Classification of material sensitivity – New approach for mould growth modeling

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SUMMARY:
Mould growth is one of the first signs of biological activity caused by excess of moisture in materials. Mould growth can be predicted numerically by using the dynamic temperature and relative humidity histories. The result is called mould growth index. The mould growth model was originally based on the mould growth on wooden surfaces (Hukka & Viitanen 1999). This has limited the use of the model to a worst case scenario for very sensitive materials. Now the model has been completed with several other building materials. The updated model can be used parallel with a heat, air and moisture simulation model or as a post processing tool for general building materials.

This paper presents how the original mould growth model has been improved using the results of laboratory and field experiments for different building materials. One of the main improvements is the classification of the materials according to their sensitivity to mould growth. General building materials are presented using four mould sensitivity classes varying from resistant to very sensitive. Different materials are presented by using correlations between these materials and wood. The mould growth sensitivity classes, decline of the growth level under cold and dry periods and comparison between experimental findings and numerically solved results are presented and discussed.

1. Introduction

The development work is based on the existing VTT model for mould growth (Viitanen 1996, Hukka & Viitanen 1999, Viitanen et al. 2000, Viitanen & Ojanen 2007) on the surface of wooden materials (Scots pine and Norway spruce sapwood). Several papers have been published about this model and how it has been applied in different building physical studies (Viitanen & Ojanen 2007, Ojanen et al. 2009, 2010). A project called “Mathematical modelling of moisture behaviour and mould growth in building envelopes” was implemented in 2005–2009 was carried out to improve the original model. The objective of this project was to make the model more uniform and suitable for different building materials. This paper presents a summary of the modelling part results of this project and is a continuation in the series of the model development and applications.

2. Experimental research carried out to improve the model

A three year research project was carried out at VTT (Technical Research Centre of Finland) and Tampere University of Technology. This project included large sets of steady-state and dynamic laboratory experiments for common building materials: Spruce board, concrete, aerated concrete, cellular concrete, polyurethane thermal insulation (with paper and polished surfaces), glass wool, polyester wool and expanded polystyrene (EPS). Pine sapwood was used as a reference material. The experiments and their findings, presented in another paper “Mould growth on building materials in laboratory and field experiments”, were used to improve the existing model for mould growth.

3. Mould growth model improvement

The idea was to keep the original model structure and to adapt the mould growth parameter values of different materials to the existing model. Some modifications were applied for the model structure to better adjust different growth phenomena. The following chapters represent the modelling principles and how the materials were presented using material sensitivity classification for mould.

4. Mould index representing mould growth level

Determination of the mould index values based on visual findings of growth level is the fundamental element of the whole simulation of this biological phenomenon.

The main difference compared to the version for wood based materials was in the area that is not visible for naked eye. It was found out that with some materials the mould growth coverage could be relatively high already in microscopic area (Figure 1). Therefore the mould index determination was updated with these microscopic growth coverage findings in index levels 3 and 4 (Table 1).

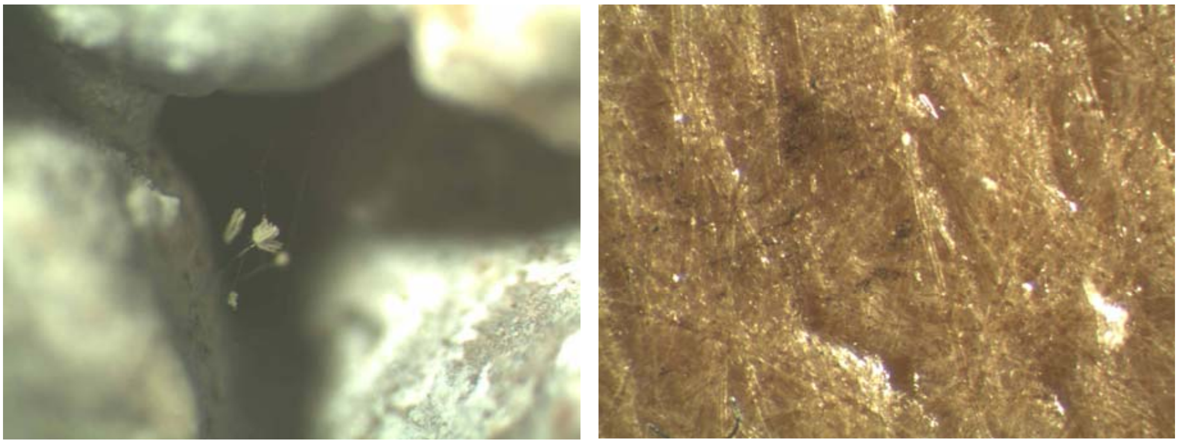


FIG 1. Mould (penicillium) in the pores of aerated cellular concrete (on the left) and growth on the paper surface of PUR insulation (on the right).

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

Mould 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 %

5. Conditions for starting mould growth

For very sensitive building materials, like wood, the relative humidity level of 80 % RH is typically considered to be the lowest possible to allow growth during long exposure time, usually months. 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 response of different materials under those conditions where mould growth is about to start. The mould growth threshold value was set for more resistant materials to 85 % RH.

6. Mould growth intensity

The main parameter in the modelling and in the classification of materials according their sensitiveness to is the mould growth intensity. The experiments carried under constant conditions produced data for different materials. The idea was to compare the mould growth of different materials to that of the pine sapwood which is the reference material for the original mould growth model. The correlations between these factors could be used to generate such factors that could be applied in the original model also with different materials. Figure 2 shows examples on the large range of the experimentally generated average mould 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 mould index. The same experiments were carried out under different constant conditions. This gives the required information for the modelling of growth.

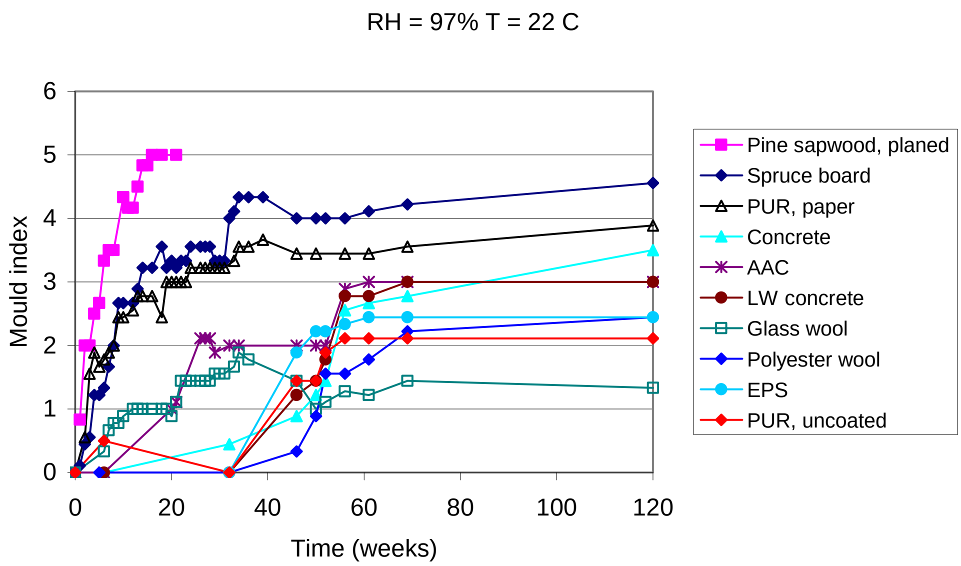


FIG 2. Monitored histories of detected mould index values (mean of 9 samples) on different building materials under constant temperature and humidity conditions (+22ºC, 97 % RH).

In the original model for wood the mould growth intensity is based on equation 1

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

Where *W* timber species (0 = pine and 1 = spruce)
SQ surface quality (SQ = 0 for sawn surface, SQ = 1 for kiln dried quality)
t time, h
k_1, k_2 coefficient for growth

For other materials than wood the value SQ = 0 is used. The factor k_1 represents the intensity coefficient that depends on growth level and the factor k_2 (Equation 4) represents the moderation of the growth intensity when the mould index (M) level approaches the maximum peak value. Coefficients k_1 and k_2 were used the scale the equation for different building materials. This was based on the experimental findings.

The experimental growth intensity results were presented for each material as relative values compared to those of the reference material, pine. These new mould growth intensity factors are presented in Equations (2) and (3).

$$k_1 = \frac{t_{M=1,pine}}{t_{M=1}} \qquad \text{when } M < 1 \qquad (2)$$

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

Where $t_{M=1}$ time needed for the material to start the growth (Mould index reaches level M = 1)
$t_{M=3}$ time needed for the material to reach level M =3

The subscript '$_{pine}$' refers to the value with reference material pine.

Factors k_1 were solved for each material used in the research (Figure 3).

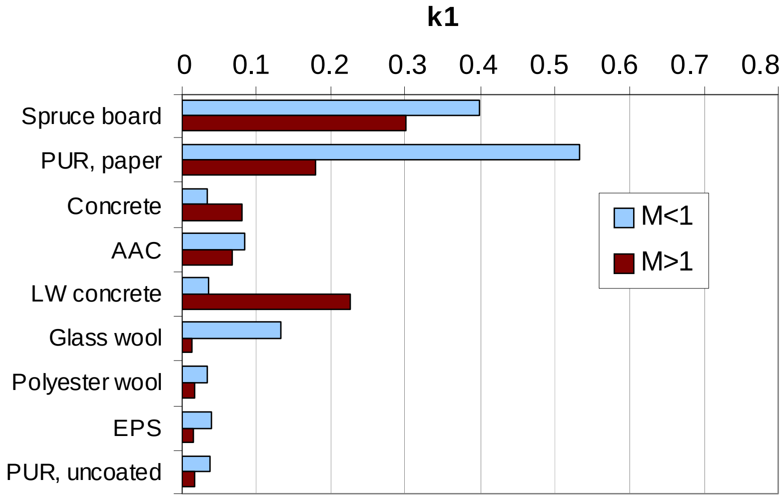


FIG 3. Mould growth factors (k_1) for different material used in the experiments.

To improve the usability of these new values, they were presented as material classes according to the sensitivity to mould growth. Four different sensitivity classes were determined (Table 2). Due to the relatively small amount of data, a proper statistical analysis were not done, but the k_1 classes were determined by using expert estimation. The determined k_1's are illustrated in Figure 4.

Table 2. Mould 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 polished surface

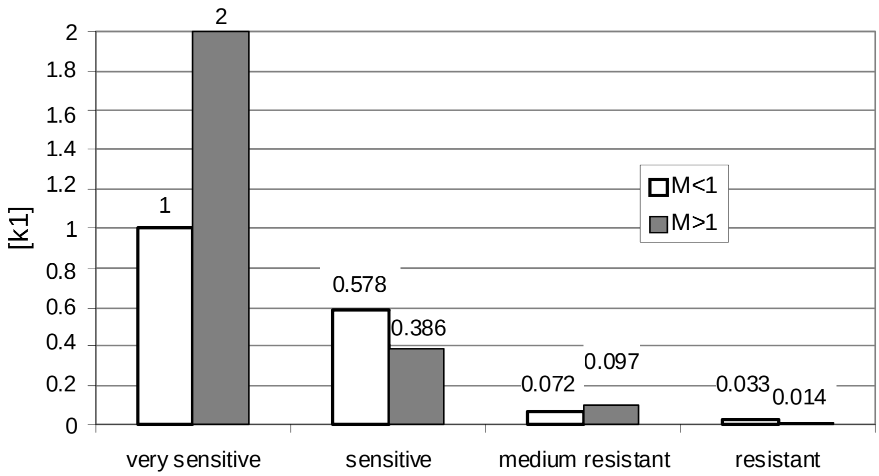


FIG 4. Mould growth intensity factors k_1 sorted to four different sensitivity classes.

The factor k_2 (Equation 4) represents the moderation of the growth intensity when the mould index (M) level approaches the maximum peak value under the prevailing conditions.

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

Where the maximum mould index M_{max} level depends on the prevailing conditions. For the new set of materials the equation of the maximum mould index level can be written in form (Equation 5):

$$M_{max} = A + B \cdot \frac{RH_{crit} - RH}{RH_{crit} - 100} - C \cdot \left(\frac{RH_{crit} - RH}{RH_{crit} - 100} \right)^2 \quad (5)$$

In this equation the coefficients A, B and C can have values that depend on the material class and RH_{crit} is the limit RH level to start the mould growth. The new M_{max} has an effect on the factor k_2 and it contributes to the simulation results.

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 mould index levels in Table 3. This table gives the values for the growth intensity parameter k1 classes and for the coefficients of the maximum mould index factors M_{max} and k_2. The factor RH_{min} represents the minimum level of relative humidity where mould growth is possible for that specific material group.

Table 3. Parameters for the different sensitivity class limits of the updated mould model.

	k_1		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 3 form the new basis for numerical simulation of mould growth on different material surfaces. These values were applied in the following studies where the model performance was studied.

7. Improved decline of mould index

The original model for wood takes into account the decrease in the mould index level when the conditions (relative humidity or temperature) are outside the favorable conditions for mould growth. The degradation of mould on wooden surface has been modeled based on cyclic changes between two humidity conditions. This decline of mould index has been presented in the form of equation 6:

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

Where M mould index
t time from the moment t_1 when the conditions on the critical surface changed from growth to outside growth conditions, h

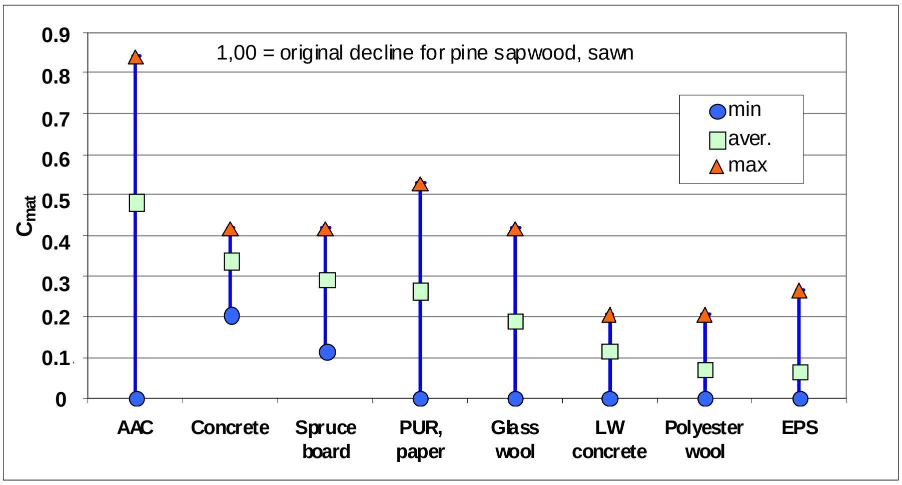
For longer periods (week, months) Equation 6 gives practically linear decrease of mould index.

Decline of mould index for other materials was presented using a constant, relative coefficient for each material (Equation 7) so that the original decline model for wood could be applied using these additional factors.

$$\left.\frac{dM}{dt}\right|_{mat} = C_{mat} \cdot \left.\frac{dM}{dt}\right|_{0} \quad (7)$$

Where $(dM/dt)_{mat}$ mould decline intensity for each material
$(dM/dt)_0$ mould decline intensity for pine in the original model (Equation 6)
C_{mat} relative coefficient for mould index decline used in the simulation model

Figure 5 represents the experimental findings and the classification for the coefficient C_{mat}.



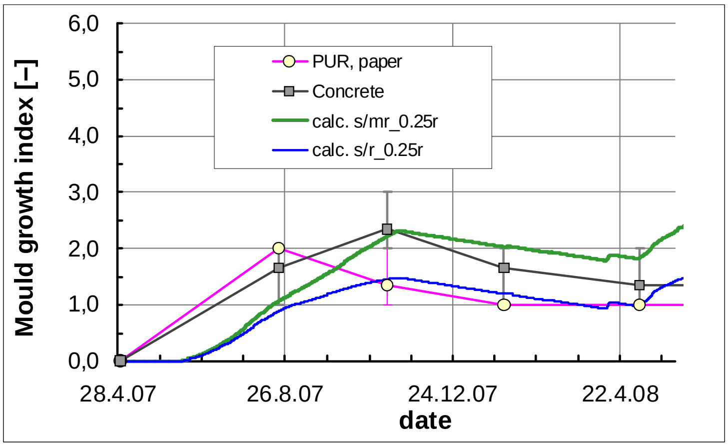
C_{eff}	Description
1.0	Pine in original model, short periods
0.5	Significant Relevant decline
0.25	Relatively low decline
0.1	Almost no decline

FIG 5. The relative decline intensity of mould (C_{mat}) on different materials when compared to the decline on pine surface in the original model.

8. Evaluation of the updated mould growth model

The updated model was compared to the experimental findings from long period laboratory experiments. The conditions and the model evaluation are presented in Figure 6. The conditions on the critical interfaces of two material layers were monitored and the numerical solutions were based on these values. The laboratory experiments corresponded to real structures having interfaces between different materials. These interfaces required a more sophisticated approach than surfaces of homogenous materials that were the basis for the mould growth sensitivity classification. A mixed combination of the growth intensity and maximum growth level classes were used to represent the mould growth in the interfaces.

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
Temperature °C	27 … 18	-5 … +3	2 … 10	20 … 24



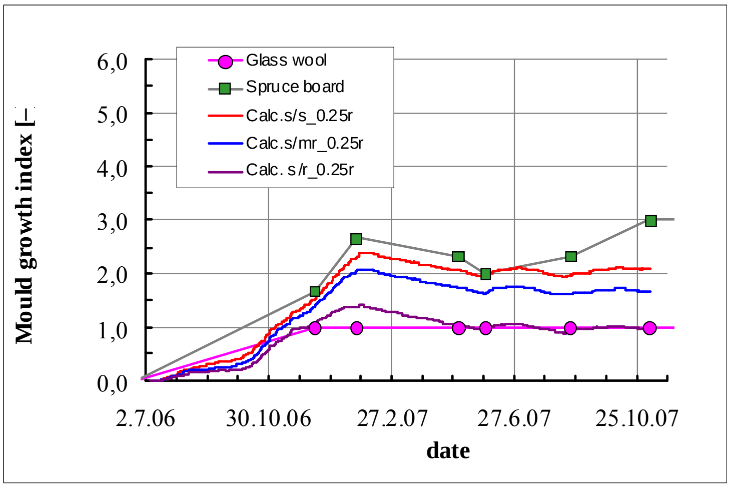


FIG 6. Seasonal conditions for experiments (above) and comparison between numerical mould growth simulations and experimental findings of growth.

In boundaries having contact of two different materials, the growth intensity was found out to correspond to that of the more sensitive material and the mould growth intensity of the materials was assumed to be in class ’sensitive’. The maximum level of mould depends on each the base material.

The relative mould decline coefficients had value 0.25. The updated model has a relatively good correlation with the experimental findings and the mould index remains close to the measured levels also during the cold period.

9. Discussion and conclusions

The mould growth model for wood (pine sapwood) has been improved by adopting new building materials classes in the model. The updating has been done by applying factors for mould growth intensity and maximum mould growth levels for different material classes. Also the critical relative humidity conditions for growth and the decline of mould index level during cold or dry periods has been updated. This updated model allows a better and more reliable prediction of the first biological growth on different materials and on the interface of material layers in order to find the best solutions to ensure safe performance for the building and the indoor climate. How to choose the right classes for different materials remains still one of the sources of error for the improved mould growth model.

10. Acknowledgement

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