Moisture and Bio-deterioration Risk of Building Materials and Structures

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ABSTRACT: There are several biological processes causing aging and damage to buildings. This is partly due to natural aging of materials and excessive moisture. The demands on durability, energy balance, and health of houses are continually rising. For mold 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. For decay development, the critical humidity is above RH 95%. Mold typically affects the quality of the adjacent air space with volatile compounds and spores. 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. Modeling of mold growth and decay 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 mold growth and to analyze the critical conditions needed for the start of biological growth. The model is also a tool to simulate the progress of mold and decay development under different conditions on the structure surfaces. This requires that the moisture capacity and moisture transport properties in the material and at the surface layer be taken into account in the simulations. In practice there are even more parameters affecting mold growth, e.g., thickness of the material layers combined with the local surface heat and mass transfer coefficients. Therefore, the outcome of the simulations and *in situ* observations of biological deterioration may not agree. In the present article, results on mold growth in different materials and wall assemblies will be shown and existing models on the risk of mold growth development will be evaluated. One of the results of

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a newly finished large Finnish research project 'modeling of mold growth' is an improved and extended mathematical model for mold growth. This model and more detailed research results will be published in other papers.

KEY WORDS: bio-deterioration, building materials, mould fungi, modeling, moisture, risk, structures.

INTRODUCTION

DURING THE SERVICE life of buildings, natural aging and eventual damage of materials due to different chemical, physical, and biological processes can take place. Aging of the materials is one aspect of the environmental processes and involve different chemical, mechanical, and biological reactions of the materials. Bio-deterioration, e.g., mold, decay, and insect damage in buildings, is caused when moisture exceeds the tolerance of structures, which may be a critical factor for durability and usage of different building materials.

Moisture availability is the primary factor controlling mold growth and decay development, but the characteristics of the substrate and environmental conditions determine the dynamics of the growth. Critical conditions for different organisms are given in Table 1. However, moist materials may also dry and become wet again, thus resulting in fluctuating moisture conditions. Mold and decay problems in buildings are most often caused by moisture damage: water leakage, convection of damp air and moisture condensation, rising damp from the ground, and moisture accumulation in the structure. Repeated or prolonged moisture penetration into the structure is needed for damage to occur.

In Northern Europe, the roofs, floors, and lower parts of walls are most often exposed to high humidity and potential attack by bio-deterioration processes (Kääriäinen et al., 1998; Paajanen and Viitanen, 1989; Viitanen, 2001a) and decay also will develop. For the decay development, the humidity and moisture conditions will be higher than that for mold growth, and modeling of decay risk is a separate task. Mold growth is often typical in materials in exterior conditions. In damage conditions, however, different decay types can be found: brown rot, soft rot, and white rot. In buildings suffering from excessive moisture loading, brown rot is the most common decay type (Paajanen and Viitanen, 1989; Viitanen 2001a).

The other abiotic factors like UV radiation and quality of substrate (nutrients, pH, hygroscopicity, water permeability) are also significant for the growth of organisms. Different organisms, e.g., bacteria, fungi, and insects, can grow and live in the building materials; microbiologically clean buildings probably do not exist, as some contamination begins as early as during the construction phase. The humidity/moisture conditions connected

Table 1. Organisms involving damages and defects of building components (Viitanen and Salonvaara, 2001; Viitanen et al. 2003).

Type of organism	Damage/Problem type	Humidity or moisture range (RH or MC %)	Temperature range (°C)
Bacteria	Biocorrosion of many different materials, smell, health problems	Wet materials, RH $>$97%	*ca*. −5 to +60
Mold fungi	Surface growth on different materials, Smell, and health problems	Ambient RH $>$75%, depends on duration, temp., and mold species	*ca*. 0 to +50
Blue-stain fungi	Blue-stain of wood permeability change of wood	Wood moisture content $>$25–120% RH $>$95%	*ca*. −5 to +45
Decay fungi	Different types of decay in wood (soft rot, brown rot, or white rot), also many other materials can be deteriorated, strength loss of materials	Ambient RH $>$95%, MC $>$25–120%, depends on duration, temperature, fungus species, and materials	*ca*. 0 to +45
Algae and lichen	Surface growth of different materials on outside or weathered material	Wet materials, also nitrogen and low pH are needed	*ca*. 0 to +45
Insects	Different type of damage in organic materials, surface failures or strength loss	Ambient RH $>$65%, depends on duration, temperature, species, and environment	*ca*. 5 to +50

with temperature and exposure time are the most important factors for development of biological problems and damage in buildings.

The research and modeling of mold growth is most often performed under constant conditions when the ambient humidity conditions and micro-climate will prevail for longer periods. Ayerst (1969) and Smith and Hill (1982) studied the effect of temperature and water activity on germination and growth of selected mold fungi. They developed isopleths for the growth conditions of mold fungi on agar media. An isopleth is a boundary that defines all combinations of temperature and relative humidity that permit a particular mold growth rate. Grant et al. (1989) analyzed and modeled the moisture requirements of some mold fungi isolated from dwellings. A certain succession, depending on the moisture requirements of different fungal species: primary, secondary, and tertiary colonizers were found.

Research with building materials will be better fitted to the moisture problems in buildings. Adan (1994) used a nonlinear regression technique to model sigmoid curves describing vegetative fungal growth of *Penicillium chrysogenum* on gypsum board material. He used the time-of-wetness (TOW) as an overall measure of water availability for fungal growth under fluctuating humidity conditions. The TOW is defined by the ratio of the cyclic wet period (RH $\geq$ 80%) and the cyclic dry period. The mold growth is a function of the effect of lowest humidity, time of wetness and high relative humidity frequency, and finally of periods of wet and dry conditions. He used low temperature scanning electronic microscope (LTSEM) to analyze the growth and studied the effect of coatings and surface quality on the mold growth. He also evaluated the effect of distribution of growth density on test results. Clarke et al. (1998) developed a simulation model and tool for mold growth prediction in buildings based on an analysis of published data using growth limit curves for six generic mold categories. These limits have been incorporated within the ESP-r (building energy software) system for use in conjunction within combined heat and moisture flow simulation.

Hukka and Viitanen (1999) and Viitanen et al. (2000) presented a model of mold growth, which is based on the duration of suitable exposure conditions required before the start of microbial growth or before the damage reaches a certain degree. Particular emphasis is focused on this time period, the so-called response time or response duration, in different humidity and temperature conditions for mold growth or decay development. The model is based on the large laboratory studies on Scots pine and Norway spruce sapwood.

The growth of mold in this model was evaluated using the ‘mold index’ scale shown in Table 2. The model can be used to evaluate the mold growth in different exposure conditions, and it can be introduced to building physic modeling to evaluate the performance of different structure. The model is

Table 2. Mold index for experiments and modeling (Viitanen and Ritschkoff, 1991).

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% coverage mold on surface (visual)	New spores produced
4	10–50% coverage mold on surface (visual)	Moderate growth
5	$>$50% coverage mold on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

not suitable for evaluating the development of decay, for which different models exist (Viitanen, 1996; Viitanen et al., 2000).

Sedlbauer (2001) studied different models to evaluate spore germination and growth of different mold species on different types of materials. He found that the isopleths developed by growth of mold on an artificial medium can be used to evaluate the growth rate of different fungi. He used a hygrothermal model based on the relative humidity, temperature, and exposure time needed for the spore germination of mold fungi based on the osmotic potential of spores. He analyzed the effect of different climatic conditions on the spore moisture content and germination. He also evaluated the spore moisture content and germination time based on calculated time courses of temperature and relative humidity in various positions of the exterior plaster of an external wall using WUFI program (Sedbauer and Krus, 2003). In Figure 1, a comparison of the critical conditions for mold growth assumed by some of mold growth models is shown. These curves represent lower limiting isopleths (humidity levels) for mold growth.

The original VTT model has been used e.g., in mold growth analysis of external wood frame walls (Vinha, 2007). During this study it came up that there were deficiencies in this model. The model is based on the laboratory measurements using different constant and fluctuated conditions, but the verification under real fluctuating temperature and humidity measurements was still lacking. Moreover, mold growth in cold conditions when temperature was below 0°C had not yet been modeled. Materials other than wood were not included in model and mold growth had not been studied in real structures between two material layers.

This study also pointed out that when the mold index value is calculated under changing conditions, its value also depends on how often it is calculated. The shorter the calculation interval, larger is the mold index in fluctuating conditions. This is due to the fact that under fluctuating conditions the mold index rises faster than it falls (Vinha, 2007).

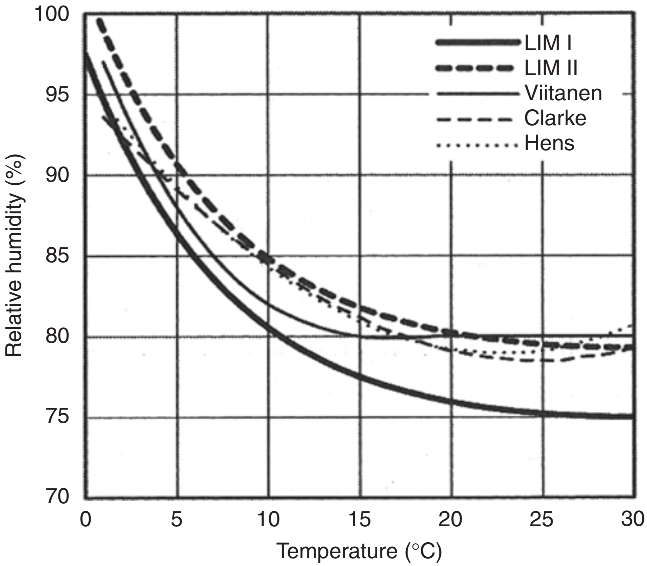

Figure 1. *Comparison of the LIMs of substrate class 1 (LIM I, biodegradable materials) and substrate class 2 (LIM II, porous materials) after Sedlbauer (2001) with data from results of building materials after Viitanen et al. (2000), Clarke et al. (1998), and Hens (1999).*

Figure 2 presents an example from the development of the mold index on the surface of regular pine sawn goods in the outdoor air conditions of Lahti, Finland in 2000–2001. The original climate data have been measured every 3 h, and 6-, 12-, and 24-h average values have been calculated from this data. The mold indexes have been calculated after that with different average values. Calculations have been done by using the original VTT model where no decline under cold conditions (temperature $\leq 0°C$) occurred. Figure 2 indicates the impact of calculation interval on the mold index. Mold index values calculated on the basis of shorter intervals are clearly larger. Therefore, it is important to know what the suitable time interval for calculations should be.

Based on these above-mentioned experiences TUT and VTT started a large research project (in the following text it is referred to as 'modeling of mold growth') in 2005. The object of this project was to improve and verify the existing VTT model and also to extend it for building materials other than wood. During this project, numerous laboratory and field tests have been done for different materials and wall assemblies (Lähdesmäki et al., 2008). Some of these test results are presented in this article to give indications for the different factors that affect mold growth in materials. These examples together with the modeling examples also point out the

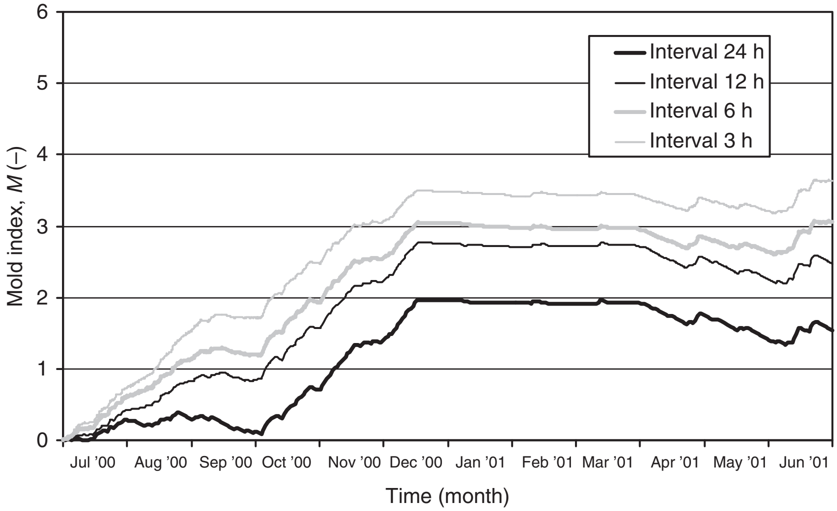

Figure 2. *Changes in the mold index on the surface of regular pine sawn goods in the outdoor conditions of Lahti, Finland during the period 1 July 2000 to 30 June 2001. Depicted here is the change in the mold index based on average outdoor air temperature and RH-values calculated at 3-, 6-, 12-, and 24-h intervals (Vinha, 2007).*

challenge we run into when we try to create usable and reliable mathematical mold growth models.

MOLD GROWTH IN DIFFERENT MATERIALS AND STRUCTURES

This chapter focuses on the North European researches and experiences on the moisture-related problems in buildings. Some of the typical moisture-related problems reported in the practice have been brought out. Furthermore, some recent results from experimental set-ups made for research purposes in order to investigate the mold growth on different materials and structures have been presented.

Practical Experiences

The excessive water into the building structure and materials is the basic cause to different biodeterioration problems. For instance, in washrooms water often penetrates through inside surfaces or pipe leakage into the structures causing long-lasting high humidity conditions. In old wooden buildings, the floor has often been built above a cold ventilated basement or crawl space, where high humidity conditions may exist. If water gets penetrated in the crawl space, the ventilation may not keep the floor dry and mold growth is obvious. If ventilation caps are closed, severe decay problems will be found, e.g., dry rot damage (Paajanen and Viitanen, 1989; Kääriäinen et al., 1998). Microbial contamination on the surfaces in the crawl space is typically much higher than inside the building. The level of fungal spores in the crawl space is about 10 times as high as indoors. In crawl spaces, spore concentrations in the range of 10^3–10^5 colony-forming units per gram (cfu/g) of material are common. The levels have usually been highest on wood-based boards and on timber (Hyvärinen et al., 2002). In cases of heavy fungal colonization, airborne spore concentrations of up to 10^3–10^4 cfu/m^3 have been detected.

The slab-on-ground structure without thermal insulation below the concrete slab has been used in old buildings. This type a floor is very sensitive for water damage and microbial growth. Especially in detached houses built between 1960 and 1980, wooden beams are often supported on concrete slabs on grade. Leivo and Rantala (2006, 2008) studied 49 specimens of fill layers under slab-on-ground structures in Finland. Some kind of microbial growth was discovered in 98% of examined soil samples. The indicator fungus species or actinomycetes–bacteria were discovered in 79% of the samples. According to the analysis there was no connection between the water content or capillarity of the soil samples and the detected microbe growth. Thus, the microbe growth in soil layers under slab-on-ground structures of a heated building is a natural boundary condition to be expected in fill layers, and is not an indicator of moisture failure of the ground slab structure. The laboratory experiments showed that fungal spores (*Aspergillus versicolor*) cannot permeate a solid concrete slab ($h = 80$ mm, $w/c = 0.7$–1.0) or EPS and polyurethane layer. Blocking the infiltration routes between the exterior wall and the slab-on-ground prevents the microbes and metabolites from permeating into structures and the indoor air.

Partial decay or insect damage is often found in the lower sill plate of exterior walls due to water penetration from the basement (Kääriäinen et al., 1998). In the Northern Europe climate, it is typical that mold growth can begin in the autumn on wooden surfaces exposed to outdoor air, when the temperature and relative humidity are relatively high. The results of several Finnish studies show that, in most buildings, minor mold growth can be found in cold parts of these structures (Kokko et al., 1999). According to the study of Suonketo et al. (1999), mold growth in concrete-element exterior walls is clearly less than in wood frame walls. Mesophilic bacteria (actinomycetes and other bacteria) and fungal spores with the cultivation method were analyzed. Only 4.8% of all samples ($n = 1534$) were found to be distinctly contaminated (actinomyces or fungal spores) while 88.7% of samples were clean. The detected fungal species were mostly *Penicillium* and *Acremonium* types. Highest spore concentrations of actinomyces and fungal spores were approximately 2×10^5 cfu/g and 1×10^5 cfu/g, respectively.

The air tightness of buildings has become more important during recent years due to its remarkable effect on the energy consumption of buildings. The air tightness also has a positive effect from the viewpoint of mold growth: Mold spores and odors could more easily flow from outside to indoor air through a leaky envelope (Airaksinen et al. 2007). Moreover, in leaky houses more moisture flows from indoor air into the envelope increasing the risk of moisture damage in envelope assemblies. Yet another benefit of an airtight envelope is that ventilation is easier to control to each room. On the other hand, ventilation has to be adjusted very carefully in airtight house, otherwise high pressure differences (10–30 Pa) between indoor and outdoor air can occur (Kalamees et al., 2007).

Effect of Material Type and Surface Quality

For evaluation of the response of different building materials to mold attack in high humidity conditions, several materials were selected for laboratory research in 'modeling of mold growth' project. The experimental work was conducted in the laboratory using chambers having high humidity conditions (RH 90% and 97%) at 22°C. The small samples (50×50 mm^2) of different materials were exposed in constant humidity and temperature conditions (Figure 3). The growth of mold was in the first step detected

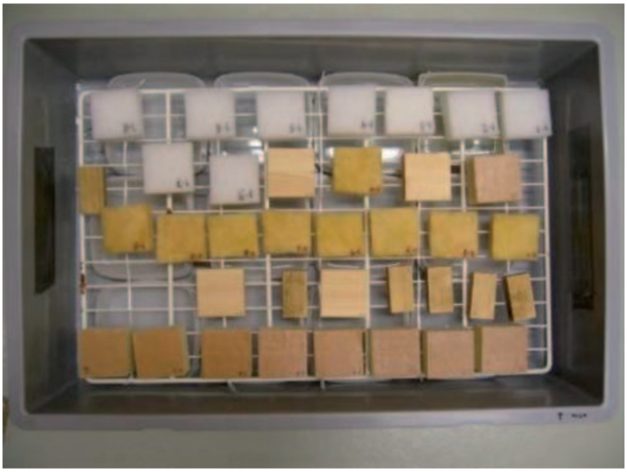

Figure 3. *The laboratory test set-up with small samples. Nine multiple samples of each material were analyzed.*

using light microscopy using the scale shown in the Table 2. In the stone-based materials, the growth was predominantly found using only microscopy, but in wood-based materials, visual growth (mycelium and spores) was also found.

The organic building materials like paper and wood are sensitive to mold growth when exposed to high humidity conditions or a water damage situation (RH above 97%). Stone-based materials like concrete and bricks are more tolerant to mold growth, but the organic dust accumulated on their surfaces will change the properties of those surfaces and they become suitable for the mold growth. Under lower humidity conditions around RH 90%, mold growth is lower and could be found in pine sap wood (Figure 4). Mold growth on edge-glued spruce board was significantly lower than that on pine sapwood.

The surface quality of wood material varies depending on the chemical composition of the wood and wood-based products. There are several factors affecting the durability of wood material: heritage, the manufacturing process (sawing, drying, transport, storage), and the end use conditions (humidity and temperature conditions of the microclimate). The nutrient content and hygrothermal properties of the surface are important material factors for mold growth. The surface of paper-coated materials seems to behave like wood-based materials. The work performed with Scots pine sapwood gives different exposure response than paper-coated building

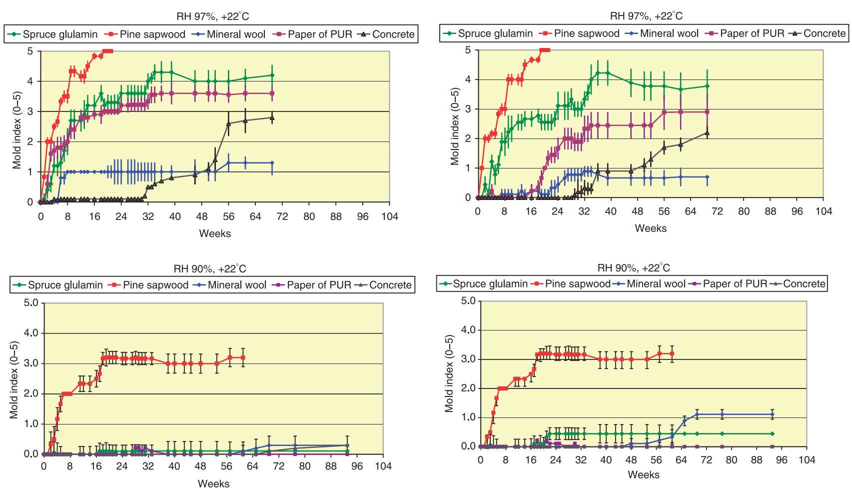

Figure 4. *Response of some building material to mold growth at RH 97–98%/20°C (above) and RH 90%/20°C (below). For some materials, the response has been higher on the upper surface subjected to mold suspension (left) than that on under side surface (right).*

materials or edge-glued spruce board (Figure 4). Different type of growth of mold fungi was found in materials (Figure 5). The ambient humidity condition and temperature were the most important for the growth of mold fungi. At high humidity, mold growth was found in all tested materials, but at lower humidity, mainly in wood materials.

The surface type and dirtiness of material has influence on mold growth. In the 'modeling of mold growth' study, materials were also tested in field conditions, where the samples were exposed to outdoor air conditions but were sheltered against rain and sun radiation. In Figure 6, the observed mold indexes are shown for a wooden and a stone material. A layer of organic dirt (for example pollen) was found on the upper surfaces of the specimens (surface 1 in Figure 6), and there was more dirt if the surface had open pores or microscopic holes. This led to the surprising result that more mold was detected in stone-based materials than in edge-glued spruce board materials.

In wood materials the finish of the surface is a critical factor. In every test condition of planed pine sapwood more mold growth was detected than in edge-glued spruce board. The test results showed that edge-glued spruce boards differ from other wood materials. In laboratory experiments the specimens were treated with a mold suspension before the experiments started. In some materials, for example paper-coated polyurethane, the mold growth was detected especially in dried spore suspension.

Coatings will protect the materials against wetting and growth of organisms, when the properties of substrate material will be changed. For wood material, however, the wood substrate will also affect the properties of coated surface when low molecular compounds (sugar and nitrogen compounds) will move through the permeable coatings (Viitanen and Ahola, 1999).

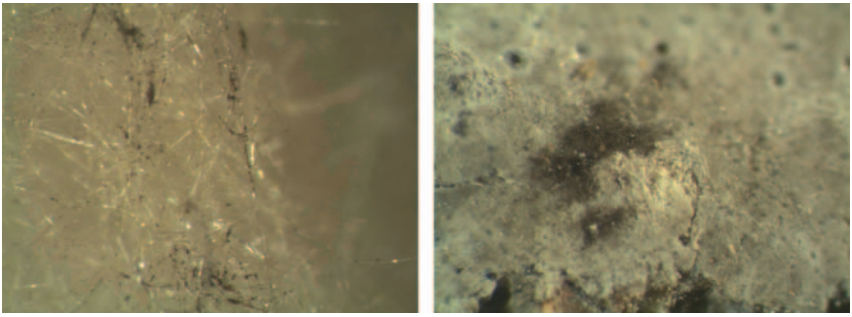

Figure 5. *Some examples on mold hyphae bonded with glass wool fibers (on the left). Dark Cladosporium mold hyphae in concrete (on the right).*

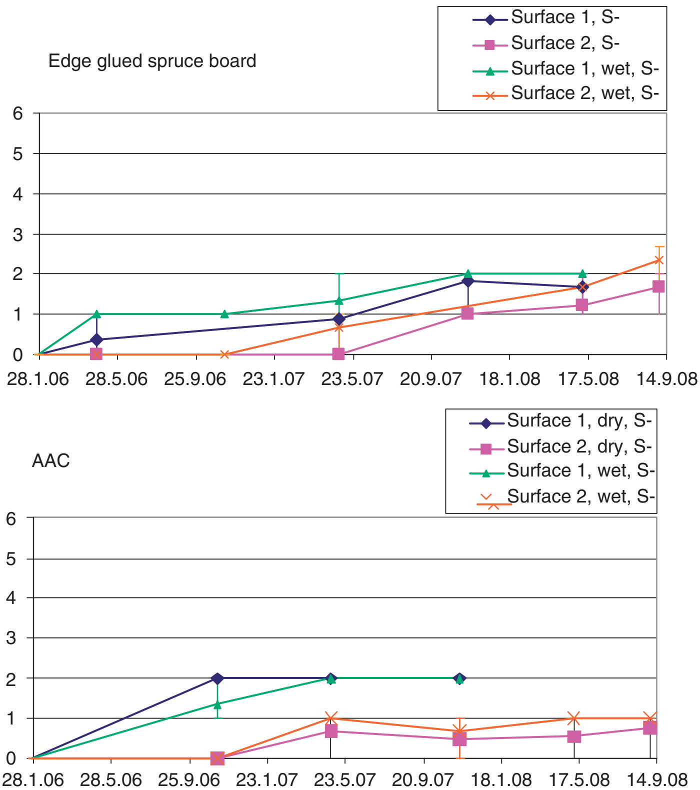

Figure 6. *The mold index curves of edge-glued spruce board (above) and autoclaved aerated concrete, AAC (below) in field conditions. Surface 1 was the upper surface on which organic dirt could be accumulated and surface 2 was the lower surface. Notation S- denotes that the surfaces of these specimens' were not treated with a mold suspension before the test.*

Effect of Fluctuated Temperature and RH Conditions

Viitanen and Bjurman (1995) studied the effect of fluctuating humidity conditions on mold growth on pine sapwood and Viitanen and Ojanen (2007) on other building materials. They found a response of mold growth to fluctuating conditions and balance between the level and duration of different humidity conditions combined with the temperature and material properties (Figures 7 and 8). According to the research results in fluctuating conditions, the moisture content of material surface will vary depending on the material, humidity, temperature, and exposure time at different humidity levels.

Under fluctuating humidity conditions, the total exposure time for response of growth of mold fungi is affected by the periods of high and low

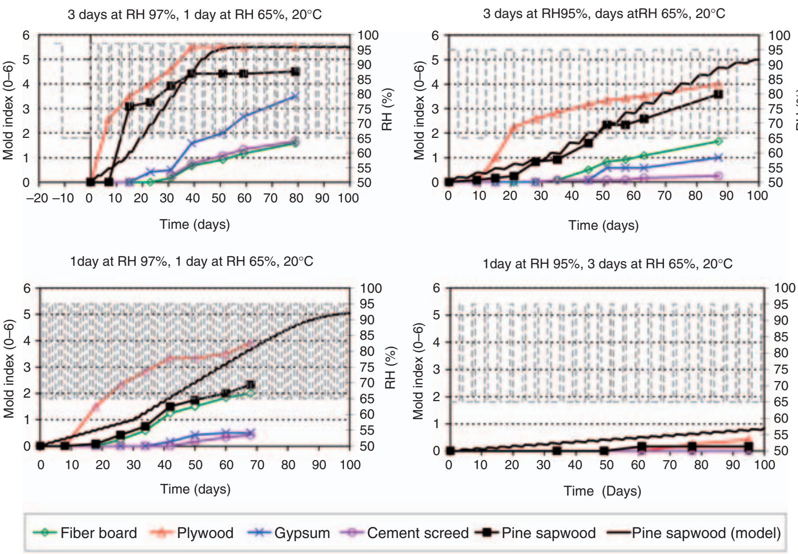

Figure 7. *The susceptibility of the different building materials to mold contamination at fluctuating humidity conditions at +20°C. 3 days at RH 97% / 1 day at RH 65%, 3 days at RH 95% / 3 days at RH 65%, 1 day at RH 97% and 1 day at RH 65%, 1 day at RH 95% and 3 days at RH 65%. The fluctuation of humidity is shown in the figure as a RH (%) line (Viitanen and Ojanen, 2007).*

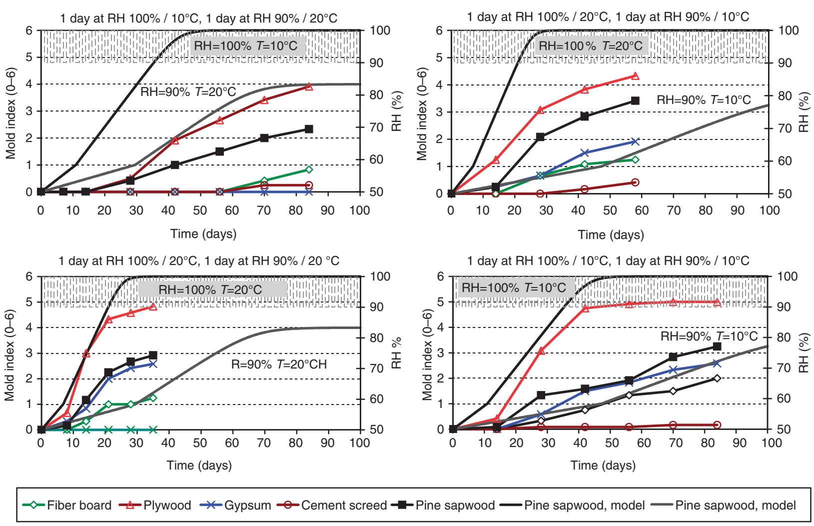

Figure 8. *The susceptibility of the different building materials to mold contamination at fluctuating humidity and temperature conditions. The fluctuation of humidity is shown in the figure as a RH (%) line. The modeled lines are calculated for constant conditions (Viitanen and Ojanen, 2007).*

humidity conditions as well as the humidity and temperature levels. Short periods at high humidity conditions will not lead to fungal growth if the periods at low humidity preventing mold growth are long enough (Viitanen and Bjurman, 1995). When the period at high RH is longer than 24 h, the effect of cumulative time at high humidity is more linear, but if the dry periods are very long, very low or negligible growth response can be expected. An exposure period at low RH prevents growth and has a direct effect on the total response time required for mold growth to occur.

As mentioned earlier, the effect of frost was not taken into account as an affecting factor in the previous studies. Therefore, this phenomenon has also been included in the research 'modeling of mold growth.' In the laboratory experiments of materials temperature or relative humidity varied cyclically. The duration of one cycle was 4–8 weeks. In these cases, the mold index decreased or stayed at the same level as before the cold or dry period. In some other cases the mold index even slightly increased during cold periods. The effect of longer periods at low temperature or low humidity, however, seemed to decrease the mold index (mold growth level), see Figures 9 and 10.

Mold Growth in Wall Assemblies

In the project 'modeling of mold growth' experiments for exterior wall structures were also done in the laboratory and under field conditions. The purpose of these experiments was to study mold growth inside the structure at the interface of two materials. Temperature and relative humidity at the interface was measured with temperature and relative humidity sensors. Experiments were done so that each insulating material (glass wool, paper-coated polyurethane (PUR), expanded polystyrene (EPS), and polyester wool) forms an interface with one of the structural materials in the study (edge-glued spruce board, concrete, autoclaved aerated concrete, and expanded clay aggregate concrete).

The exterior wall structures of the first series of tests were exposed to varied humidity and temperature conditions simulating summer/autumn, winter, spring, and also high exposure condition (Table 3). The tested structures were treated with mold suspension before the experiments started.

In Figures 9 and 10 two examples of these research results have been presented. The analyzed material pairs were edge-glued spruce board–glass wool and autoclaved aerated concrete–glass wool.

After about 3 months from the start of the experiments mold growth was detected on the surfaces of some test specimen. Mold growth was found on both edge-glued spruce boards and the autoclaved aerated concrete. After about 6 months from the start of the test the mold indexes were analyzed for the first time from all test specimens. The mold indexes varied on the

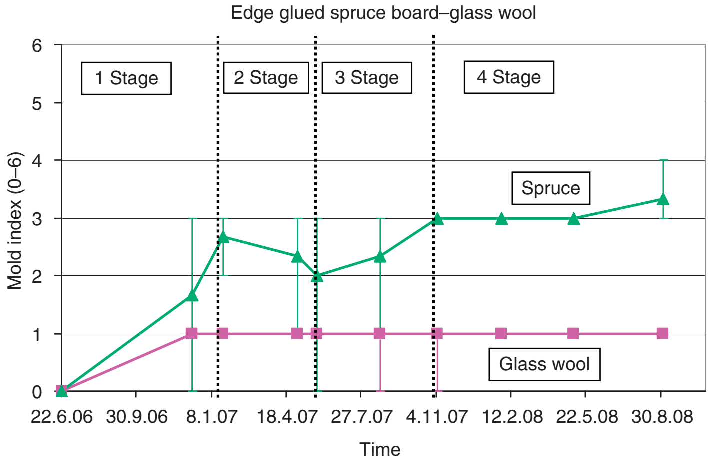

Figure 9. *Mold index of edge-glued spruce and glass wool in the assembly test 1.*

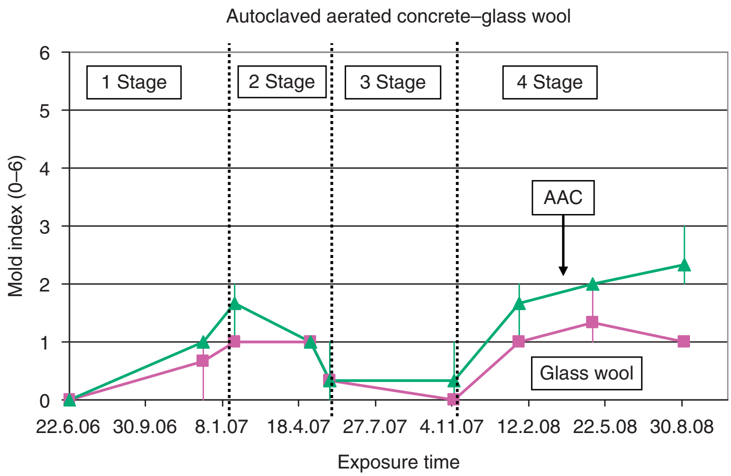

Figure 10. *Mold index of autoclaved aerated concrete and glass wool in the assembly test 1.*

Table 3. Simulated exposure conditions during the wall assembly test 1.

Stage	**1**	**2**	**3**	**4**
Simulation	Summer/autumn	Winter	Spring	High exposure
Time (months)	7	4	6	12
RH	80–100	92–100	60–95	94–100
Temperature	27–18	−5 to +3	2–10	20–24

surfaces of the edge-glued spruce board specimens between 1 and 3. At the same time the mold index 1 was detected on glass wool contact surface (Figure 9). The mold indexes found from autoclaved aerated concrete and other material combinations varied between 0 and 1 (Figure 10).

After the stage 1 the mold indexes varied between 2 and 3 on the surfaces of edge-glued spruce board and between 1 and 2 on the surfaces of autoclaved aerated concrete. The mold indexes on the surfaces of the glass wool specimens were 1. In some other material combinations the mold index also reached value 2 on the surfaces of glass wool.

Declination of the mold index was found after the cold period (stage 2) in both material combinations. This same phenomenon was also noticed in most of the other material combinations. During spring period (stage 3) the mold indexes increased again on the surfaces of the edge-glued spruce board specimens whereas it stayed in the same level on the surfaces of autoclaved aerated concrete. In other material combinations the mold indexes both increased and decreased during the stage 3. After the high exposure conditions (stage 4), the mold index was on the average 2.3 on the surfaces of edge-glued spruce board and 3.3 on the surfaces of autoclaved aerated concrete.

MODELING OF MOLD GROWTH

Modeling of mold growth will be discussed in this section. Mold growth depends on three main characteristics of the material. The threshold conditions enabling mold growth on material surface, the intensity of mold growth under different conditions and mold growth level, and the maximum level of mold growth under prevailing conditions should be known for the base material. Modeling of mold growth is based on the assumption of uniform susceptibility of different species of mold spores allowing a 'general approximation' of the growth pattern for different material surfaces.

In the simulation of mold growth it is crucial to know the lowest (threshold) conditions where fungal growth is possible in different materials. Also the duration of these conditions is significant. There are certain minimum and maximum levels for moisture content of material (or water activity) or temperature between which fungi can grow. 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 specific organisms involved and the properties of the materials. Several mold fungi will grow on lower humidity conditions than that needed for decay development, and separate models are needed to evaluate the development of biodeterioration.

The favorable temperature range for growth is 0–50°C, and the critical relative humidity required for initiation of mold growth is a function of temperature (Figure 11(a)). Based on experiments this boundary curve has been described using a polynomial function (Hukka and Viitanen, 1999; Viitanen et al., 2000). The response times proved to be short (from a few days to a few weeks) in pine sapwood at conditions favorable to the growth of microorganisms and long (from a few months to a year) in conditions close to the minimum and maximum moisture or temperature levels. Decay development was also modeled (Viitanen, 1996). Time periods needed for decay development are also significantly longer than that for development of mold growth (Figure 11(b)). Critical humidity levels at different temperatures for mold and rot, respectively, are also shown in Figure 11(a) and (b).

The model describes the dynamic nature of mold growth under varying temperature and humidity conditions as it gives the predicted mold index as a function of time. Simulation results with the model show that under fluctuating humidity, the mold index will decrease during low humidity or temperature periods, depending on the time periods (Figure 12). This kind of behavior can also be found in the 'modeling of mold growth' study.

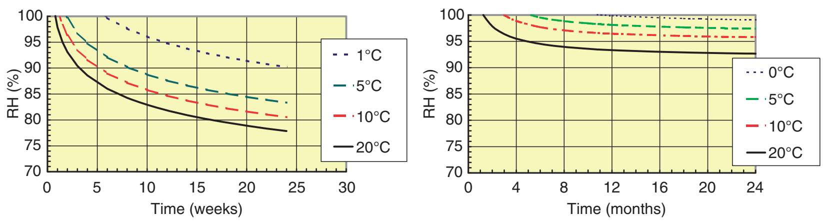

Figure 11. *Critical humidity (RH %), time (weeks/months) and temperature needed to start mold growth on pine sapwood (a) and early stage for brown rot development (b) in pine sapwood. Both figures are modeled, not measured (Viitanen, 1996).*

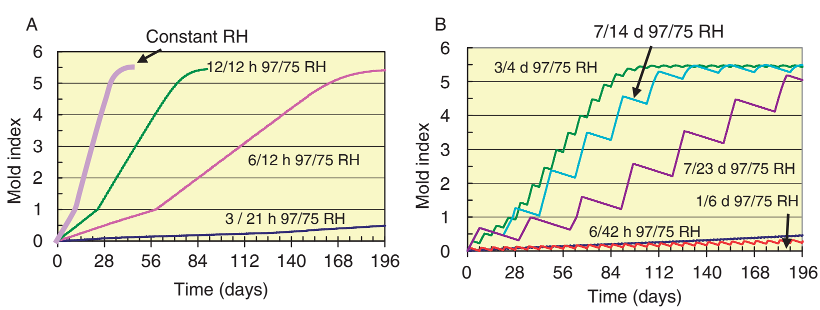

Figure 12. *Modeling the effect of varied fluctuating humidity conditions on the development of mold index in pine sapwood (Viitanen et al., 2000).*

The following case study shows an example on how to use a mathematical model for predicting mold growth. The emphasis is on studying the effect of different assumptions on the resulting calculation result – the sensitivity analysis. The hygrothermal simulation tool used was TCCC2D (Ojanen et al., 1994) with the mold index calculation according to the original VTT model and using the data from the field measurements of the 'modeling of mold growth' study (Lähdesmäki et al., 2008). Also the biohygrothermal model implemented in WufiBio was used for comparison.

The monitored temperature and humidity conditions from a field test of different building materials were used as boundary conditions for simulations when solving the mold growth for pine. The 48-h average values are shown in Figure 13.

The samples of pine sapwood were exposed to outdoor conditions, but sheltered from rain and solar radiation. The detected mold growth level of pine samples were compared to those solved using different approaches for the mold index calculations. In simulations, the measured hourly climate data was used as boundary conditions. The results are presented in Figure 14. The analyzed period was almost 1 year long, starting in 22nd June.

In Figure 14, the results of VTT model were calculated with and without a decline in mold growth. This decline, based on shorter period dynamic laboratory experiments, was used when the conditions were unfavorable for the growth. The measurements showed that during the study period the top surface of the pine samples, exposed to outdoor air causing dust and spore settling, had average mold index level 2. The lower surface, which was better protected against dust, had the level of 1, corresponding to first microscopic signs of growth. The VTT model, taking into account the decline of growth, predicted mold index level between 1 and 2 for this case. Despite the differences in the dynamics, the predicted risk level corresponds well to the measured.

Figure 14 presents also a comparison of two totally different models – WufiBio and the original VTT Model. The governing limit for mold growth in these comparisons was pine sapwood for the VTT model and LIM I for the WufiBio model. The calculation results show that VTT model with no decline under dry and cold conditions is the most comparable with the WufiBio model. However, when VTT model and WufiBio are compared, it has to be kept in mind that the used units (mold index and growth, mm) are not comparable to each other like they are presented in Figure 14. In Figure 14, the curve calculated by VTT model without declinations under dry and cold periods is just fitted so that the end value of this curve is on the same level than the end value of the curve calculated by WufiBio model.

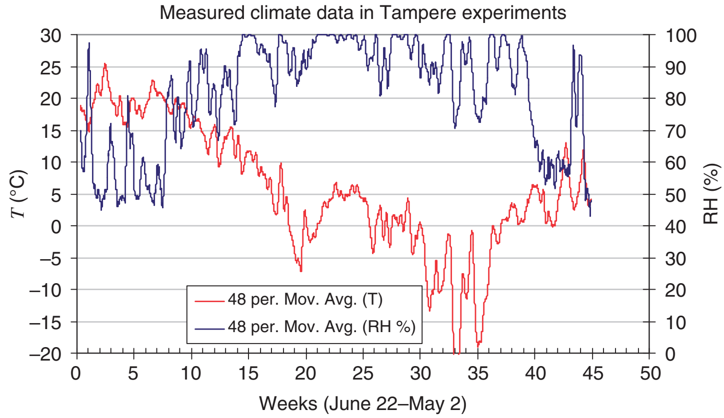

Figure 13. *Measured climate data presented using 48-h moving average values. The simulations use the original hourly measured data.*

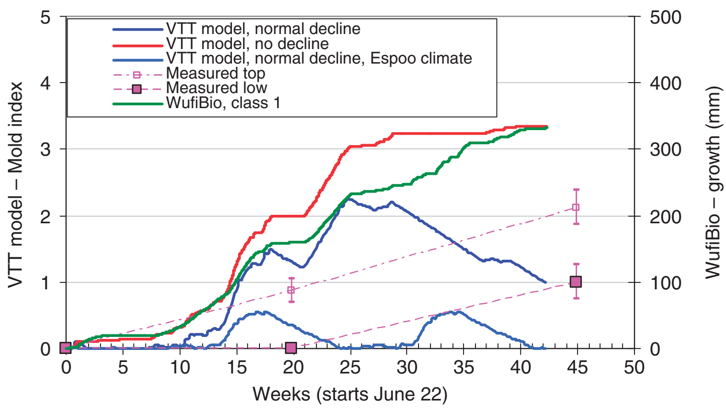

Figure 14. *Comparison of VTT model and WufiBio – and measured mold index – on the surface of pine sapwood. Results with VTT model have been calculated under several assumptions. VTT model with no decline under dry and cold conditions is the most comparable with the biohygrothermal model of WufiBio.*

The above simulation results are based on temperature and relative humidity of air, and not the microclimatic surface conditions, which can result in rather different conditions for materials with/without hygrothermal capacity under heavily fluctuating conditions.

In addition, prediction of mold growth should be thought of as an attempt to predict the risk of mold growth and not the exact growth. The influence of the uncertainties, whether it is in the model itself or, for example, in the weather data used, is significant.

DISCUSSION

The most critical factors for mold and microbe development are the humidity (or moisture content) and temperature conditions at the material surface as well as the exposure time and the type of material. The mold growth intensity and rate and even the possibility for initiation of growth depends on the nutrition and pH level of the material surface, i.e., the material type (Block, 1953; Viitanen, 1996, 2004; Theander et al., 1993; Ritschkoff et al., 2000). Pristine materials typically have different growth performance characteristics than those in contact with other materials or if they have soiled surfaces containing organic impurities. The present research contains results for both pristine materials and those having surfaces with organic material components or dust settling on their surfaces. Concrete is one example of materials having higher pH level.

The response of mold growth in fluctuating humidity conditions is dependent on the long-term moisture conditions of materials, and microbial growth reflects slowly to fast changes in humidity conditions. Based on the dynamic experiments, the effect of the moisture capacity of materials and the changes in surface conditions under dynamic conditions are included in the changes and the delay in biological activity. The simulation of mold growth under dynamical cases should include the effect of both of these factors (Ojanen et al., 1994; Ojanen and Salonvaara, 2000). The time and cycles needed to show initial stages of mold growth can vary strongly depending on the properties of the materials. In the fluctuating conditions, the effect of material type may have higher impact on the mold growth when compared to the results with the existing models.

When applying the mold growth models for building physics, the great natural variability of materials, different treatments, and organisms should also be taken into consideration. Different types of microbial growth will be found on stone-based materials, insulation, and wood materials. The aging of material and accumulation of dust and other material on the surface of building material will also change the response of the material to moisture and biological processes. The susceptibility of different materials to mold fungi mainly depends upon the water activity and nutrient content of the substrate. During manufacturing of different wooden products, the properties of materials and their surfaces as well as the equilibrium moisture content (EMC) can be changed. For example the EMC of particle board is lower than the EMC of solid wood. Norway spruce sapwood has often proved to be less susceptible to mold than Scots pine sapwood. It has been shown, that after fast kiln drying, the amounts of nitrogen and low-molecular hydrocarbon compounds on the surface layers of sawn sapwood timber can be higher than inside the wood (Theander et al., 1993;

Viitanen, 2001b) and this may promote the mold growth. Heartwood of several wood species is often more resistant than sapwood. In buildings, some materials are often coated, treated, or painted with different products and treatments. In such cases, the surface treatments play an important role on durability of the substrate. Degradation of surfaces by microorganisms is affected by interaction of materials, surfaces, and the surrounding environment and microclimate. The chemical and physical structure of the substrate as well as the surface treatment has a significant effect on the quality and service life of the treated system.

There are several aspects that have to be taken into account in the interpretation of the experiments and analysis of the mold growth levels: Under dynamic tests the conditions at the interface of the air and test sample are typically different from the air conditions adjacent to the test sample. Therefore, it may cause errors if the measured dynamic climate conditions are used as the critical surface conditions.

Even in constant conditions the initial moisture content of the test material should be known and taken into account. Under dynamic conditions the heat and moisture capacity of material and the heat and mass transfer coefficients on the surface may cause severe changes in the change of surface conditions, differences in the humidity level and in the mold growth when compared to the adjacent conditions. Dynamic simulation that solves the surface conditions should be used both in the analysis of dynamic mold growth experiments and when predicting the mold growth in structures under real climate conditions.

The use of full simulation enables to separate the increase and delay in the actual mold growth from the occasionally favorable and nonfavorable surface conditions. In practise, this means that short high humidity excursions cause no risk for mold growth, if the moisture of a structure is not increased for longer time. For example, in the fluctuating humidity conditions when RH of 95% is affecting during 2 h in each day on material surface, it will cause no harm if the humidity condition is below RH 75% rest of the time. Temperature fluctuations can cause condensation of water or a high RH near the surface, if RH of indoor air is high (e.g., above RH 35% during winter time in Finland). In fluctuating temperature conditions at a high RH, a fall in temperature will add or even condense moisture on the surface of materials and drastically enhance the available moisture for microbial growth. Organisms growing on the outer surfaces of materials can also tolerate the cold periods. Some findings show, that some mold and blue stain fungi can even grow at below 0°C temperature, around −5 to −7°C (Land et al., 1985). However, the effect of frost for damage development is not very clear.

The existing VTT model can model the declination of mold index when the conditions are not suitable for growth. The original attempt was to model the delay of mold growth during the short period dynamic conditions (in the course of days). This declination seems to be artificial and it is much more important to analyze this delay during seasonal conditions. New seasonal experiments have provided information about the mold growth during and after very dry or cold conditions, which will enable improved modeling of the phenomena.

Within the project 'modeling of mold growth,' the described existing VTT model has also been extended to other building materials than pine and spruce sapwood. The extended model and simulation results with the extended model will be described in separate publications. However, the existing model is based on experiments on untreated softwood materials – pine and spruce sapwood – that are understood as being relatively sensitive to mold growth. Therefore, using the existing model will provide one with safe guidelines for the risk of mold growth.

CONCLUSIONS

There are several factors involved with the biodeterioration of materials and buildings, and mathematic modeling that may help us to understand the complicated interaction of many factors. These factors and how they can take into account in mathematical modeling of mold growth have been described in this article. The mathematic modeling, however, will not give the answers for all problems and users should be aware of the limitations to give the true picture of the complicated process of biodeterioration and damage development in buildings. Future research will give more knowledge to allow us to develop more applicable models.

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