Estimation of mould growth levels on rendered facades based on surface RH and surface temperature measurements

Johansson, Sanne; Wadsö, Lars; Sandin, Kenneth

Published in:
Building and Environment

DOI:
10.1016/j.buildenv.2009.10.022

2010

Citation for published version (APA):
Johansson, S., Wadsö, L., & Sandin, K. (2010). Estimation of mould growth levels on rendered facades based on surface RH and surface temperature measurements. *Building and Environment*, *45*, 1153-1160. https://doi.org/10.1016/j.buildenv.2009.10.022

Total number of authors:
3

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

Citation for the published paper:
Johansson, S; Wadsö, L.; Sandin, K.
Estimation of mould growth levels on rendered facades based on surface relative humidity and surface temperature measurements.
Building and Environment, 2010, 45, pp. 1153-1160

DOI:
http://dx.doi.org/10.1016/j.buildenv.2009.10.022

Estimation of mould growth levels on rendered façades based on surface RH and surface temperatures measurements

Sanne Johansson*, Lars Wadsö, Kenneth Sandin

Building Materials, Lund University, Box 118, 221 00 Lund, Sweden

*Corresponding author: sanne.johansson@byggtek.lth.se

Abstract

Many façades made with thin rendering on thermal insulation have problems with biological growth. In this study surface temperature and surface RH were monitored over a 20 month period on test house façades with different constructions (thermal inertia), surface color and compass directions. This data were used to test three theoretical indices of biological growth with the aim of indicating the potential of mould growth on different types of rendered façades. The result show that thin renderings on thermal insulation have significantly higher surface humidities compared to façade constructions with higher thermal inertia and therefore have a higher potential for mould growth. The color is the most important factor for the surface humidity levels on south facing façades (on the northern hemisphere) as darker surfaces absorb more solar radiation and therefore have a higher average temperature. On a north facing façade the heat storage capability of the façade and its effect on the surface temperature is most import

Keywords

Rendering, mould growth, temperature, moisture, ETICS, façade

Introduction

Although most buildings most likely will be discolored by biological growth over time, current building tradition and the demand for energy savings has led to changes in our way of building residential houses, which in some cases have increased the occurrence of biological growth on façades. In Sweden many new houses have for the last decades been built with a construction with thin rendering on thermal insulation, often called ETICS (external thermal insulation composite systems). Biological growth often occurs on the surfaces of such façades only a few years after the buildings have been constructed. Even though this problem might only be of aesthetic character, it can lead to various economical and social consequences for the building owner. A façade, being perhaps the building’s most salient architectural feature, will give an impression of a poorly maintained building if it is discolored, even if the rest of the building is in good condition. Avoiding such growth is therefore important.

Sweden is not the only country that has experienced biological growth on newly built ETICS; several papers from Germany deal with the same problem [1-6], but studies of biological growth on modern buildings façades is otherwise scarce.

Previous research has shown that the organisms found on buildings, especially moulds, algae, lichens and cyanobacteria are especially adapted to survive the repeated drying and rehydration cycles that are found on external building façades [7-8] (note that we use the term hydration for uptake of water either from the vapor or the liquid state). Numerous studies have also shown that the main limiting factors for biological organisms to establish and grow on building materials are relative humidity (RH) and temperature [9-12]. As early as 1969 Ayerst measured how RH and temperature influenced spore germination and mycelial growth of various mould species [9]. The results were given in the form of isopleths, i.e., contour lines in the T-RH-diagram connecting points of equal growth rates. These isopleths were based on growth on agar medium, but others have tried to make isopleth systems also for mould growth on building materials [13]. However, as different species have different needs with respect to RH and temperature, a specific isopleth may actually be needed for each mould species on each substrate.

In trying to predict the potential of mould growth in and on building materials, several mould growth prediction methods have been developed [13-16]. All are based on previously published isopleths or other similar mould growth-limit data, which are measured at stationary temperature and RH conditions. Moon and Augenbroe [16] have however tried to further develop this type of analysis by taking ”exposure time” into account. In addition, these methods use heat and mass transfer models to determine the surface temperature and surface RH. These hygrothermal models either focus on heat and moisture flow in different parts of the building envelope or make calculations for the whole building envelope as one unit. Either way, these models have their limitations, primarily because there is usually a lack of relevant input data (climate, material properties etc.).

In the present study we have measured the surface conditions on different façades of a test building with the aim of investigating the complex abiotic factors (physical and chemical environmental factors) related to biological growth on rendered façade systems. The primary focus is on surface RH and surface temperature as these factors are the most important. Previous research has shown that the surface RH determines the conditions for microbial surface growth, not the ambient air RH [17]. This is especially important for ETICS as these systems can get surface condensation even if the ambient RH is under 100%. Measurements of surface temperature and RH should therefore be a good basis for mould growth predictions for ETICS. This has been studies by Sedlbauer and Künzel [2, 4, 18] who measured surface temperature and calculated surface RH (from surface temperature and ambient RH) on an ETICS wall facing west and two walls of aerated light bricks facing north and south. They also discuss the importance of driving rain and condensation, and innovative ways to overcome the problem of surface growth.

We have measured both surface temperature and surface RH (one measurement per hour) on different façades of a test house over a 20 month period. We use this data to test three theoretical indices of biological growth to give an indication of when and where a mould will have the possibility to grow on different types of rendered façades. We have not made any studies of the actual biological growth on these façades, as it is not trivial to compare the biological growth on different façades (this is discussed further in the Discussion). This aim of this study was to give a deeper understanding of the building façade as a biological habitat and to consider how to reduce the growth by non-chemical means.

Materials and Methods

A test house was built to study the temperature and RH on rendered façade surfaces (Fig.1). The frame and all interior parts of the house are made of wood. The house is oriented in an east-west direction, so that the main façades are facing north and south.

Each façade has replaceable façade elements (1050 mm x 2100 mm). The house is located in Lund, a city situated in the southernmost part of Sweden (55° 42′ N, 13° 12′ E) that has a temperate climate with cloudy winters and partly cloudy summers. The average temperature is -2-0°C in January and 15-17°C in July and the annual precipitation is 500-1000 mm.

On each side of the test house, two façade elements were built; one “heavy” and one “light”. The light system consists of (from the outside) a thin rendering on polystyrene insulation and the interior insulated wood frame. The heavy wall had a thin rendering on a brick wall placed outside the polystyrene insulation and the insulated wood frame. Both construction types had the same type of organic rendering system (Stolit K, STO AB, Sweden) with a thickness of 3 mm. With an organic rendering system we mean a rendering with a binder system that is wholly or mainly of organic (polymeric) origin. The only difference between the two construction types was that the “heavy” façade had a layer of bricks between the rendering and the thermal insulation. Both construction types still had the same total thickness of the thermal insulation layer. The constructions are described in more detail in Fig. 2. In the following we use the terms “light” and “heavy”, but also more specifically their “thermal inertia”. The thermal inertia of a layer is a function of its specific heat capacity, its thermal conductivity and its thickness.

To investigate the influence of façade color, half of each façade element had a final rendering layer with red pigments, whereas the other half had a white pigmented final rendering. It should be noted that the biocidal contents of the renderings are unknown, so the biological growth was not assessed on this test house.

The surface RH and surface temperature of the four façade elements were monitored continuously every hour from May 2005 to December 2006. Both surface RH and surface temperature were measured using monolithic IC devices (Honeywell IH-3602C) in teflon filters mounted under the rendering as close to the surface as possible and placed in the upper half of the façade. These devices combine an RH sensor with a Pt1000 resistance thermometer. The IC sensors have a stated “total accuracy” of ±2% RH in the range 0-100% RH under non-condensing conditions, and a stated stability of ±1% over 5 years at 50% RH . In the present study the sensors were tested before they were mounted in the rendering and found to be within specifications, but it is not known whether sensors were within specifications during the whole measurement period. The ambient temperature was monitored with sensors placed above each façade element under the roof.

Mould growth indices

From the measurements of surface temperature and surface RH we would like to calculate index of integrated mould growth/activity over certain periods, e.g. months. There have been described a few indices that are used to grade the risk of mold growth or the level of mold growth. For example have IAE/ASHRAE a set of conditions that should be fulfilled to avoid mold growth [19], Another more advanced concept is RHT [20] which is defined as the summation of values at 10-day intervals of RH minus a reference RH, multiplied by temperature minus a reference temperature (the summation is only made when both terms are positive). Although conceptually similar to some of our indices it has the drawback that it does not limit the index when the temperature is too high for mold growth; something that is an index for façades should do. We have used the measurement result to compare the results of two more advanced indices (2 and 3 below) and a simple indoor index (1 below). Indices 2 and 3 are based on knowledge of how mold growth depends on temperature and RH. Although such measurements are scarce today (and usually made for food microorganisms) we believe that they will be useful in the future when more such measurements become available. In all cases higher values indicates more growth.

1. In studies of indoor mould growth it is common to find that mould growth only occurs above a certain RH (at room temperature). Different growth limits from 70% to 80% have been found, depending on the experimental conditions ([10-11, 17, 21-23]). Our first index is therefore based on RH only. Index 1 is calculated as the fraction of time that the RH (φ) is equal to or above a certain threshold value φ_t:

$$I_1 = \frac{\int\limits_{\tau=t_0}^{t_1} f(\tau)d\tau}{t_1 - t_0}, \quad f = \begin{cases} 1 & \rightarrow \quad \varphi(\tau) \geq \varphi_t \\ 0 & \rightarrow \quad \varphi(\tau) < \varphi_t \end{cases} \tag{1}$$

We use the value of φ = 80%, as it is a common threshold value for preventing mould occurrences in buildings.

2. Ever since the studies of Ayerst in 1969, different researchers have measured the activity of moulds as a function of both temperature and RH. This has been done by exposing specimens at different combinations of temperature and RH. The most complete studies have been made with mould genera of primary importance in the food- and health industry (*Penicilllium spp.* and *Aspergillus spp.*) on agar [24-26]. The studies on building materials are typically less detailed and growth is often quantified

into only four to six degrees of coverage on a sample [8, 12]. The most common mould on rendered façades is *Cladosporium spp.* [27-29], but only a very few studies of building and moulds concern this mould genera [14, 30]. From the more complete studies (like Ayerst’s) it is possible to derive isopleths, i.e., suites of curves connecting points of equal activity (spore growth time, hyphal elongation rate etc.) in the temperature-RH diagram, but as no reliable isopleths have been published for *Cladosporium spp.* growing on building materials, we therefore have used data from other types of growth data of *Cladosporium spp.* [11, 31-37] to construct two functions f_φ and f_T, which give the influence of RH and temperature on growth of *Cladosporium spp.* With these functions we can calculate the second index that takes into account both temperature and RH:

$$I_2 = \int_{\tau=t_0}^{t_1} f_T(\tau) f_\varphi(\tau) d\tau \qquad (2)$$

The functions f_φ and f_T are given in Fig. 3 together with isopleths calculated from these curves. Note that Eq. 2 generates isopleths that are qualitatively similar to those shown by references [9, 26, 37]

3. It is known that after a mould has been exposed to adverse conditions like drying or high temperatures, it does take some time for it to recover back to the activity it had before the exposure [8, 32, 34]. The third index is similar to index 2, but it also includes a recovery function f_r that limits the increase of the index when the organism has been outside its growth limits. It is defined as:

$$I_3 = \int_{\tau=t_0}^{t_1} f_r(\tau) f_T(\tau) f_\varphi(\tau) d\tau, \quad f_r = \begin{cases} 0 \rightarrow \quad f_T f_\varphi = 0 \quad \textit{has been true during the last } t_r \\ \qquad 1 \rightarrow \quad \textit{otherwise} \end{cases}$$

(3)

”Outside the growth limits” are here defined as when either or both of f_φ and f_T are zero, i.e. when temperature is below $T_{\min}$ or above $T_{\max}$, or when RH is below $\mathrm{RH}_{\min}$ (cf. Fig. 3).

Results and discussion

We use the following abbreviations for the different façade parameters:

- direction (**N**orth- or **S**outh–facing façade)
- thermal inertia of construction (**L**ight or **H**eavy façade)
- surface color (**R**ed or **W**hite façade)

For example is NLR the north facing light and red façade.

This study of surface temperature and surface RH conditions on different façades and especially the following index simulations is focused on the differences between the different façades to investigate why we experience more rapid mould growth on ETICS façades than on other façade constructions.

Measurements of surface temperature and surface RH

The measurements were made during a 20 month period, but for clearness we only show results from a 12 day period in September that shows typical patterns in surface temperature and surface RH (Figs. 4-7). From the results of the whole measurement series we observed the following:

- On the south-facing façades the surface temperature was influenced both by façade color and construction type during the daytime, but mainly by the construction type during the night-time.
- As expected, the midday surface temperatures of the red façades were higher than for the white façades. More specifically:
    - On the south side the surface temperature of SLR was always higher than that of SHR (Fig. 4).
    - On the north side the surface temperature of NLR was also highest, but NHR and NLW had almost same surface temperature levels (Fig. 5).
- During night, the surface temperature on the light façades was always lower than on the heavy façades (up to 4 K difference on the south side, cf. Figs. 4-5).
- During summer, especially when the sun was shining, the surface temperature difference between the different façade constructions became more pronounced.
- When the difference in air temperature was small between day and night (typically in the winter), the surface temperature differences on the façades were also small, clearly seen on 18 and 19 September in Fig. 4.
- SHW reached the lowest surface temperatures of all façades during the daytime, but it still had a higher night surface temperature than SLW and SLR (Fig. 4).
- The surface RH on the south-facing façades is mainly governed by façade color (both during day- and night-time) as darker surfaces absorb more solar radiation and therefore have a higher average temperature.
- On the south side, the surface RH was typically lower on the red than on the white façades (Fig. 6).

- On the north side, the surface RH was generally slightly lower for the red than for the white façades during the daytime, but the red façades did not always reach the lowest night-time surface RH.
- Even if the heavy façades were warmer than the light façades during the nighttime (Figs. 4-5), the surface RH on SHW was higher than on SLR (Fig. 6).
- Except for the summer months, all façades regularly reached surface RH-values close to 100%. The light façades were during the wintertime close to 100% day and night (data not shown).
- The red façades typically had an surface RH under 70% day and night during summer on the south facing façade (data not shown).

The daytime surface temperature variations on the light façades were much higher than on the heavy façades as the sun heats the surface by shortwave radiation. However, which may not be so well known, the light façades become colder in the night than the heavy façades, due to their lower thermal inertia. The heavy façades with a higher thermal inertia in the brick layer can store the heat from day to night. In addition, because of night-time longwave radiation from the surface to the sky, the light façade can even get temperatures below the ambient air temperature. This is especially true if we have a night with a clear cold sky that is typical during autumn. This phenomenon will never occur for the heavy façades because of the higher thermal inertia of this construction. Because of the night time longwave radiation from the façades to the sky, the light façades can be covered with condensation on the surfaces in the mornings, something that we frequently observed on our test house during autumns.

We have calculated the three mould indices with the data from the eight façades. All indices have been calculated for each month during the test period.

Index 1. Fraction of time with an RH above a threshold value

As before mentioned we have used 80% as a threshold value for index 1. The results given in Fig. 8 show that index 1 is more or less the same for the four north-facing façades, but on the south side, there is a significant difference between the façades, especially during autumn and spring. All façade elements – irrespectively of construction type, colour and direction - reach index value of 1.0 during the wintertime.

Even though a threshold value of around 80% RH is widely used in studies of potential mould growth and by building physics consultants, it has a serious deficiency : it does not take the temperature into account. It is therefore only meaningful to use in indoor environments with more constant temperatures in the range of suitable mould growth temperatures, which in the case of most indoor moulds are in the range of 15-30°C [38]. Most of the time when index 1 is high, the temperature is low, and the mould growth will be limited.

Index 2. Potential for growth based on isopleth method

The results from the calculations of index 2 are shown in Fig. 9. Here it is seen that if we include the temperature in our theoretical evaluation of potential mould growth, the results differ markedly from the results for index 1. It is also clearly seen that the differences seen between the façade elements are caused by different factors on the north and south sides. On the south side color is most important and the dark (red) façades have the lower index-values, whereas on the north facing façades the construction type determines the index-value and the heavy façades have the lower index-values. This is most clearly seen during the autumns, when both temperature and RH is suitable for mould grow. It is also seen that conditions for mould growth are most favourable in spring and autumn. In the wintertime it is too cold, and in the summer-time it is too dry. This type of index seems to be relevant to use for mould growth potential on exterior façades.

Index 3. Potential for growth based on isopleth model with a time delay

Although index 2 seems to be a relevant index, it has one deficiency: it does not take into account that it may take time for a mould to start growing again after being exposed to conditions outside its growth range, for example to dry conditions. We therefore introduced a recovery parameter into the index 3.

As it is not known for how long time the mould needs to recover (and this time would most probably be different for different exposures), we made calculations for index 3 with different recovery times (t_r) from 5 to 72 h. The calculations gave a reduced mould growth potential with increasing recovery time, but did not change the order among the façade elements. Results from calculations with a recovery time of 5 h are given in Fig. 10. The results are qualitatively similar to the results for index 2.

General discussion

In an earlier similar study the surface RH was calculated from surface temperature and ambient RH [4, 39]. In the present study both surface temperature and surface RH was measured. The sensors were in the rendering, as close to the surface as was practically possible, but they were not placed on the surface and did therefore not measure the exact surface conditions. However, as RH-sensors are rather sensitive to condensation, it is not possible to make a long-term outdoor study with the sensors on the surface. We did not measure the intensity of driving rain, but it is clear that from time to time the surfaces were wet. However, in most cases this was because of condensation on the constructions with low thermal inertia.

In this study a test-house built specifically for this study was used. We could therefore measure surface conditions (temperature and RH) on identical light/heavy and white/red façades facing south and north. This makes the discussion of the influence of the three factors (thermal inertia, color, compass direction) easy. Our conclusions essentially agrees with the conclusions by Künzel [2] from various studies performed at Fraunhofer Institute for Building Physics.

The main limitation of this study is that we have not made any studies of the actual biological growth on the façades. However, to do this in a relevant way for naturally exposed façades is far from trivial. In this study the façades were made from standard commercial products with proprietary composition. This means that the study was made on systems that exist on the market today, but it also means that we have no knowledge or control of the chemical composition of the materials. Therefore any comparisons of biological growth between the different façades are of little value.

An alternative would have been to make our own rendering products, so that we would have known their chemical composition. However, this is difficult for two reasons. Firstly, modern rendering products are sophisticated products with a large number of components, and it is not trivial to compose such products with similar properties as commercial products. Secondly, it is not possible to make renderings with different colors that do not also have different chemical compositions as pigments can be biologically active.

It is also possible to build the same façades, but expose them to different conditions, for example by placing them in different locations. This is similar to what we have done, as we have both south and north facing façades. Unfortunately, also in this case it will be difficult to evaluate the influence of surface temperature and surface RH on biological growth as there are a number of other factors that can also influence biological growth and that can be quite different in different locations. Some examples of such factors are light intensity, spore concentrations, cleaning by driving rain, and fouling by particulate materials. We believe that chemical and nutritional aspects of growth on façades are best studied in the laboratory where the above factors can be controlled.

Because of the above mentioned limitations we have in this work chosen to work with temperature and RH measurements and theoretical growth indices. Quantification of biological growth can, however, be done in other types of studies. For example can one expose different rendering systems under controlled conditions with the aim of finding out which system that gets the least growth to increase the understanding of how growth depends on temperature and RH.

Conclusions

We have measured surface temperature and surface RH on rendered façades with different thermal inertia, colors, and orientation. With this data we test three theoretical mold indices, and discuss why thin rendering on thermal insulation can have more problems with biological growth than traditional façades. We show that that the color is the most important factor for the surface humidity levels on a south facing façade (on the northern hemisphere), while on a north facing façade the thermal inertia is most important.

Acknowledgements

This project was funded by the Swedish research council FORMAS and we also appreciate the support from STO Scandinavia AB.

References

1. Karsten, U., et al., *Aeroterrestrische Mikroalgen. Lebensraum Fassade.* Biologie Unserer Zeit, 2005. **35**(1): p. 20-30.
2. Künzel, H.M. *Factors determining surface moisture on external walls.* in *Performance of Exterior Envelopes of Whole Buildings X*. 2007. Clearwater Beach, Florida, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).
3. Künzel, H.M. and K. Sedlbauer, *Algen und Wärmedämm-Verbundsystemen*, in *IBP-Mitteilung*. 2001.
4. Künzel, H.M. and K. Sedlbauer. *Biological growth on stucco.* in *Performance of Exterior Envelopes of Whole Buildings VIII*. 2001. Clearwater Beach, Florida, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).
5. Sedlbauer, K. and M. Krus, *Schimmelpilzbildung auf WDVS infolge "Baufehlern"?*, in *IBP-Mitteilung*. 2001. p. 43-45.
6. Sedlbauer, K., et al., *Neue erkentnisse zum mikrobiellen Bewuchs auf Aussenoberflächen.* Wärme, Kälte, Schall- und Brandschutz, 2006. **56**: p. 10-18.
7. Ortega-Calvo, J.J., M. Hernandez-Marine, and C. Saiz-Jimenez, *Biodeterioration of building materials by cyanobacteria and algae.* International biodeterioration, 1991. **28**(1-4): p. 165-185.
8. Viitanen, H.A. and J. Bjurman, *Mould growth on wood at fluctuating humidity conditions.* Material und Organismen, 1995. **29**: p. 27-46.
9. Ayerst, G., *The effect of moisture and temperature on growth and spore germination of some fungi.* Journal of Stored Products Research, 1969. **5**: p. 127-141.
10. Coppock, J.B.M. and E.D. Cookson, *The effect of humidity on mould growth on construction materials.* J Sci Food Agric, 1951: p. 534-537.
11. Grant, C., et al., *The moisture requirements of moulds isolated from domestic dwelling.* International biodeterioration and biodegredation, 1989. **25**: p. 259-284.
12. Nielsen, K.F., et al., *Mould growth on building materials under low water activities. Influence of humidity and temperature on fungal growth and secondary metabolism.* International biodeterioration and biodegradation, 2004. **54**(4): p. 325-336.
13. Sedlbauer, K., *Prediction of mould growth by hygrothermal calculation.* Journal of Thermal Envelope and Building Science, 2002. **25**(4): p. 321-336.
14. Clarke, J.A., et al., *A technique for the prediction of the conditions leading to mould growth in buildings.* Building and Environment, 1999. **34**(4): p. 515-521.
15. Hukka, A. and H.A. Viitanen, *A mathematical model of molud growth on wooden material.* Wood Science and Tecnology, 1999. **33**: p. 475-485.
16. Moon, H.J. and G.L.M. Augenbroe, *Towards a practical mould growth risk indicator.* Building Serv. Eng. Res. Technology, 2004. **25**(4): p. 317-326.
17. Pasanen, A.-L., et al., *Occurrence and moisture requirements of microbial growth in building materials.* International biodeterioration and biodegradation, 1992. **30**: p. 273-283.

18. Sedlbauer, K. *Unwanted biological growth in and around buildings* in *Rosenheimer Fenstertage 2002*. 2002. Rosenheim, Germany: Institut für Fenstertechnik.
19. TenWolde, A., *ASHRAE standard 160P – criteria for moisture control design analysis in buildings.* ASHRAE Trans, 2008. **114**(1): p. 167-169.
20. Beaulieu, P., *Report from task 8 of MEWS project. MEWS methodology for developing moisture management strategies – application to stucco-clad wood-frame walls in North America,* . 2002, National Research Council: Ottawa, Canada.
21. Block, S.S., *Humidity requirements for mould growth.* Applied and Environmental Microbiology, 1953. **1**: p. 287-293.
22. Nielsen, K.F., P.A. Nielsen, and G. Holm. *Growth of moulds on building materials under different humidities.* in *Healthy Buildings 2000.6th International Conference on Healthy Buildings, the principal international conference on construction technology of healthy buildings.* 2000. Espoo, Finland.
23. Viitanen, H.A., *Modelling the time factor in the development of mould fungi - the effect of critical humidity and temperature conditions in pine and spruce sapwood.* Holzforschung, 1997. **51**(1): p. 6-14.
24. Ayerst, G., *Influence of physical factors on the deterioration by moulds.* Soc Chem Indust Monograph, 1966. **23**: p. 14-20.
25. Pasanen, A.-L., et al., *Laboratory studies on the relationship between fungal growth and atmospheric temperature and humidity.* Environment International, 1991. **17**(4): p. 225-228.
26. Smith, S.L. and S.T. Hill, *Influence of temperature and water activity on germination and growth of Asgergillus restrictus and Aspergillus versicolor.* Transactions of British Mycological Research, 1982. **79**(3): p. 558-560.
27. Shirakawa, M.A., et al., *The development of a method to evaluate bioreceptivity of indoor mortar plastering to fungal growth.* International biodeterioration and biodegradation, 2003. **51**: p. 83-92.
28. Shirakawa, M.A., et al., *Fungal colonization and succession on newly painted buildings and the effect of biocide.* FEMS micobiology letters, 2002. **39**: p. 165-173.
29. Shirakawa, M.A., et al., *Mould and phototroph growth on masonry facades after repainting.* Materials and structures, 2004. **37**(271): p. 472-479.
30. Sedlbauer, K., et al. *Mold growth prediction by computational simulation.* in *ASHRAE*. 2001. San Francisco: IAQ.
31. Burge, H.A., *Airborne allergenic fungi. Classification, nomenclature, and distribution.* Immunology and Allergy Clinics of North America, 1989. **9**(2): p. 307-319.
32. Gill, C.O. and P.D. Lowry, *Growth at sub-zero temperatures of black spot fungi from meat.* Journal of Applied Bactereriology, 1982. **52**: p. 245-250.
33. Hocking, A.D., B.F. Miscample, and J.I. Pitt, *Water relations of Alternaria alternata,Cladosporium cladosporoides, Cladosporium sphaerospermum, Curvularia lunata and Curvularia pallescens.* Mycological Research, 1994. **98**(1): p. 91-94.
34. Panasenko, V.T., *Ecology of microfungi.* The Botanical Review, 1967. **33**(3): p. 189-215.
35. Pelhate, J., *Recherche des besoins en eau chez quelques moisissures des grains.* Mycopathologia, 1968. **36**(2): p. 117-128.

36. Scott, W.J., *Water relations of food spoilage microorganisms.* Advances in Food Research, 1957. **7**: p. 83-127.
37. Sedlbauer, K., *Vorhersage von schimmelpilzbildung auf und in bauteilen (Prediction of mould fungus formation on the surface of and inside building components)*, in *Fraunhofer Institute for Building Physics*. 2001, Universität Stuttgart: Stuttgart.
38. Pasanen, A.-L., et al., *Fungal growth and survival in building materials under fluctuating moisture and temperature conditions.* International biodeterioration and biodegredation, 2000. **46**: p. 117-127.
39. Sedlbauer, K., *Unwanted biological growth in and around buildings.*, in *Rosenheimer Fenstertage*. 2002. p. 1-12.