Mold Growth Modeling of Building Structures Using Sensitivity Classes of Materials

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ABSTRACT

Numerical simulation of mold growth can be used as one of the hygrothermal performance criteria of building structures. Mold growth is one of the first signs of too-high moisture content of materials, and it may affect the indoor air quality and also the appearance of the visible surfaces. Mold growth potential can be predicted by solving a numerical value, mold index, by using the dynamic temperature and relative humidity histories of the subjected material surfaces.

The model was originally based on mold growth of wooden materials, but it has now been completed with several other building materials. The model can be used parallel with heat, air, and moisture simulation models or as a post-processing tool.

This paper presents the latest findings of mold growth and the modeling of these factors on different materials. The mold growth model has been improved by taking into account the effect of seasonal, long dry or cold periods that do not allow growth. This includes mechanisms for the decrease of mold level (decline of mold index) during unfavorable growth periods and the intensity of the growth after these periods. The laboratory and field results show that the sensitivity of the mold index level may vary in a large range depending on materials. Also, the performance on the interface of two materials has been studied. Instead of modeling the performance separately for each material or product, the materials are presented as different mold sensitivity classes varying from resistant to very sensitive. The sensitive class corresponds to the performance of pine sapwood, which was one basic material in the original model format. Other materials are presented by using the detected correlations between these materials. The mold growth sensitivity classes, decline of the growth level, comparison to detected mold level in materials, and numerical application in practical hygrothermal performance analysis are presented and discussed.

MOTIVATION AND OBJECTIVES FOR FURTHER DEVELOPMENT OF THE MOLD GROWTH MODEL

Numerical simulation of heat, air, and moisture performance of building structures generates the prediction of hygrothermal conditions in different parts of the analyzed structure. Also, monitoring of laboratory experiments and site investigations produces large amounts of data from critical parts of structures. This data should be post processed in order to evaluate the risks connected to overall performance, service life, interaction with indoor climate conditions, and structural safety. Mold growth is one of the first signs of biological deterioration caused by excess moisture; therefore, mold growth can be used as one of the best hygrothermal performance criteria of building structures. Mold 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, such as decay. Mold affects the appearance of the surface and can severely affect the indoor air quality when the growth is in contact with indoor air or with the leakage air flowing into the room space.

The mathematical model of mold growth was developed by Hukka and Viitanen (1999) based on regression analysis of the measured data (Viitanen 1996; Viitanen and Ritschkoff 1991) for calculating the development of mold growth, which is expressed as the *mold index*. An index value from 0 to 6 is defined to describe the evaluation of mold growth on a surface

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a) on a microsopic level (1– 2) and b) when the growth can be detected visually (3–6). This mold index is based on the detectable growth of different mixed mold species. The first version of this model was based on a great number of measurements on pine and spruce sapwood material. This model has been used to analyze (in parallel or in post processing) the result derived from numerical simulation models for the dynamic temperature and relative humidity histories of the critical material surfaces.

The mold growth risk analysis based on sensitive wooden materials has been applied also for different material layers that have soiled, dusty surfaces and those surfaces having contact with wood-based materials. Since the first version of the model, the research has included several experimental studies on conditions for mold growth, primarily on wood but also on other building materials. In order to predict the risks of mold growth in varying types of structures made of several building products and materials, it is obvious that an improved model to cover several typical building materials has to be developed.

RESEARCH CARRIED OUT TO IMPROVE THE MODEL

A three-year research project was carried out at Technical Research Center of Finland (VTT) and Tampere University of Technology. This project included large sets of steady-state and dynamic laboratory experiments for common building materials (Salminen et al. 2009), monitoring of mold growth in material surfaces and structures under real climate conditions, and long-period climate chamber experiments. The results of these findings were used to improve the existing numerical model for mold growth.

This paper presents the development of the mold growth model in this project (Peuhkuri et al. 2009; Ojanen et al. 2009), which items were taken into account and how these parameters were studied, and the results interpreted numerically for different materials and conditions.

The experiments and their findings are presented and discussed only from the modeling aspect. These results are presented in a concise way, and the main findings are shown as the improvements of the numerical model. The emphasis is on the comparison between experiments and the outcome of the new modeling principles.

MATERIALS USED IN THE RESEARCH

Some typical building materials were chosen for the experiments: 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). Pine sapwood was used as a reference material. This set of products cannot entirely represent all the products in the building material group, but it gives improved approximation on the mold growth sensitivity of each.

The following results are based on the controlled laboratory and well-monitored site experiments of the chosen materials and structures where these products were used.

UPDATING THE EXISTING NUMERICAL MOLD GROWTH MODEL

The mold growth model based on experiments with wood was updated to be valid also for the mold growth prediction of other building materials. The idea in this research was to keep the original model structure and to adapt the mold growth parameter values of different materials to the existing model. Some improvements were applied for the model structure to better adjust different growth phenomena. The following sections represent the modeling principles for different mold growth parameters.

MOLD GROWTH LEVEL—MOLD INDEX

Determination of the mold growth levels is the fundamental element of the whole simulation of this biological phenomenon. This determination sets an interpretation of the visual growth levels as numerical values. This is needed both in the evaluation of the experimental results and in the assessment of the simulation results.

Figure 1 represents how mold growth was studied under constant conditions for this research. Closed containers had saturated salt solution vessels to maintain known constant humidity levels. There were nine test samples of each material used in the tests. Some focusing was done to better take into account the different mold growth types with different materials and surfaces. The main difference compared to the version for wood-based materials was in the area that is not visible to the naked eye. It was found out that with some materials the mold growth coverage could be quite high already in microscopic areas (see Figure 2). Therefore, the mold index

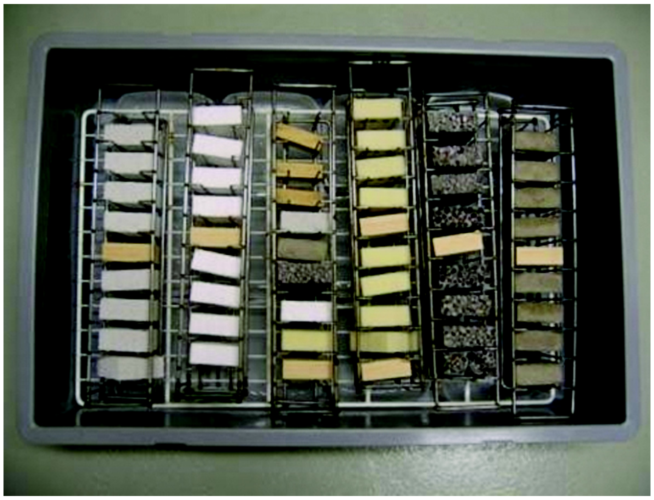
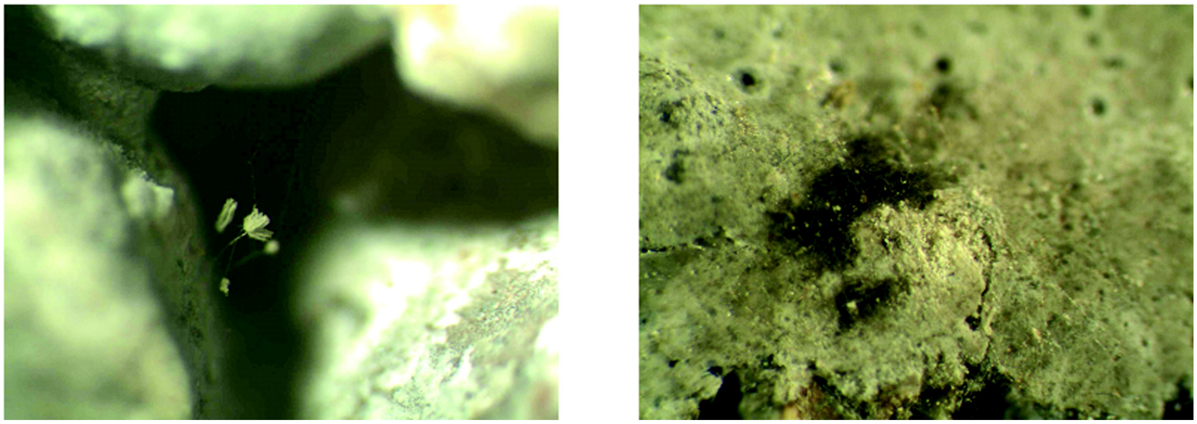


Figure 1 *Laboratory test setup with small samples; there were nine samples of each material.*



(a) (b)

Figure 2 *(a) Mold (penicillium) in the pores of aerated cellular concrete and (b) dark Cladosporium-mold hyphae on a concrete surface.*

Table 1. Mold Index for Experiments and Modeling (New Determinations for Index Levels 3 and 4 are Presented in Bold)

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

determination was updated with these microscopic growth coverage findings in index levels 3 and 4 (Table 1). With wood-based materials, these index levels (index 3 and higher) were attained only with visual findings using the naked eye.

These new mold index specifications were used when evaluating the experimental results and are included in the mold growth modeling of the materials included in the updated model.

LIMIT CONDITIONS TO INITIATE MOLD GROWTH

The VTT model (Viitanen 1996; Hukka and Viitanen 1999; Viitanen et al. 2000; Viitanen and Ojanen 2007) of mold growth is based on duration of suitable exposure conditions required before microbial growth will start. For wood (Scots pine and Norway spruce sapwood), the limit growth conditions for mold are presented in Figure 3. This figure represents also the lower limiting isopleths curves (humidity levels) for mold growth presented by Sedlbauer (2001), Clarke et al. (1998), and Hens (1999).

For very sensitive building materials, such as wood, the relative humidity level of 80% RH is typically considered to be the lowest possible to allow growth during a long exposure time, usually months. Even lower levels of relative humidity

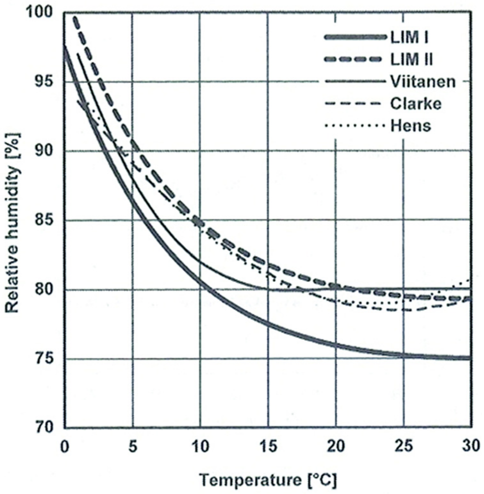


Figure 3 *Comparison of limiting growth conditions after Viitanen et al. (2000) with limits of different substrate class 1 (LIM I, biodegradable materials) and substrate class 2 (LIM II, porous materials) after Sedlbauer (2001); also limits based on the results of Clarke et al. (1998) and Hens (1999).*

have been used (75% RH), but mainly for other than building materials. The lowest relative humidity level that starts the growth in wooden material corresponds to 17%–19% (by weight) moisture content. With more resistant materials, the required growth condition is obviously higher or, at least, the required exposure time is much longer.

Equation 1 represents the critical relative humidity (RH_{crit}) in different temperatures. This critical value is the lowest humidity where mold growth is possible when the material (wood) is exposed to it for a long enough period.

$$\mathrm{RH}_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100.0, & \text{when } T \le 20 \\ \mathrm{RH}_{min}, & \text{when } T > 20 \end{cases} \tag{1}$$

For wood and wood-based products, RH_{min} is 80% RH. For other materials, the factors of the equation should be defined separately.

In this research, particular emphasis was focused on this time period, the so-called response time, enabling mold growth in different humidity and temperature conditions. The large set of experiments done could be used to set new limits for growth conditions for different materials. These relative humidity minimum values are still approximations, but they correspond better to the actual responses of different materials under those conditions where mold growth is about to start. The mold growth threshold value was set for some more resistant materials to 85% RH. The new relative humidity value categories for different materials are presented in more detail way in the section covering growth intensity.

MOLD GROWTH INTENSITY

Mold growth intensity tests were carried out using constant conditions. Some experiments also had changing conditions corresponding to seasonal load variations in building structures. Both material samples and multilayer structures made of the chosen experimental materials were used in the experimental analysis of mold growth. The mold index levels of the critical surfaces were observed in suitable intervals and when the conditions were changed. Material sample experiments supplied information about mold growth on surfaces against adjacent air. Special interest was also taken in the mold growth on the boundaries of two different materials: the mold index levels on both material surfaces were analyzed and the mold growth intensity as well as other parameters of the growth process could be evaluated under the conditions inside a structure.

The mold growth intensities were determined from the constant-condition experiments for the material samples. The idea was to compare the mold growth of different materials to that of the pine sapwood, which is the reference material for the original mold growth model. The correlations between these factors could be used to generate such factors that could be applied in the original model with different materials. Figure 4 shows examples on the large range of the experimentally generated average mold growth curves for different materials under constant conditions. These results show that there are clear differences between the intensity and delay of growth and the maximum level of mold index. The same experiments were carried out under different constant conditions. This gives the required information for the modeling of growth.

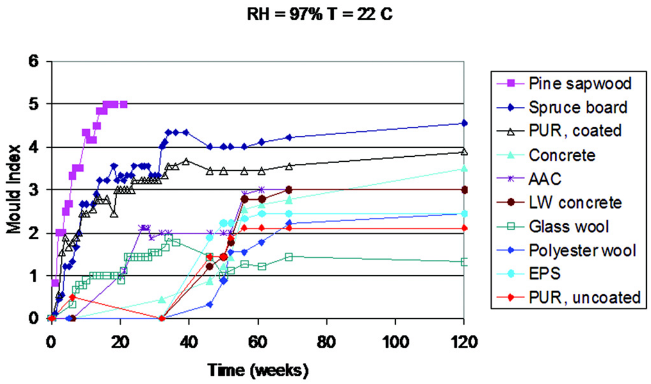


Figure 4 *Monitored histories of mold index on the surface of different building materials under constant temperature and humidity conditions (+22°C, 97% RH). Mean values of nine samples.*

Original Model for Wood

In the original model for wood, the mold growth is based on Equation 2:

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68\ln T - 13.9\ln \mathrm{RH} + 0.14W - 0.33SQ + 66.02)}k_1 k_2 \tag{2}$$

where the factor k_1 represents the intensity of growth (see Equation 3), W is the timber species (0 = pine and 1 = spruce), and SQ is the 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. In the original model, the time unit used in the equations (as in Equation 2) is days; this is due to the relatively long monitoring periods used in the model development. Numerical simulation is typically carried out using one-hour time steps (climate data intervals), and in the new model hours are used instead of days in the equations.

$$k_1 = \begin{cases} 1 & \text{when M} \le 1 \\ \dfrac{2}{t_{M=3}/t_{M=1} - 1} & \text{when } M > 1 \end{cases} \tag{3}$$

In Equation 3, the factor $t_{M=1}$ is the time needed to start the growth (mold index reaches level $M = 1$), and $t_{M=3}$ is the time needed to reach level $M = 3$. For pine, $t_{M=3}$ is about two times higher than $t_{M=1}$, and the approximation for k_1 is 2 when $M > 1$ (see Figure 6).

The factor k_2 (Equation 4) represents the moderation of the growth intensity when the mold index level (M) approaches the maximum peak value in the range of $4 < M < 6$:

$$k_2 = max[1 - \exp[2.3 \cdot (M - M_{max})], 0] \tag{4}$$

where the maximum mold index level M_{max} depends on the prevailing conditions (Equation 5):

$$M_{max} = 1 + 7 \cdot \frac{\mathrm{RH}_{crit} - \mathrm{RH}}{\mathrm{RH}_{crit} - 100} - 2 \cdot \left(\frac{\mathrm{RH}_{crit} - \mathrm{RH}}{\mathrm{RH}_{crit} - 100}\right)^2 \tag{5}$$

In Equation 5, RH_{crit} is the limit relative humidity level to start the mold growth. This curve for wood is presented in Figure 3.

Updated Growth Intensity Factors for Different Materials

The principle when updating the original mold growth model for other materials was that new values for the factors presented in Equations 1–5 were determined for these materials using the results from several experiments.

The growth intensity factor k_1 was determined using the time needed for the mold index to change from level $M = 1$ to level $M = 3$. The observations from experiments under +22°C and 97% RH conditions were used to solve these values. The spread between the parallel measurements was very low and the results are quite reliable.

These results are presented for each material as relative values compared to those of the reference material, pine. These new mold growth intensity factors are presented in Equations 6 and 7:

$$k_1 = \frac{t_{M=1,\,pine}}{t_{M=1}} \qquad \text{when } M < 1 \tag{6}$$

$$k_1 = 2 \cdot \frac{(t_{M=3,\,pine} - t_{M=1,\,pine})}{(t_{M=3} - t_{M=1})} \qquad \text{when } M \geq 1 \tag{7}$$

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

For the reference material pine, the time difference between mold index levels $M = 1$ and $M = 3$ under +22°C and 97% RH conditions is about 1.4 weeks. For each material used in the research, the same time difference could be determined and thus the factors k_1 could also be solved for each material (Figure 5). To improve the usability of these new values, they are not presented as exact values for each material but as material classes according to the sensitivity of the material to mold growth. Four different sensitivity classes were determined. In Table 2 are listed the tested materials, whose resulting mold indexes were used for the determination of k_1 for the respective classes. Due to the relatively small amount of data, a proper statistical analysis was not done; the k_1 classes were determined by using expert estimation for most suitable values. The determined k_1 values are illustrated in Figure 6.

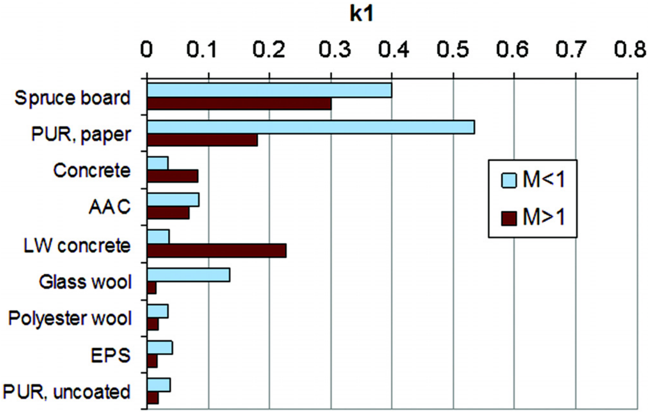


Figure 5 *Mold growth factors* (k_1) *for different materials used in the experiments.*

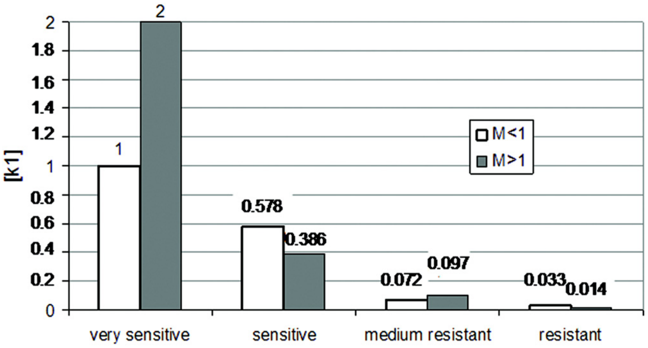


Figure 6 *Mold growth intensity factors* k_1 *sorted into four sensitivity classes.*

Table 2. Mold Growth Sensitivity Classes and Some Corresponding Materials in the Research

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 with polished surface

Maximum Levels of Mold Index for Different Materials

The mold growth intensity is the dominating factor in the simulation of growth when the mold index is not close to the maximum index values typical for the material under such conditions. The characteristic 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 mold index level (4) can be written in the form of Equation 8:

$$M_{max} = A + B \cdot \frac{\mathrm{RH}_{crit} - \mathrm{RH}}{\mathrm{RH}_{crit} - 100} - C \cdot \left(\frac{\mathrm{RH}_{crit} - \mathrm{RH}}{\mathrm{RH}_{crit} - 100}\right)^2 \tag{8}$$

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 contributes to the simulation results.

Table 3 presents the expected maximum level of mold index for different materials under different conditions. These values are based on steady-state experiments and are valid for the set of products used in the tests. These values can be taken as the best approximations for products made of similar materials. Using these experimental results, the approximations for the maximum mold index levels could be determined for different conditions and materials.

To simplify the use of these factors, they were also classified to be used as material sensitivity groups. The result of this classification is presented both for growth intensities and maximum mold index levels in Table 4. This table gives the values for the growth intensity parameter k_1 classes and for the coefficients of the maximum mold index factors M_{max} and k_2.

The factor RH_{min} represents the minimum level of relative humidity where mold growth is possible for that specific material group. The RH_{min} factor is one part of Equation 1 and has an effect on the conditions allowing mold growth. All the values in Tables 3 and 4 were determined as best expert approximations based on different numerical post processing of the experimental results.

The factors presented in Table 4 form the new basis for numerical simulation of mold growth on different material surfaces. These values (in Table 4) were applied in the following simulation studies to evaluate the model performance.

EVALUATION OF THE UPDATED MOLD GROWTH PARAMETERS

The first evaluation of the mold growth model with the new material sensitivity class factors (Table 4) was done by producing mold index curves under constant conditions. These curves were compared to the mold index levels monitored in the experiments. Some selected cases of this comparison are presented in Figures 7–9. The monitored humidity and temperature conditions could be slightly different than the nominal target conditions for the experiments. The nominal conditions are mentioned in the figure headings and the actual conditions are in figure captions. The actual conditions were used in the numerical solutions of the mold indexes.

Table 3. Maximum Mold Indexes for Different Materials Under Different Steady-State Conditions

Material	22°C, 97% RH	5°C, 98% RH	22°C, 90% RH	5°C, 92% RH
Pine	6	5	4	3
Spruce, glued	5	5	2	2
PUR, paper surface	4	3	0.5	0.5
Concrete	3.5	4	1	1
Aerated concrete	3	3	2	1
Cellular concrete	3	3	1	0.5
Glass wool	2	2	1.5	1.5
Polyester wool	3	3	1	1
EPS	3	3	1.5	1
PUR, polished surface	3	2	0.5	0.5

Table 4. Parameters for the Different Sensitivity Class Limits of the Updated Mold Model

Sensitivity Class	k_1		k_2 (M_{max})			RH_{min}
	$M < 1$	$M \geq 1$	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

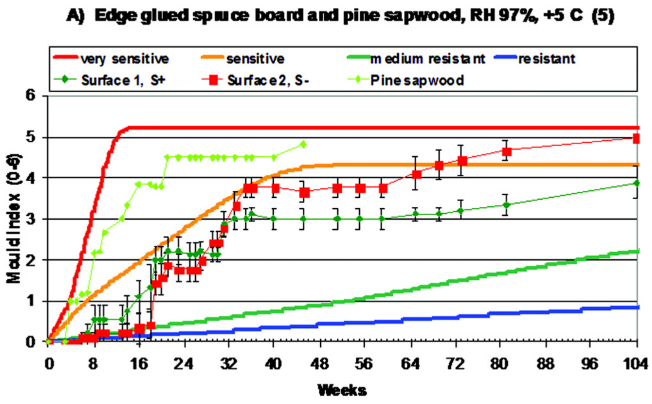


Figure 7 *Numerically solved sensitivity classes and experimentally analyzed mold growth on pine sapwood and spruce boards under monitored average conditions +4.5°C and 98% RH.*

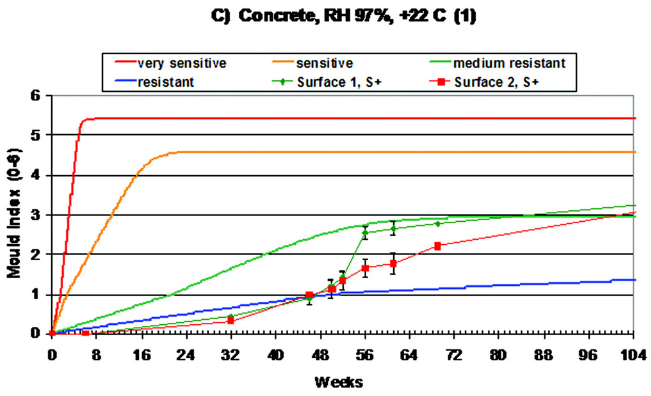


Figure 8 *Numerically solved sensitivity classes and experimentally analyzed mold growth on concrete under monitored average conditions +21°C and 96.5% RH.*

The observed mold index levels are presented with the deviations of the findings and for both surfaces of the samples. Surface 1 had initial treatment with spray suspension in order to guarantee similar exposure to mold spores under each experimental chamber.

The objective of this comparison was to study the suitability of the set sensitivity classes and also the maximum mold index levels on the mold growth analysis. The overall result of the large number of comparisons confirms the use of the presented classifications in the material mold growth studies.

DECLINE OF MOLD INDEX

The original model for wood takes into account the change in the mold index level when the conditions are outside the favorable conditions for mold growth, i.e., when the relative humidity is lower than the critical value solved in Equation 1. This includes also the temperature limits: mold does not grow at temperatures below 0°C. The warm end (about +50°C and above) of the growth criteria has not been modeled.

The degradation of mold on wooden surfaces was modeled based on cyclic changes between two humidity conditions. This decline of the mold index is presented in the form of Equation 9:

$$\frac{dM}{dt} = \begin{cases} -0.00133, \text{ when } t - t_1 \le 6 \text{ h} \\ 0, \text{ when } 6 \text{ h} \le t - t_1 \le 24 \text{ h} \\ -0.000667, \text{ when } t - t_1 > 24 \text{ h} \end{cases} \tag{9}$$

where M is the mold 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. For longer periods (week, months), this gives a practically linear decrease of mold index.

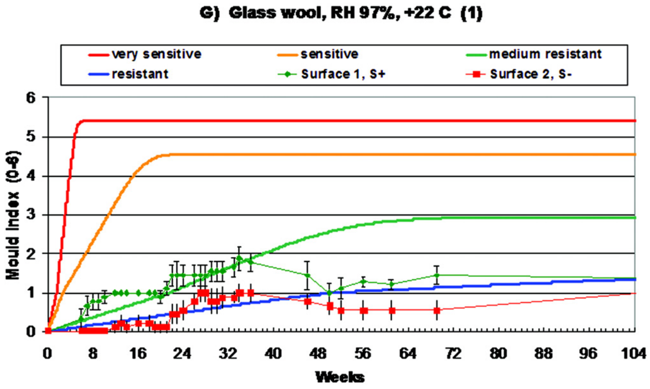


Figure 9 *Numerically solved sensitivity classes and experimentally analyzed mold growth on glass wool under monitored average conditions +22°C and 97% RH.*

It is likely that long-period seasonal variations of humidity conditions may cause different declines of mold indexes than short cycles. Also, the material itself may have a significant effect on the decline process of the mold growth appearance. Updating the mold decline process under unfavorable growth conditions was one task in this actual mold growth model development. Some delay or declination effect on the growth is needed, because monotonically increasing growth does not correspond to the experimental findings and may lead to overestimated growth levels as the comparison of different assumptions for decline in Figure 10, where results with another model, WufiBio (Sedlbauer 2001, Sedlbauer and Krus 2003), which predicts monotonically increasing biological mold growth are shown.

The decline of the mold index for other materials was presented using a constant, relative coefficient for each material (Equation 10) so that the original decline model for wood could be applied using these additional factors.

$$\frac{dM}{dt}_{mat} = C_{mat} \cdot \frac{dM}{dt}_{0} \tag{10}$$

where $(dM/dt)_{mat}$ is the mold 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 mold index decline used in the simulation model.

The relative decline of mold for different materials was determined using laboratory experiments with walls. The temperature and relative humidity conditions on the critical boundary layers between two materials were monitored continuously. The mold index level of the material surfaces was determined with suitable intervals by opening the structure from three different parts. The experimental target conditions at the interface of the two materials are presented in Table 5.

These experimental walls had mold growth after the first warm and humid period (Summer/Autumn) (Lähdesmäki et al. 2009). The mold decline was determined by the change of the mold index during the second period, a four month long Winter period causing freezing temperatures at the critical boundary. The mold index values were determined for both material surfaces on each critical interface. Figure 11 presents the relative mold decline values (C_{mat}) solved from the observations in the experiments. The results include the detected mean, minimum, and maximum mold index values.

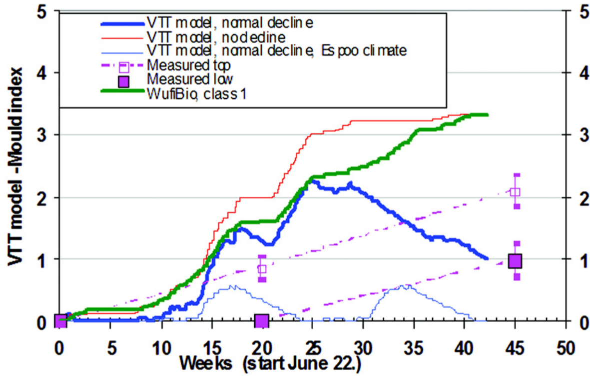


Figure 10 *Monotonic growth is not the best possible model for varying conditions. First approximation of decline is based on wood under short periods with varying conditions.*

Table 5. Exposure Conditions during the Wall Assemblies Tests

Stage	1	2	3	4
Season	Summer/ Autumn	Winter	Spring	High Exposure
Time, months	7	4	6	12
RH, %	80 … 100	92 … 100	60 … 95	94 … 100
Temp., °C	27 … 18	–5 … +3	2 … 10	20 … 24

The decline of mold intensity on materials under unfavorable mold growth conditions could be presented as decline classes (Table 6). This classification is based on few measurements with relatively large scattering and should be considered only the first approximation of these classes.

NUMERICAL SIMULATION INCLUDING THE UPDATED MOLD DECLINE PARAMETERS

The following study is based on the experimentally detected mold index values on the critical interfaces of wall assemblies exposed under high moisture loads under controlled cold-side conditions. The conditions had four stages (Table 5), and the conditions on the critical interfaces were monitored and the numerical solutions were based on these values.

One example of the simulations is presented in Figure 12. This figure presents the comparison between experimental findings and numerically simulated mold index values. The mold growth intensity of the materials was assumed to be in the Sensitive class. In boundaries having contact of two different materials, the growth intensity was found to correspond best to that of the more sensitive material. The maximum level of mold depends on each of the base materials. The relative mold decline coefficients had values 0.50, 0.25, and 0.1 in the simulations.

With the original decline factor (relative coefficient 1.0), the index would have reached level 0 in six months after the

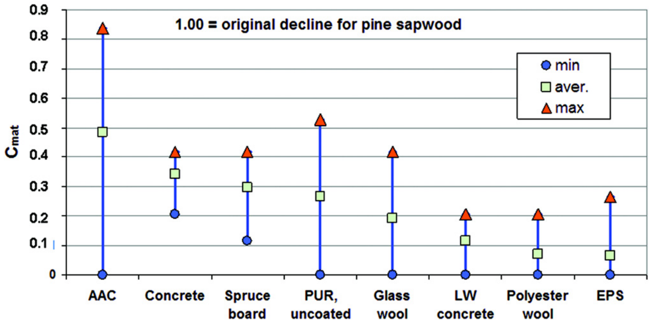


Figure 11 *The relative decline intensity of mold* (C_{mat}) *on different materials when compared to the decline on a pine surface in the original model.*

Table 6. Classification of Relative Mold 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

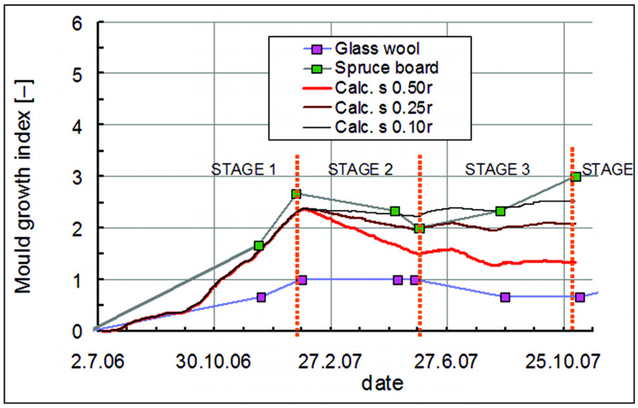


Figure 12 *Comparison between experimentally detected and simulated mold index histories on the interface of glass wool and spruce board.*

peak value. The updated model has a relatively good correlation with the experimental findings; the mold index remains close to the measured levels also during the cold period.

UNCERTAINTY ESTIMATION

The presented model for mold growth is based on measured values from steady-state and dynamic experiments of selected building materials. The deviation of the measured local mold index values was relatively large, especially with low mold index levels. In the worst case, some samples had mold index 2 when some did not have any signs of growth yet. In this work, the average values were used to form the model. Using maximum index values would have led to a model with more intensive growth. The determined parameter values of the different sensitivity classes of the model must not be understood as exact borders: they represent qualified division of the favorable growth conditions for various types of mold fungi in building materials. The sensitivity classes cover the predicted growth potential of mold from the most sensitive pine sap wood to the practically inert materials such as plain glass or materials treated with fungicides.

Another objective in this research was to predict mold growth dynamics with improved accuracy; the approximation for the error is in the order of ±0.5 in the mold index. When the materials of the real structure differ from those used in the modeling experiments, the possible error tends to increase from the first approximation. Even though the uncertainty can not be properly quantified, the model is capable of predicting the risks for mold growth for a range of typical building materials. The presented model with the material classes is very suited for sensitivity analysis for mold growth in different products and material types.

DISCUSSION AND CONCLUSIONS

The mold growth model for wood (pine sapwood) has been improved by adopting new building materials classes in the model. Experimental results for very different building materials were used for the model development: spruce board (with glued edges), concrete (K30, maximum grain size 8 mm), aerated concrete, cellular concrete, PUR (with paper surface and with polished surface), glass wool, polyester wool, and EPS. Pine sapwood was used as the reference material.

Table 7. Mold Sensitivity Classes and Their Material Groups

Mold Sensitivity Class	Materials
Very Sensitive	Untreated wood; includes lots of nutrients for biological growth
Sensitive	Planed wood, paper-coated products, wood-based boards
Medium Resistant	Cement or plastic based materials, mineral fibers
Resistant	Glass and metal products, materials with efficient protective compound treatments

The updating has been done by applying factors for mold growth intensity and maximum mold growth levels for different material classes. Also, the critical relative humidity conditions where mold growth can start were updated for different classes. The decline of the mold index level during cold or dry periods was also updated by presenting relative coefficient values for the decline intensity of different material classes.

The classification of the mold sensitivity levels of general material groups is presented in a summary in Table 7.

The presented classification for mold growth intensity, maximum mold index levels, and the decline of mold under unfavorable growth conditions allows a better and more reliable applicability of the model to predict the first biological growth on different materials and on the interfaces of material layers.

The presented improvements of the mold growth simulation model do not guarantee exact prediction of mold in different cases and conditions. 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 mold species have different requirements for growth, and the evaluation of the actual conditions in the critical material layers may include uncertainties.

The main objective of the numerical mold growth model development and application is, nevertheless, 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.

ACKNOWLEDGMENT

The project “Modelling of mold growth” was financed by TEKES (The Finnish Funding Agency for Technology and

Innovation), VTT (Technical Research Centre of Finland), and building material manufacturers. It was carried out at VTT and Tampere University of Technology from 2005–2008.

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