Improved Model to Predict Mold Growth in Building Materials

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ABSTRACT

Mold growth is one of the first signs of biological growth linked to too high local moisture content in structures. The numerical mold growth model was based on comprehensive laboratory studies with northern wood species, and it could be used to predict the mold growth in structures. The mold growth is presented as a mold index that may have values between 0 and 6, and it is solved from the changing temperature and humidity conditions. This model can be used as a part of heat, air, and moisture transfer models or to post-process the data derived from simulations or experiments. The numerically solved mold index can be used as one criterion for the moisture performance of the analyzed structure. The main deficiency of the model is that it includes only wood material as the mold growth breeding ground. This study presents new results for modeling of mold growth on the surface of other building materials, such as gypsum board, cement screed on concrete, porous wood fiberboard, and spruce plywood. In addition to extended material data, some evaluations were carried out to better predict the dynamic effect of humidity on the mold growth. This study is active, and further information about the effect of changing dry and cold conditions on the regression and recovery of mold growth will be produced in the new project.

INTRODUCTION

Moisture damage in buildings is caused by moisture exceeding the tolerance of materials and structures, which may lead to the growth of harmful organisms and damage to materials after a critical exposure time. Organisms can have permanent or temporary effects (aesthetic or technical), and the requirements for repairing the problems and damages are varied. For evaluation of the response of humidity, temperature, and exposure time for mold growth on wood material, a numerical mold growth model (Viitanen 1997; Hukka and Viitanen 1999; Viitanen et al. 2000) was based on comprehensive laboratory studies with Northern wood species (Viitanen and Ritschkoff 1991). Other types of models were presented by Adan (1994) and Clarke et al. (1999). The research on modeling moisture and microbial problems in building has been more active over the past few years (Sedlbauer 2001; Moon 2005). Further development of Viitanen's mold growth model is underway (Vinha et al. 2006) in order to adapt the model for analysis of structures made of various building materials for different climatic conditions.

Many building materials can support the growth of microbes, and mold problems more common than decay damage in building structures. Various organisms and microbes have been found within damaged buildings. Often these organisms are also found in nature (soils, decaying materials, and waste). The ambient relative humidity (RH, relative humidity of microclimate) above 75%–80% or water activity (a_w) above 0.75–0.80 is critical for the development of mold fungi on the surface of wood, but the critical humidity level is also dependent on temperature and exposure time (Viitanen and Ritschkoff 1991). It has been found that the mold growth on other building materials may not be equal to that on wood-based materials (Ritschkoff et al. 2000). Also the exposure time needed for the growth to begin may be longer. This paper presents and discusses results from different studies made at VTT Technical Research Centre of Finland and the possibili-

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ties and requirements to numerically model the biological growth on different materials based on these laboratory studies.

EXISTING MOLD GROWTH MODEL

The existing mold growth model for pine and spruce sapwood material and its applications has been presented in several papers (e.g., Hukka and Viitanen [1999], Viitanen et al. [2000], Ojanen and Salonvaara [2000], and Viitanen et al. [2003]). The model is based on the laboratory work reported by Viitanen and Ritschkoff (1991).

For the simulation of mold growth, it is crucial to know the lowest (threshold) conditions where fungal growth is possible in different materials. The duration of these conditions is also significant. There are certain minimum and maximum levels for moisture content of material (or water activity) or temperatures between which fungi can grow in wood. Under these favorable conditions, mold growth may start and proceed at different rates, depending upon the interrelationship between humidity and temperature and upon other factors, such as the organisms and the properties of the materials. Different species of mold may exist, but the mold index used is based on the growth activity of different mixed mold species. The evaluation of mold growth is based on a mold index shown in Table 1 (Viitanen and Ritschkoff 1991).

Growth of mold fungi and the time needed for the initiation of mold growth is mainly regulated by water activity, temperature, exposure time, and surface quality of the substrate. The experiments suggest that the possible temperature and RH conditions favorable for mold growth on wooden material can be described as a mathematical diagram (see Figure 1). The favorable temperature range is 0°C–50°C, and the critical RH required for mold growth is a function of temperature. Based on experiments, this boundary curve has been described using the following polynomial function:

$$RH_{crit} = \{-0.00267T^3 + 0.160T^2 - 3.13T + 100.0, \text{ when } T \leq 20;\ 80\% \text{ when } T > 20 \quad (1)$$

Equation 2 shows the mold growth intensity using temperature and relative humidity values.

Table 1. Mold Growth Index for the Experiments and Modeling

Index	Growth Rate	Description
0	No growth	Spores not activated
1	Small amounts of mold on surface (microscope)	Initial stages of growth
2	<10% coverage of mold on surface (microscope)	—
3	10%–30% coverage of mold on surface (visual)	New spores produced
4	30%–70% coverage of mold on surface (visual)	Moderate growth
5	>70% coverage of mold on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

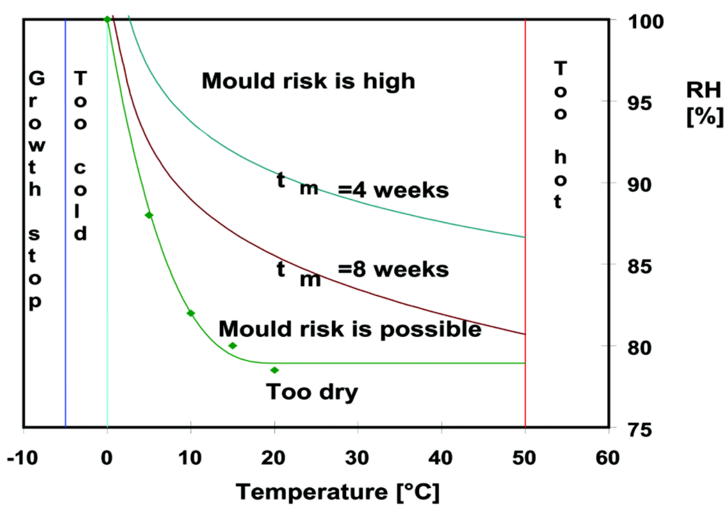

Figure 1 The overall conditions favorable for mold growth on wooden material as a mathematical model (Hukka and Viitanen 1997).

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

where M is the mold growth index, t is time (weeks), W is the wood species (0 = pine and 1 = spruce), SQ is the surface quality (0 is for kiln dried timber and 1 for timber dried under normal kiln drying process), and

$$k_1 = \begin{cases} 1, \text{ when } M < 1 \\ \dfrac{2}{t_v / t_m - 1}, \text{ when } M > 1 \end{cases} \tag{3}$$

Taking into account the upper limit for mold growth as defined by regression equations, the use of a correction coefficient is needed. The retardation of the growth in the later stages is defined by coefficient k_2 (Equation 4). This means that when the mold index approaches levels 4 to 6, or the maximum growth level, the response curve will bend. Assuming the delay to affect the growth rate by 10% at 1 unit below the maximum value of the index gives this coefficient the following form:

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

A mathematical description of the delay of mold growth when conditions become unfavorable (RH drops below critical RH) can be written by using the time elapsed since the beginning of the dry period $(t - t_1)$:

$$\frac{dM}{dt} = \begin{cases} -0.032, \text{ when } t - t_1 \le 6 \text{ h} \\ 0, \text{ when } 6 \text{ h} \le t - t \le 24 \text{ h} \\ -0.016, \text{ when } t - t_1 > 24 \text{ h} \end{cases} \tag{5}$$

The numerical values of the parameters included in the model are fitted for pine and spruce sapwood using large sets of data from various constant and short-term dynamic experiments that use wooden test samples. Special features have been included in the model to simulate the effect of the dynamically changing conditions on the delay of initiation of mold growth. These relatively short-term cycles (seven days or fewer) represent the delay of mold growth on a timber surface. The effect of long seasonal cycles is not taken into account.

OBJECTIVES TO IMPROVE THE MODEL

The existing model has been applied in mold growth risk analysis for pine and spruce sapwood. It is quite suitable for such analysis because the growth intensity is modeled using some comprehensive North-European timber. The deficiency of the model is in the simulation of long seasonal cycles, where the conditions are too dry or cold for mold to grow. The other weakness is the lack of comprehensive information about mold growth characteristics of building materials other than pine and spruce sapwood products. Timber may typically represent very sensitive material for humidity, and the mold growth starts quite easily on pine sapwood compared to other materials. Variation also exists among different wood materials. Timber typically represents sensitive material for mold growth under humid conditions. One of the timber materials most sensitive to mold growth is pine sapwood that has a relatively high nutrient content. Mold growth on pine sapwood can be used to represent the risk of mold growth on any material surface containing organic compounds (dust, spores, soil, etc.) promoting biological growth, and the model has been applied for risk analysis of structures with various materials.

The objective was to produce data to improve the mold growth model so that seasonal cycles and typical building materials, in addition to timber, could be analyzed. The first and simplified approach was to apply the data derived from studies of other materials to the mold growth intensity equation (Equation 2). This simple approach was chosen to make the best of the available data from a reasonable amount of experiments. A redesign of the whole model would require very thorough experiments and significantly more experimental data. This approach has been studied and discussed in this paper.

MATERIALS AND METHODS

In the first part of the study, the experimental material consisted of small samples (50 × 50 mm) of different building materials: pine sapwood, spruce plywood, fiberboard, gypsum board, concrete, and cement screed on concrete. They were exposed to fungal spores and particles at 90% and 97% RH and a temperature around 15°C and 23°C. The samples were exposed to continual humidity in small chambers (90 × 210 × 260 mm). The different humidity conditions were achieved using saturated salt solutions.

Mold growth at fluctuated humidity conditions between 65% and 95% RH was studied using varied exposure periods in the automatically controlled humidity chamber. The humidity conditions and exposure periods are shown in Table 2, and the varied humidity and temperature fluctuations are illustrated in Table 3.

In the other study, a test series using different building materials with and without organic dust was also performed. The materials in this part were: fiberboard, concrete (K30), class wool, rock wool, and expanded polystyrene (EPS) at a sample size of 50 × 50 mm. The organic dust was derived from sawdust from coniferous trees (pine and spruce). The tests were performed in different humidity conditions: 98%–100% RH, 95%–97% RH, and 88%–90% RH at 20°C.

Prior to incubation, the initial weights of the material blocks were measured after conditioning of the blocks at 65% RH. During the exposure test, the moisture content of the test blocks was monitored by weighing. The assessment of the microbial contamination was carried out weekly at the beginning of the incubation and then every two weeks after. The degree of the extent of mold growth and coverage of each surface of the blocks was evaluated microscopically or visu-

Table 2. Tested Fluctuated Humidity Conditions

Cycle	Time (Days) at 95% RH	Time (Days) at 65% RH	Repetition/Total Time
1	3	1	20/80 days
2	3	3	15/88 days
3	1	1	30/70 days*
4	1	3	24/96 days

* This test also included some longer cycles.

Table 3. Tested Fluctuated Humidity and Temperature Conditions

Cycle	Time (Days)	Conditions	Time (Days)	Conditions	Repetition/Total Time
5	1	100% RH/10°C	1	90% RH/10°C	43/86 days
6	1	100% RH/20°C	1	90% RH/10°C	29/58 days
7	1	100% RH/20°C	1	90% RH/20°C	18/36 days
8	1	100% TH/10°C	1	90% RH/10°C	42/84 days

ally by using the scale 0–5 for each individual block as follows.

The results were expressed as mold indexes 1–6 (Table 1). Mold index 1 is equivalent to the initiation of the mold growth (microscopic level), and mold index 3 equates with visible mold growth. The results were compared with the evaluations using an existing model of pine sapwood.

RESULTS

The results of mold growth on different materials and in different constant conditions in the first part of the study are shown in Figure 2. The various building materials showed varying tolerance against fungal growth under the test conditions. The results of the wood-based material fitted best with the model of pine sapwood. In the lower temperature (15°C), there was a lag time for the start of the growth, and this was not well fitted with the model.

All the building materials tested were susceptible to mold growth in humidities higher than 90% RH at temperatures above 15°C (Figure 2). At a lower humidity condition (80% RH), the growth of the mold fungi was not found during the one year exposure. Expectedly, wood-based materials needed lower critical humidity levels and exposure time for fungal growth to begin (mold index 1). Among the wood-based materials tested, the particle board seemed to be the most susceptible to biological contamination. In different exposure conditions, fungal growth began in particle board after one, three, and seven weeks from the start of the incubation, depending on the exposure humidity and temperature. The initiation of the fungal growth on the fiberboard and plywood was observed to be slower (Figure 2).

Results from the materials in different fluctuated conditions are shown in Figures 3 and 4. The mold growth on different building materials was evaluated using the basic model of Viitanen et al. (2000) as a reference data. The modeled data were used based on the results of the exposure in the constant conditions 97% RH/23°C and 97% RH/15°C and in the fluctuated conditions of three days at 97% RH and one day at 65% RH at 20°C. A combination of humidity and temperature fluctuation was also studied (Figure 4). Each material showed different responses to the mold growth depending on the humidity and temperature conditions as well as the exposure time. The mold-growth model for wood material seemed unsuitable for all materials. Also, significant variations were found within the same material types. The mold growth was retarded due to low temperature and low humidity periods, and this effect increased when these periods were longer. The mold growth slowed as a result of low temperatures but also because of shorter periods of high humidity. This effect was also found in the modeled data for pine sapwood, but it was best fitted in tests using high humidity at 20°C.

In Figure 5, the results of mold growth on different materials with and without organic dust are shown. The development of microbe growth was more abundant and faster in construction materials whose surfaces contained organic material and were in unrestricted contact with ambient air when the humidity was high (95% to 100% RH). The development of mold growth was clearly less abundant and slower in clean samples of concrete and thermal insulation. The growth of mold was clearly slower and less abundant in humidity conditions of 88% to 90% RH in comparison with higher humidity conditions, and growth could only be observed in samples containing organic material. After 12 months of exposure to an RH of 78% to 80%, no growth of mold or microbes could be found in any construction material samples.

DISCUSSION

The most critical factors for mold and microbe development are the humidity (or moisture content) and temperature

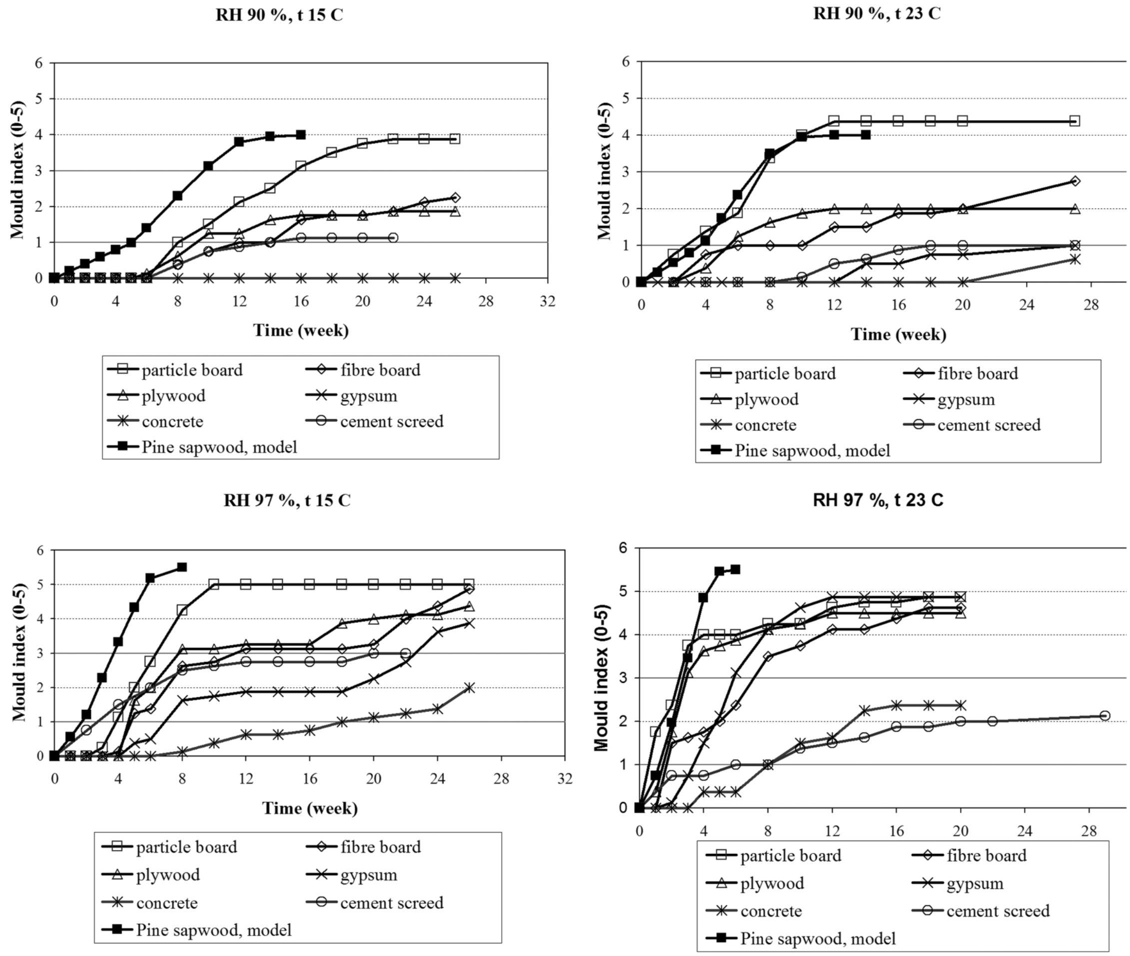

Figure 2 The susceptibility of the wood-based and stone-based building materials to mold contamination at constant humidity and temperature conditions (90% RH/15°C, 90% RH/23°C, 97% RH/15°C, 97% RH/23°C). Results on pine sapwood are in reference to the pine sapwood model. Results on other materials are shown by Ritschkoff et al. (2000).

conditions of the material surface, as well as the exposure time and the type of building material being exposed. The mold growth intensity and rate—and even the possibility for growth—depends on the nutrition and pH level of the material surface, i.e., the material type (Adan 1994; Ritschkoff et al. 2000; Sedbauer 2001; Viitanen 2004). Pure materials typically have different growth performance characteristics than those in contact with other materials or with soiled surfaces that possibly contain organic impurities. Present research contains results for both pure materials and those having surfaces with organic material components, including those that cross boundaries with inorganic/organic materials or those where dust settles on the surface. Concrete is one example of a material with a higher pH level.

The rate of mold growth in fluctuated humidity conditions is dependent on the long-term moisture conditions of materials. Fast changes in humidity conditions are reflected slowly by the corresponding response of microbial growth. In dynamic experiments, the effect of the moisture capacity of materials and the delay in surface conditions under dynamic conditions are included in the changes and delay in biological activity (Viitanen and Bjurman 1995). The simulation of mold growth under dynamic cases includes the effect of both of these factors. The time and cycles needed to show initial stages of mold growth can vary depending on the materials' properties. In fluctuating conditions, the effect of material type may have higher impact on the mold growth when compared to the results of existing models. If materials are wet, however, the humidity of the microclimate near the surface can be higher for a long time and may promote the microbe growth. The high pH level, however, may suppress the growth of organisms on the material or will determine the type of organisms that have the potential to grow there.

The present mold growth model is based on mathematical relations for the growth rate of the mold index in different conditions, including the effects of exposure time, temperature, RH, and dry periods on wood material. Through this approach, the model was compared to results from other mate-

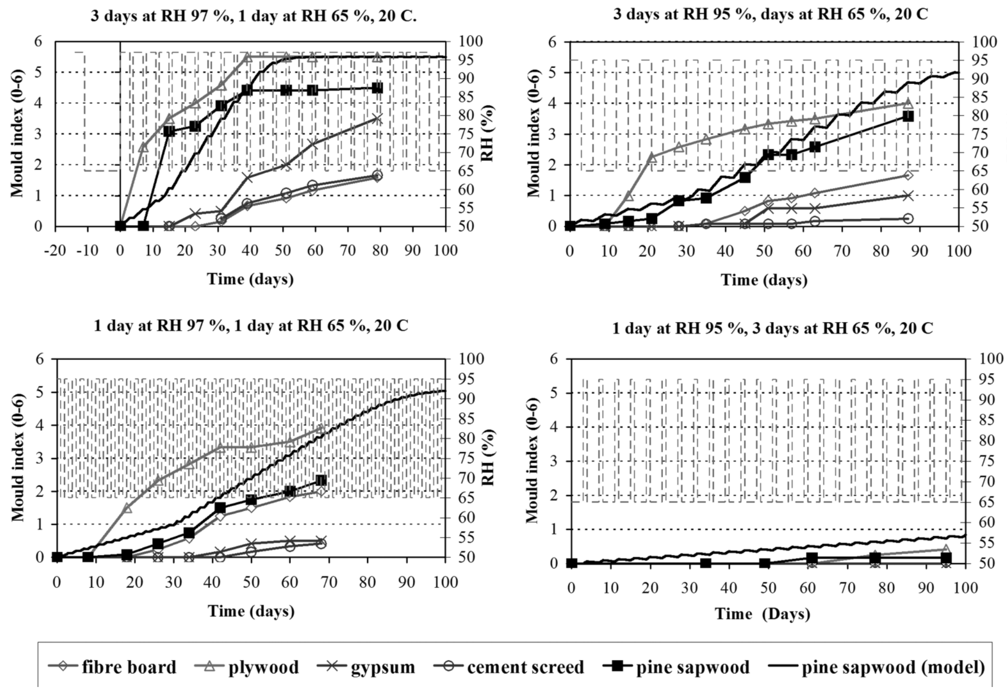

Figure 3 *The susceptibility of the different building materials to mold contamination at fluctuated humidity conditions at 20°C; three days at 95% RH/one day at 65% RH, three days at 95% RH/three days at 65% RH, one day at 95% RH and one day at 65% RH, one day at 95% RH and three days at 65% RH. The fluctuating of humidity is shown in the figure as an RH (%) line.*

rials without significant modifications. The coefficients in the mold growth intensity may need a unique equation determined for each material, and the improvement of the core model developed for pine and spruce sapwood also need to be modified for other materials. If the materials are exposed to organic substances, the present model will fit the need to predict the mold growth risks on material boundaries. If a full mold-growth simulation is needed, the presented corrections of the growth factors are not adequate, and the model should be redesigned. This would require significant amounts of additional tests and mathematical calculations with the materials under an extensive range of conditions. New research on mold growth on different building materials has begun (Vinha et al. 2006).

The present model is purely mathematical in nature, and as mold growth is only investigated with visual inspection, it does not have any direct connection to biology in the form of the number of living cells or particles. The correct way to interpret the results of the present model is that the mold index represents the possible activity of the different mold fungi. The model does not make any distinction between the mold species, but it represents the risk for any possible mold growth on the material surface. The numerical values of the parameters in the model are well fitted for pine and spruce sapwood. The functional form of the model will be analyzed in the future, using the test results of different building materials.

The highest risk of mold development in buildings exists where the humidity conditions are high and the temperature is suitable for fungal growth. Therefore, mold growth is fast to occur in moisture damage situations. The lowest humidity level for mold growth in building materials is around 80% RH. The humidity of materials at time of construction is often high, and the efficiency and speed of drying is one of the fundamental prerequisites for avoiding humidity and mold problems. The humidity limit for mold growth on surfaces connected with ambient air is more than 88% to 90% RH for concrete and more than 78% to 80% RH for materials including organic sawdust or other organic dust (Viitanen 2004). In this case, the organic material accumulated on the surface forms a boundary surface that is critical for mold growth. Aging of the surface of the material (e.g., concrete), surface treatment, and organic dust accumulating on the surface over time all affect microbe growth. The critical humidity conditions for a concrete structure with dense surface layers (such as a floors) are higher than those for free surfaces. The most sensitive point for microbe growth in a dense concrete structure is a material layer containing organic material, where the critical humidity level for air in the pores exceeds 80% to 90% RH. For new clean concrete, the limit for microbe growth in a dense layer exceeds 97% to 98% RH (Viitanen 2004). Clean EPS and mineral wool insulation can also become molded during long-term exposure to humidity exceeding 97% to 98% RH. For these materials and conditions, the exposure time must be very long, typically several months. The results are limited to new materials and cannot be assessed in connection with moisture damage as such.

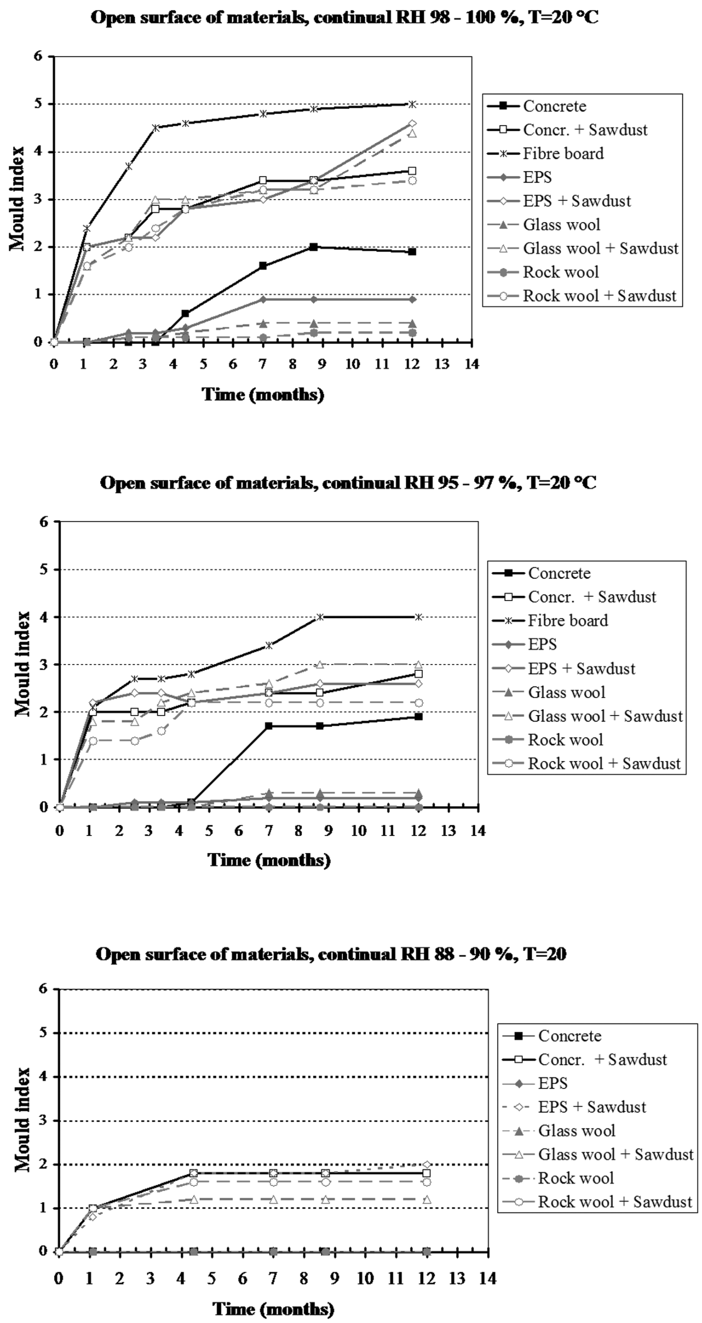

Figure 4 *Mold growth on different building material with and without organic dust (sawdust) at RH conditions between 88% and 100% at 20°C (Viitanen 2004).*

ACKNOWLEDGMENTS

This paper is based on the VTT projects "Building Biology" and "Integrated Prevention of Moisture and Mould Problems" as well as on the TEKES project "Building Conditions." We thank Liisa Seppänen, Hellevi Botska, and Kaarina Kainulainen for their technical assistance.

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