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Mould Growth Modelling to Evaluate Durability of Materials

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ABSTRACT

This paper presents the latest findings of mould growth and the modelling of these factors on different materials. Expected risk and durability of materials to mould growth can be predicted by solving a numerical value, so called mould growth index, by using the dynamic temperature and relative humidity histories of the subjected material surfaces. An improved mould growth model has been developed by taking into account different materials and the effect of seasonal, long period dry or cold periods that do not allow growth. The laboratory and field results show that the sensitivity of mould growth index level may vary in a large range depending on materials and the boundaries of materials. Different mould sensitivity classes of materials have been found varying from resistant to very sensitive.

KEYWORDS

Mould fungi, Modelling, Moisture, Temperature, Building materials.

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1 INTRODUCTION

There are several biological processes causing aging and damage to buildings. Partly this is due to natural ageing of materials (like gray surface of wood in outdoor conditions), and partly it is caused by excess moisture (damage during use). The critical factors for these processes are water and temperature. Mould typically affects the quality of the adjacent air space with volatile compounds and spores (Airaksinen et al 2004). The next stage of moisture induced damage, the decay development, forms a serious risk for structural strength depending on moisture content, materials, temperature and time. The worst decay damage cases in North Europe are found in the floors and lower parts of walls, where water accumulates due to different reasons. For mould development, the minimum (critical) ambient humidity requirement is shown to be between RH 80 and 95 % depending on other factors like ambient temperature, exposure time, and the type and surface conditions of building materials (Clarke et al. 1998, Sedlbauer 2001, Viitanen 1996). For decay development, the critical humidity is above RH 95 % or wood moisture above 25 – 30 %, depending on temperature (Viitanen 1996).

2 CRITICAL CONDITIONS FOR THE ACTIVITY OF ORGANISMS AND DAMAGE

In the table 1, general overview on the critical humidity or moisture conditions for decay activity of some organisms are shown. We know that the mould fungi are often the first colonizers microbes on building materials. On the exterior surfaces, growth of mould fungi, algae and even lichens is a normal part of the reaction to outdoor climate.

On indoor surface, the growth of mould fungi or bacteria should be avoided, and the modern life style where people spend more time indoors and are more exposed to indoor air sets higher demands for the reliable function of the whole building system. The economical consequences of the humidity and microbial growth related problems in buildings are remarkable. E.g. poor indoor air quality in schools or in working places has been shown to interfere with learning or working activities and can cause discomfort, irritation, and various short- and long-term health problems. This is especially acute in Nordic countries, where the climate is colder and the air ventilation through open window is not suitable during cold winter periods.

With very sensitive building materials, like pine sapwood, the relative humidity level of 80 % RH is typically considered to be the lowest possible to allow growth during long exposure time. Even lower levels of relative humidity has been used (75 % RH), but mainly for other than building materials. With more resistant materials the required growth condition is obviously higher or, at least, the required exposure time is much longer.

Modelling of mould growth and mould development based on humidity, temperature, exposure time and material will give new tools for the evaluation of durability of different building materials and structures. The models make it possible to evaluate the risk and development of mould growth and to analyse the critical conditions needed for the start of mould growth. It is also a tool to measure the progress of mould development under different conditions on the structure surfaces.

3 MODELLING OF MOULD GROWTH

3.1 Original mould growth model based on the work with untreated pine and spruce sapwood

The first version of the mould growth model was based on large laboratory studies with pine sapwood (Viitanen and Ritschkoff 1989). The mould growth intensities were determined at the constant conditions. In the later stages, studies in varied and fluctuated humidity conditions were performed and based on these studies, mould growth model (equation 1) was presented by Hukka and Viitanen 1999.

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02)} k_1 k_2 \quad (1),$$

where the factor k_1 represents the intensity of growth (Equation 3), W is the timber species (0 = pine and 1 = spruce) and SQ is the term for surface quality (SQ = 0 for sawn surface, SQ = 1 for kiln dried quality). For other materials than wood the value SQ = 0 is used, which omits this factor. Numerical simulation is typically carried out using one hour time steps (climate data intervals) and hours are used in the equations instead of days.

$$k_1 = \begin{cases} 1 & \text{when } M \leq 1 \\ \dfrac{2}{t_{M=3}/t_{M=1} - 1} & \text{when } M > 1 \end{cases} \quad (2).$$

In this equation (2) the factor $t_{M=1}$ is the time needed to start the growth (M = 1, Table 2), and $t_{M=3}$ the time needed to reach level M =3. The factor k_2 (Equation 3) represents the moderation of the growth intensity when the mould index (M) level approaches the maximum peak value in the range of 4 < M < 6.

$$k_2 = \max\left[1 - \exp\left[2.3 \cdot (M - M_{max})\right], 0\right] \quad (3),$$

where the maximum mould index M_{max} level depends on the current conditions (Equation 4):

$$M_{max} = 1 + 7 \cdot \frac{RH_{crit} - RH}{RH_{crit} - 100} - 2 \cdot \left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \quad (4).$$

In Equation 5 RH_{crit} is the limit RH level to start the mould growth.

3.2 Models for the mould growth on other building materials

Mould growth model was improved in a project carried out at VTT (Technical Research Center of Finland) and Tampere University of Technology. This project included large sets of steady-state and dynamic laboratory experiments for typical building materials: Spruce board (with glued edges), concrete (K30, maximum grain size 8 mm), aerated concrete, cellular concrete, polyurethane thermal insulation (PUR with paper surface and with polished surface), glass wool, polyester wool and expanded polystyrene (EPS) (Salminen et al. 2009). Pine sapwood was used as a reference material. The results of these experiments were used to improve the existing numerical model for mould growth. Based on the experimental data, new mould growth threshold value could be set for some, more resistant materials to 85 % RH.

The mould growth intensities were determined from the constant condition. The idea was to compare the mould growth of different materials to that of the pine sapwood. These correlations could be used to generate such factors that could be applied in the original model for different materials.

3.2.1 Growth intensity factors for other materials

The factors presented in equations (1) – (5) were determined for different new materials using the experimental results. The growth intensity factor k1 was determined using the time needed for the mould index to change from level M = 1 to level M = 3. The original moudl index scale was adjusted for the other building materials (Table 1).

Table 1. Mould Index for Experiments and Modeling. New determinations for index levels 3 and 4 are presented using bold fonts.

Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10 % coverage, or, **< 50 % coverage of mould (microscope)**
4	Visual findings of mould on surface, 10 - 50 % coverage, or, **>50 % coverage of mould (microscope)**
5	Plenty of growth on surface, > 50 % coverage (visual)
6	Heavy and tight growth, coverage about 100 %

The new mould growth intensity factors are presented as relative values compared to those of the reference material pine by using Equations (5) and (6).

$$k_1 = \frac{t_{M=1,pine}}{t_{M=1}} \quad \text{when } M < 1 \tag{5}$$

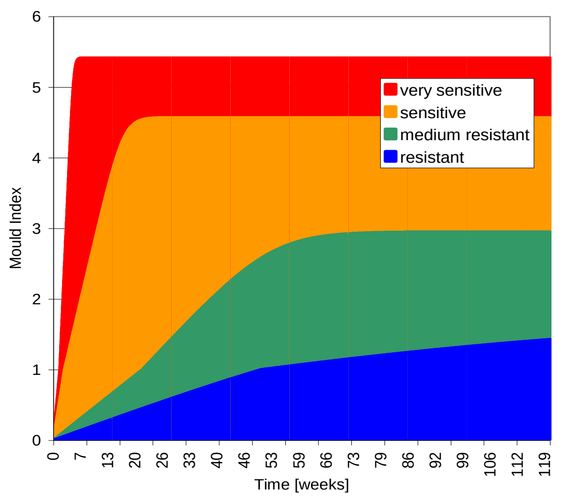
$$k_1 = 2 \cdot \frac{(t_{M=3,pine} - t_{M=1,pine})}{(t_{M=3} - t_{M=1})} \quad \text{when } M \geq 1 \tag{6}$$

where $t_{M=1}$ is the time needed for the material to start the growth (Mould index reaches level M = 1), and $t_{M=3}$ the time needed for the material to reach level M =3. The subscript $_{pine}$ refers to the value with the reference material pine

Table 2 represents the tested materials, whose resulting mould indexes were used for the determination of k_1 for the respective classes. The k_1 classes were determined by using expert estimation for most suitable values.

Table 2. Mould growth sensitivity classes and some corresponding materials in the research. The figure in table illustrates the predicted mould growth for the established sensitivity classes for constant conditions at 97 % RH and 22 C.

Sensitivity class	Materials
Very sensitive	Pine sapwood
Sensitive	Glued wooden boards, PUR with paper surface, spruce
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool
Resistant	PUR polished surface



The mould growth maximum values set restrictions for the growth and limit the index to realistic levels. For the new set of materials the equation of the maximum mould index level was written in form (Equation 7):

$$M_{\max} = A + B \cdot \frac{RH_{crit} - RH}{RH_{crit} - 100} - C \cdot \left(\frac{RH_{crit} - RH}{RH_{crit} - 100} \right)^2 \quad (7)$$

In this equation the coefficients A, B and C can have values that depend on the material class. The new M_{max} has an effect on the factor k_2 (Equation 3) and it contributes to the simulation results. Table 4 presents the maximum levels of mould index values for different materials under different conditions. These results were classified to material sensitivity groups, presented both for growth intensities and maximum mould index levels. Table 3 gives the values for the growth intensity parameter k_1 classes and for the coefficients of the maximum mould index factors M_{max} and k_2. The factor RH_{min} represents the minimum humidity level for starting mould growth for each material group.

Table 3. Parameters for the sensitivity classes of the updated mould model.

			k_2 (M_{max})			RH_{min}
Sensitivity class	**M<1**	**M≥1**	**A**	**B**	**C**	**%**
very sensitive, vs	1	2	1	7	2	80
sensitive, s	0.578	0.386	0.3	6	1	80
medium resistant, mr	0.072	0.097	0	5	1.5	85
resistant, r	0.033	0.014	0	3	1	85

The factors presented in Table 5 form the new basis for numerical simulation of mould growth on different material surfaces. These values will be applied in the following studies where the model performance will be evaluated.

3.2.2 The decline of the mould growth and mould index caused by frost or dry condition

As living organisms mould fungi need water and suitable temperature to grow. When conditions are unfavorable for fungi, activity of mould fungi will be inactivated depending on the extent of the frost or dryness and the time periods of unfavorable conditions, see
Figure 1.

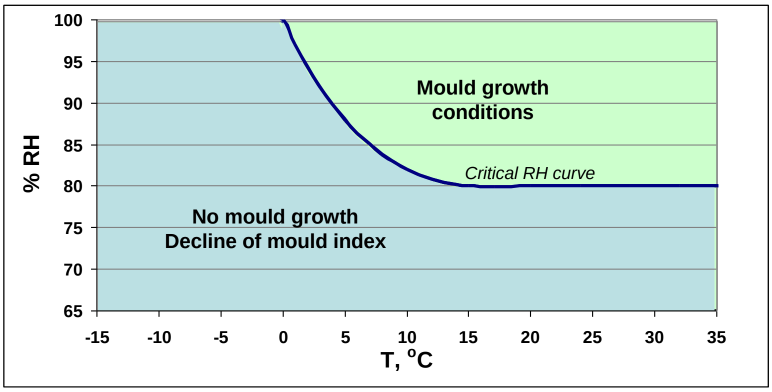


Figure 1: Illustration of the regimes for the favaourable and unfavourable conditions for mould growth**.**

The degradation of mould on wooden surface has been modeled based on cyclic changes between two humidity conditions (Equation 8).

$$\frac{dM}{dt} = \begin{cases} -0.00133, \text{when } t - t_1 \le 6 \text{ h} \\ 0, \text{when } 6 \text{ h} \le t - t_1 \le 24 \text{ h} \\ -0.000667, \text{when } t - t_1 > 24 \text{ h} \end{cases} \quad (8),$$

where M is the mould index and t is the time (h) from the moment t_1 when the conditions on the critical surface changed from growth to outside growth conditions.

Under long period seasonal variations of humidity conditions the decline of mould index may e differ from that presented in Equation 8. Also the material may have a significant effect on the decline process. The decline of mould index for other materials was presented using a constant, relative coefficient for each material (Equation 9).

$$\left.\frac{dM}{dt}\right|_{mat} = C_{mat} \cdot \left.\frac{dM}{dt}\right|_{0} \quad (9),$$

where $(dM/dt)_{mat}$ is the mould decline intensity for each material, $(dM/dt)_0$ is that for pine in the original model (Equation 9), and C_{mat} is the relative coefficient for mould index decline used in the simulation model. The original decline model for wood could be applied using these additional factors.

The decline of mould intensity on materials under unfavorable mould growth conditions could be presented as decline classes (Table 4). This classification is based on few measurements with relatively large scattering and it should be considered as the first approximation of these classes.

Table 4. Classification of relative mould index decline.

C_{eff}	Description
1.0	Pine in original model, short periods
0.5	Significant Relevant decline
0.25	Relatively low decline
0.1	Almost no decline

4 USING THE MODELS TO PREDICT THE EFFECT OF EXPOSURE CONDITIONS ON DURABILITY OF BUILDING MATERIALS

Mould growth is one of the first signs of biological deterioration caused by excess of moisture, and therefore mould growth can be used as one of the best hygrothermal performance criteria of building structures. Mould does not deteriorate the material, but it is a sign of too high moisture content and it represents a risk for other moisture caused problems, like decay. This has been one of the main motivations to develop and use numerical models for mould growth.

When evaluating the performance and durability of the building constructions with the mould growth model, the results from dynamic hygrothermal simulations can be easily post processed with the presented mould growth model. For more serious damage to develop, decay development model should be used (Viitanen et al. 2010).

One of the basic outputs from the dynamic heat and moisture simulations are the hourly temperature and relative humidity conditions in a specific location of the construction. These locations depend strongly on the studied construction type. For the assessment purpose of the performance, a set of hygrothermal simulations with parameter variations can be created in such way that a potential trend of solutions will be revealed. The issue to investigate could be e.g. what effects the insulation thickness or a specific insulation material or exterior finish or if a non-ventilated construction have on the hygrothermal performance of the construction. In Figure 2 there is an example on the mould modelling calculations of such an investigation

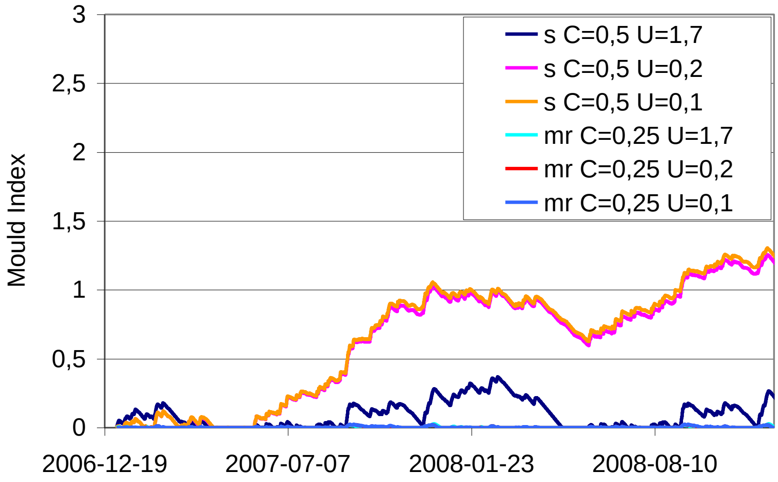


Figure 2: Calculated mould index on the extetior surface of a wall. Effect of different U-values (U=0,1 -1,7 W/m2K) and assumptions for sensitivity classes (s= sensitive and mr = medium resistant) including decline (C=0,5 and C=0,25).

If the assumptions for the presented mould growth calculation were that the material of the exterior surface is moderate resistant to biological growth, i.e. inorganic material, there will be no risk for mould growth. But if the surface contains organic material, there will be a risk of mould growth both moderately and very well insulated constructions.

It must be emphazied that the results of mould modelling calculations must be seen in relation to other solutions and not as absolute values. Often the most important information from the calculations is, however, if the modelled mould growth is increasing from year to year - or not. For the example case, this makes the hygrothermal conditions of this construction risky if the surface includes organic material. On the other hand, mould spores are naturally everywhere and therefore hard to avoid especially on the exterior part of the building constructions. In addition, the conditions of the exterior parts of the building envelope are close to exterior weather conditions, which in many climate regions are favourable for mould growth.

DISCUSSION AND CONCLUSION

The presented numerical mould growth model is based on experimental results from several research projects. It is suitable for post-processing temperature and humidity data from any numerical simulation of hygrothermal conditions in building constructions. However, it must be kept in mind when performing the assessment that there are a great uncertainty coupled to this kind of analysis:
the variation of the material sensitivities is high, estimation of a product sensitivity class is difficult without testing, the surface treatments may enhance or reduce growth potential, different mould species have different requirements for growth and the evaluation of the actual conditions in the critical material layers may include uncertainties.

Nevertheless, the motivation to use and develop numerical mould growth models and application of them is to give tools for better prediction and evaluation of the risks for biological growth on structure surfaces and to find the best solutions to ensure safe performance for the building and the indoor climate. The best way to use the predicted mould growth as an assessment tool is to compare different solutions with each others: The solution with the lowest risk for the mould growth would most probably also have least other moisture related problems.

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