation on the internal surface of the vertical walls, for the different exposures (North, South, East and West). Critical conditions emerge for all the analysed cases, with greater intensity for the cases regarding the unoccupied building without heating and cooling system, and for the Rome location. The graph in Fig. 2 shows the percentage of occurrence (calculated on the basis of hourly simulation intervals) in which relative humidity equal to or higher than 75% and 80% is recorded within the environment. It is worth noting that relative humidity not only reaches high values, but these high values are also maintained for extended periods, favouring the condensation and germination of spores. For example, the graph in Fig. 3 reports surface temperature of the north-facing wall and relative humidity of the air for the case study CS6 (Limestone, Rome, no heating/cooling system).

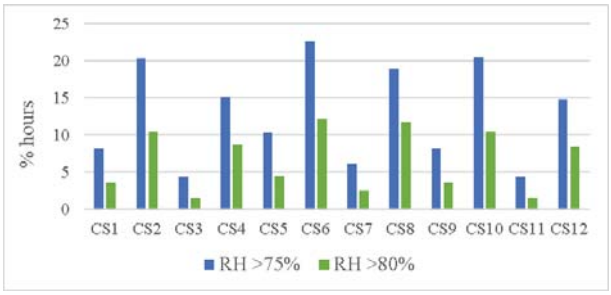


*Fig. 2. Percentage of hours over the total (based on simulation steps) in which RH values are equal to or higher than 75% and 80%.*

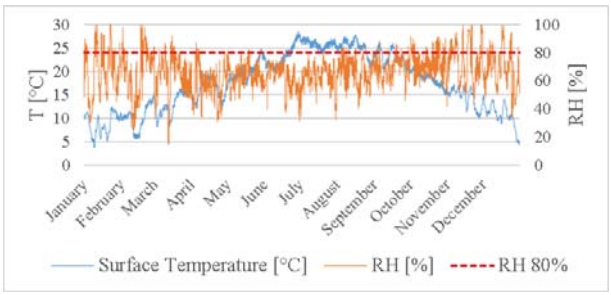


*Fig. 3. Surface temperature (north-facing wall) and relative humidity of the air for the CS6.*

In the graph in figure 4, relating to the north-facing wall of the CS8 case (Limestone, Helsinki, no heating/cooling system), it is possible to observe how during the month of January, the surface temperature drops several times below the dew point, thus causing condensation.

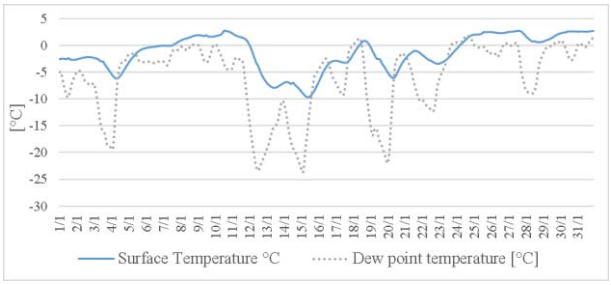


*Fig. 4. Surface and dew point temperature trend for the north-facing wall of the CS8 during the month of January.*

As can be seen from Table 5, the risk of condensation is present in all the analysed cases. The abacus highlights the months in which condensation occurs at least in a simulation interval. It should be noted that condensation is generally present on all the walls (North, East, South and West). However, a greater presence is found on the north face.

*Table 5. Condensation risk.*

| | January | February | March | April | May | June | July | August | September | October | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CS1 | | | | | | | | | | ■ | ■ | |
| CS2 | ■ | ■ | | | | | | | | | ■ | ■ |
| CS3 | ■ | ■ | | | | | | | | | ■ | ■ |
| CS4 | ■ | ■ | | | | | | | | ■ | ■ | ■ |
| CS5 | ■ | ■ | | | | | | | | ■ | ■ | ■ |
| CS6 | ■ | ■ | | | | | | | | | ■ | ■ |
| CS7 | ■ | ■ | | | | | | | ■ | ■ | ■ | ■ |
| CS8 | ■ | ■ | | | | | | | ■ | ■ | ■ | ■ |
| CS9 | | | | | | | | | | ■ | ■ | |
| CS10 | ■ | ■ | | | | | | | | | ■ | ■ |
| CS11 | ■ | ■ | | | | | | | | | ■ | |
| CS12 | ■ | ■ | | | | | | | | ■ | ■ | ■ |

## IV. CONCLUSIONS

A reference database of fungi genera and species associated with some commonly used materials in historical buildings was created. In typical uninsulated envelopes such as those analysed, the study showed, according to the boundary conditions, the formation of condensation. In particular, the analysis highlighted that high relative humidity conditions are generated in the absence of heating and cooling systems. However, condensation conditions occur, in different percentages, in all the examined cases. This represents a serious problem for the conservation of historic buildings, as the occurrence of condensation conditions constitutes a risk for the germination of moulds. Regarding the studied materials, the limestone is more vulnerable to the formation of condensation. Based on the results obtained, two types of solutions can be suggested to mitigate the risk of biodeterioration. The first solution is related to reducing the thermal transmittance of the wall. This allows to increase the dew point and eliminate surface condensation, which causes mould. Further solutions consist in the reduction of internal relative humidity. A low-cost strategy that can be adopted consists in activating natural ventilation in two cases: in the presence of high occupancy, or when the specific external humidity X ($g_v/Kg_a$) is lower than the internal one.

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