Moisture and biodeterioration risk of building materials and structures

Hannu Viitanen [1], Juha Vinha [2], Kati Salminen [2], Tuomo Ojanen [1], Ruut Peuhkuri [1], Leena Paajanen[1], Kimmo Lähdesmäki[2]

ABSTRACT

There are several biological processes causing aging and damage to buildings. Partly this is due to natural ageing of materials, and partly it is caused by excess moisture. The demands on durability, energy balance and health of houses are continually rising. For mould development, the minimum (critical) ambient humidity requirement is shown to be between RH 80 and 95 % depending on other factors like ambient temperature, exposure time, the type and surface conditions of building materials. For decay development, the critical humidity is above RH 95 %. Mould typically affects the quality of the adjacent air space with volatile compounds and spores. Decay development forms a serious risk for structural strength depending on moisture content, materials, temperature and time. The worst decay damage cases in Finland are found in the floors and lower parts of walls, where water accumulates due to different reasons. Modelling of mould 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 analyse the critical conditions needed for the start of biological growth, but it is also a tool to measure the progress of mould and decay development under different conditions. Numerical simulation makes it possible to evaluate the risk and development of mould growth on the structure surfaces. Thus the moisture capacity and moisture transport properties in the material and at the surface layer have to be taken into account in the simulations. In practice there are even more parameters affecting mould 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 paper, results on mould growth in different materials and wall assemblies will be shown and models on the risk of mould growth and decay development will be evaluated.

[1] H. Viitanen, T. Ojanen, R. Peuhkuri and L. Paajanen are senior research scientists, VTT, Technical Research Centre of Finland, Espoo, Finland

[2] J. Vinha is senior assistant and senior research scientist, K. Salminen is research scientist and K. Lähdesmäki is assistant research scientist, Faculty of Built Environment, Department of Civil Engineering, Tampere University of Technology, Tampere, Finland.

1. 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. Ageing of the materials is one aspect of the environmental processes and involve different chemical, mechanical and biological reactions of the materials. Biodeterioration, e.g. mould, 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 (Grant et al 1989, Hyvärinen et al. 2002). 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 (Leivo and Rantala 2008). The humidity / moisture conditions connected with temperature and exposure time are the most important factor for development of biological problems and damage in buildings.

The research and modelling of mould growth is most often performed under constant conditions when the ambient humidity conditions and microclimate will prevail for longer periods under laboratory conditions. Research with building materials will be better fitted to the building problems. Adan (1994) used a non-linear regression technique to model sigmoidal 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>= 80 %) and the cyclic dry period. The mould 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) technique to analyse the growth of mould fungi and studied the effect of coatings and surface quality on the mould 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 mould growth prediction in buildings based on an analysis of published data using growth limit curves for six generic mould 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 mould growth in pine sapwood which is based on **duration** of suitable exposure conditions required before microbial growth will start or the mould growth will reach 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 mould growth. The model is based on the large laboratory studies on Scots pine and Norway spruce sapwood.

Sedlbauer (2001) studied different models to evaluate spore germination and growth of different mould species on different types of materials. He found, that the isopleths developed by growth of mould 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 mould fungi based on the osmotic potential of spores. He analysed 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 periods of temperature and relative humidity in various positions of the exterior plaster of an external wall using WUFI program (Sedbauer and Krus 2003). Viitanen (1996) presented a separate model concerning the development of brown rot decay in pine sapwood. Results pointed out, that the minimum humidity conditions for decay development is above 95 % and wood moisture content above 25 %, depending on the temperature and duration of the exposure.

In practice there are many cases where it is very difficult to differentiate the normal ageing of the structures from damage. The overall functionality of a building is important to keep in mind during design, construction and reparation of a building. The structures should be functional, and the ventilation and plumbing systems together with automation should support the overall functionality (Airaksinen et al 2007). Even though separate parts and devices of a building function well independently, this does not guarantee proper functioning of the whole product. In this sense, simple, clear operating and service instructions are important matters. They should be included in all types of buildings. Maintenance and upkeep are important from the standpoint of long-term functionality of a building. Most important is preventive maintenance, which helps in eliminating undesirable factors beforehand. For the design of durable structural solutions, including proper material choices both for new and old buildings, modelling of the critical conditions for biodeterioration processes will be a tool to diminish the risk of biological problems in building.

2 MOULD GROWTH IN DIFFERENT MATERIALS AND WALL ASSEMBLIES

The growth of organisms on material can be evaluated using different methods. Viitanen and Ritschkoff (1991) developed mould index evaluation method (Table 1). In the previous works, numerous samples of pine and spruce sapwood were exposed to different constant and varied humidity and temperature conditions (Viitanen and Ritschkoff 1991, Viitanen and Bjurman 1997). In later stages, also different building materials were studied (Ritschkoff et al 2000, Viitanen and Ojanen 2007).

In 2005 TUT and VTT started a large research project (in the following text it is referred to as "Modelling of mould growth") the object of which is to improve the above mentioned model and to extend it also for other building materials than wood. During this project numerous laboratory and field tests have been done for different materials and wall assemblies (Lähdesmäki et.al 2008). In this section some of these test results are presented to indicate the different factors that affect mould growth in materials. These examples also point out the challenge we run into when we try to create usable and reliable mathematical mould growth models. In the first step, laboratory work using small samples was performed under different humidity and temperature conditions: RH 97 % / 22 °C, RH 97 % / 5 °C, RH 90 % / 22 °C and RH 90 % / 5 °C. Also periods in frost (-5 and -20 C) were studied.

TABLE 1:
Mould growth index for experiments and modeling (Viitanen and Ritschkoff 1991).

Index	Growth rate	Description
0	No growth	Spores not activated
1	Small amounts of mould on surface (microscope)	Initial stages of growth
2	< 10% coverage of mould on surface (microscope)	
3	< 10 % coverage mould on surface (visual)	New spores produced
4	10-50% coverage mould on surface (visual)	Moderate growth
5	> 50% coverage mould on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

4.1 Effect of material type and surface quality

The organic building materials like paper and wood are sensitive to mould 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 mould growth, but the organic dust or material accumulated their surfaces will change the properties of those surfaces and become suitable of mould to grow. Under lower humidity conditions around RH 90 %, mould growth is lower and could be found in pine sap wood (Figure 1). Mould growth on edge glued spruce board was significant lower than that on pine sapwood.

The surface quality of wood material varies depending on the chemical composition of the wood. 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 mould growth.

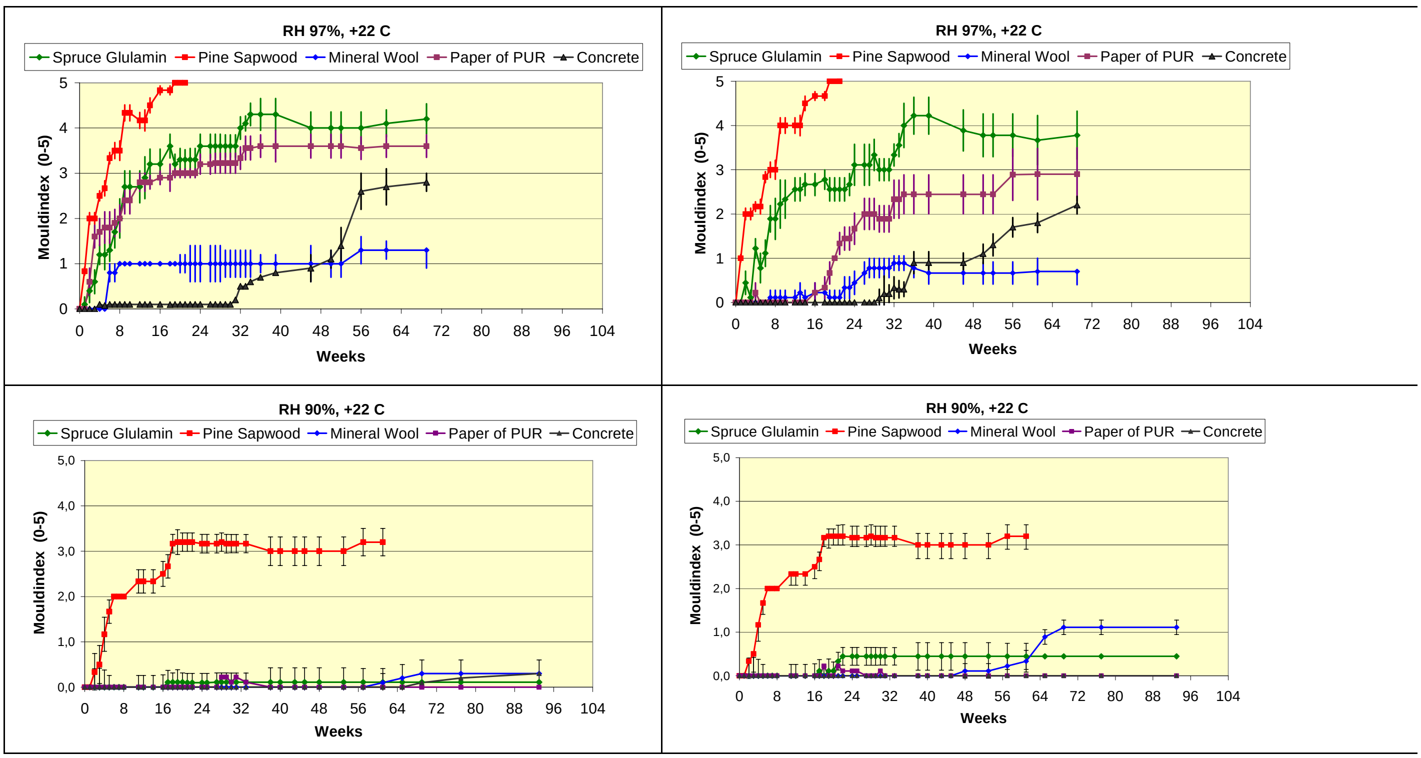

Figure 1. Response of some building material to mould growth at RH 97 – 98 % / 20 °C (above) and RH 90 % / 20 °C (below). For some materials, the response has been higher on the upper surface subjected to mould suspension (left) than that on under side surface (right).

The results shown in Figure 1 are based on the exposure of small samples (50 x 50 mm) in constant humidity and temperature conditions in laboratory. The growth of mould was in the first step detected using light microscopy (Figure 2). In the stone based materials, the growth was predominantly only found using microscopy, but in wood based materials, also visual growth (mycelium and spores) was found.

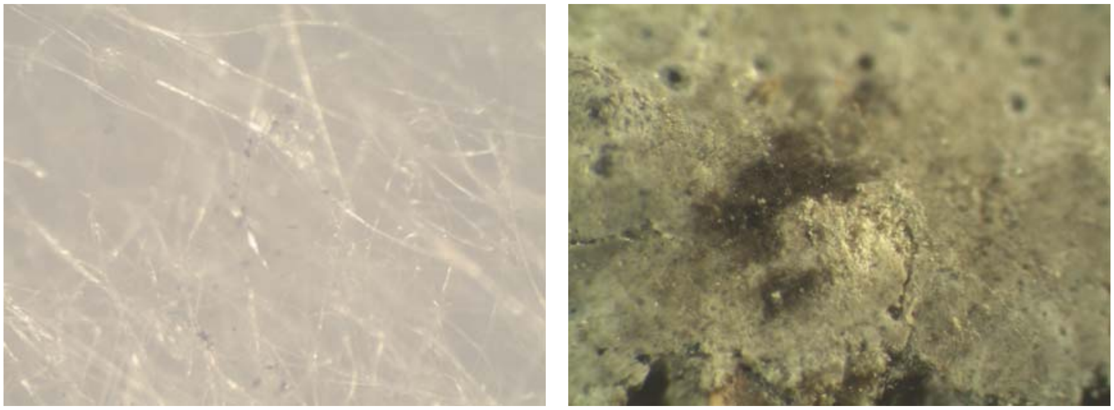

Figure 2. Mould hyphae bonded with glass wool fibres (on the left). Dark Cladosporium-mould hyphae in concrete (on the right).

In the "Modelling of mould growth" study, material tests were also performed under field conditions, where temperature and humidity conditions are same as in open air but the specimen are sheltered against rain. In Figure 3, the observed mould 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, and there was more dirt if the surface had open pores or microscopic holes. This led to the surprising result that more mould was detected in stone based materials than in edge glued spruce board materials.

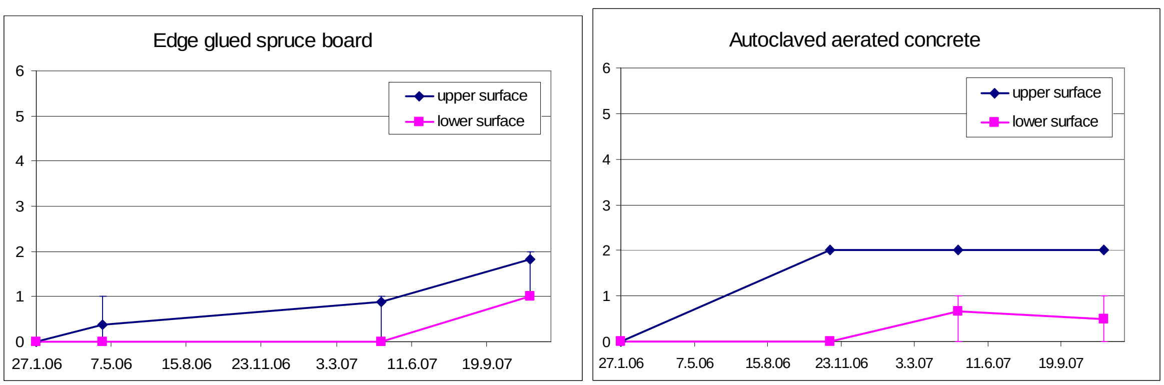

Figure 3. The mould index curves of edge glued spruce board (on the left) and autoclaved aerated concrete (on the right) in field conditions.

In wood materials the finish of the surface is a critical factor. In every test condition of planed pine sapwood more mould growth was detected than in edge glued spruce board. The test results showed that edge glued spruce boards differ from other wood materials.

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).

2.2 Effect of fluctuated temperature and RH conditions

Viitanen and Bjurman (1995) studied the effect of fluctuating humidity conditions on mould growth on pine sapwood and (Viitanen and Ojanen 2007) on other building materials.

They found a response of mould growth to fluctuating conditions and balance between the level and duration of different humidity conditions combined with the temperature and material properties. According to the research results in fluctuating conditions, the moisture content of material surfaces will vary between the average humidity and moisture conditions depending on the humidity, temperature and exposure time at different humidity levels.

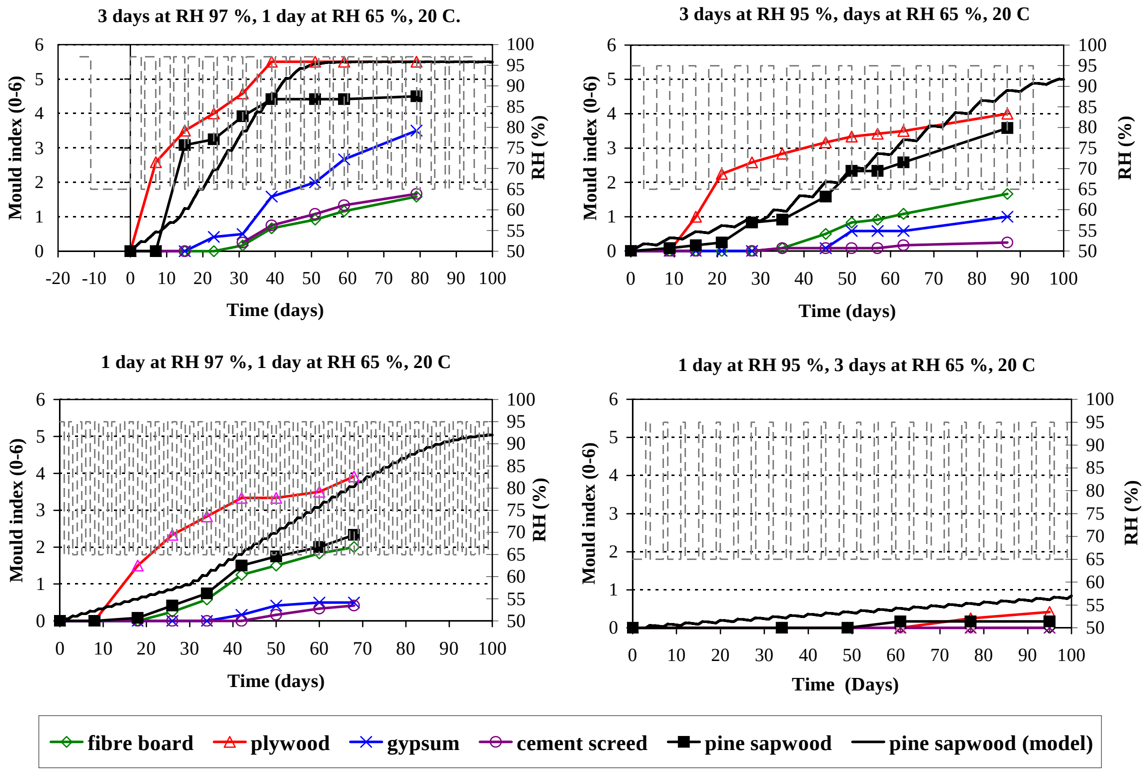

Figure 4. The susceptibility of the different building materials to mould contamination at fluctuated humidity conditions at +20 °C. 3 days at RH 95 % / 1 day at RH 65 %, 3 days at RH 95 % / 3 days at RH 65 %, 1 day at RH 95 % and 1 day at RH 65 %, 1 day at RH 95 % and 3 days at RH 65 %. The fluctuating of humidity is shown in the figure as a RH (%) line (Viitanen and Ojanen 2007).

Under fluctuating humidity conditions, the total exposure time for response of growth of mould fungi is affected by the periods of high and low 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 mould growth are long enough (Viitanen and Bjurman 1995). When the period at high RH is longer than 24 hours, 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 mould growth to occur.

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 ongoing research “Modelling of mould growth”. In these experiments temperature or relative humidity varies cyclically. The duration of one cycle is 4 to 8 weeks. In these cases the mould index decreased or stayed at the same level as before the cold or dry period. In some other cases the mould index even slightly increased during cold periods. The effect of longer periods at low temperature or low humidity, however, seemed to decrease the mould index (mould growth level).

2.3 Mould growth in wall assemblies

In the project ”Modelling of mould growth” the experiments for exterior wall structures are being done in the laboratory and under field conditions. The purpose of the experiments in structures is to study mould growth inside the structure at the interface of two materials. Temperature and relative humidity at the interface is measured with temperature and relative humidity sensors. Experiments are 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 for approximately 7 months to conditions in the first phase (summer and autumn) and approximately 4 months to conditions in the second phase (winter) and approximately 6 months to conditions in the third phase (spring and summer). The tested structures were treated with mould suspension before the experiments started.

After about three months from the beginning of the experiments mould growth was detected on the surfaces of edge glued spruce boards. In the edge glued spruce board-glass wool–combination mould was detected at Index 1 growth rate. In edge glued spruce board-polyester wool–combination mould was detected at the Index 3 growth rate. Mould growth was not detected on the surfaces of glass wool or polyester wool. After six months from the beginning of the test the mould growth indexes on the surfaces of the edge glued spruce board specimens varied between 1 and 3. The mould growth indexes found for other material combinations varied between 0 and 1.

At the end of the first phase the mould index values on the surfaces of edge glued spruce board were the highest. In the edge glued spruce board-glass wool combination the indexes varied between 2 and 3 and in edge glued spruce board-polyester wool combination they varied between 1 and 3. The mould indexes on the surfaces of the glass wool specimen were between 1-2 depended on the structure. On the surfaces on polyester wool the index was 1, on the surfaces of autoclaved aerated concrete indexes were between 0-1 and on the surfaces on concrete the index was 1.

After three months from the beginning of the second phase there was no increase in mould growth in any material. On the surfaces of some materials like autoclaved aerated concrete the mould indexes declined by one level. The mould indexes on the surfaces on the wood specimen were same as at the end of the first phase. After the third phase the mould indexes were at same level as in the end of the second phase. Monitoring of this project is still going on.

3. MODELLING

In this paper, modelling of mould growth is in focus. In the simulation of mould 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 favourable conditions mould 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 mould fungi will grow on lower humidity conditions than that of needed for decay development, and separate models are needed to evaluate the development of biodeterioration.

The favourable temperature range for growth is mould fungi is 0-50°C, and the critical relative humidity required for initiation of mould growth is a function of temperature. Based on experiments this boundary curve has been described using a polynomial function (Hukka and Viitanen 1991, Viitanen *et al* 2000). The response of ambient conditions to the early stage of mould growth is based on the mould index 1 presented in the table 1. The response times proved to be short (from a few days to a few weeks) in pine sapwood at conditions favourable to the growth of micro-organisms 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 modelled (Viitanen 1996). Time periods needed for the early stage of decay development (mass loss 1 – 3 %) are also significant longer than that for development of mould growth. Critical humidity levels at different temperatures for mould and rot, respectively, are shown in Figure 5.

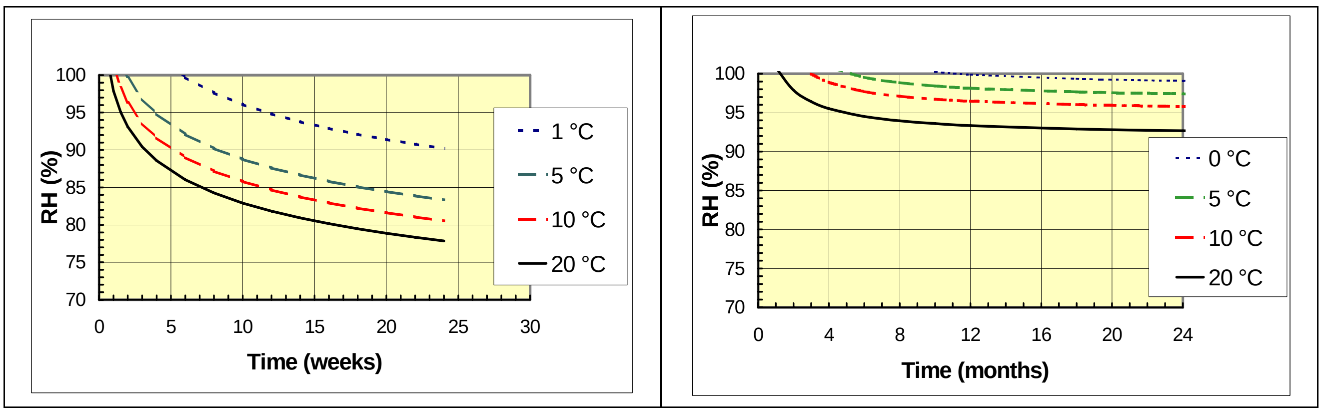

Figure 5. Critical humidity (RH %), time (weeks / months) and temperature needed to start mould growth on pine sapwood (A) and early stage for brown rot development (B) in pine sapwood (according to Viitanen 1996). Both figures are modelled, not measured.

Under fluctuating humidity, the mould index will decrease during low humidity or temperature periods, depending on the time periods (Figure 6). This could also found in the "Modelling of mould growth" study.

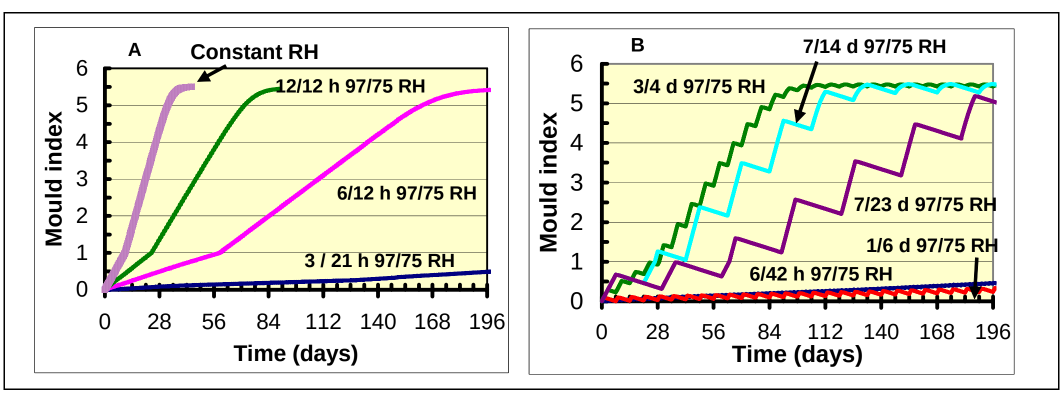

Figure 6. Modelling the effect of varied fluctuating humidity conditions on the development of mould index in pine sapwood (According to Viitanen et. al 2000).

The models generated to simulate mould growth are most often based on laboratory studies. When comparing two models, the hygrothermal model by Sedbauer (2001) and the VTT mould growth model, the time periods in the hygrothermal model for spore germination are shorter than for the start of growth (mould index 1) used in the model by Viitanen *et al* (2000). Also different types of materials have an effect on the time periods needed for spore germination. In Figure 5, a comparison is shown of the critical conditions for mould growth assumed by some of models proposed. Effectively, these curves represent lower limiting isopleths for mould growth. In Sedlbauer's (2001) case he chose the lowest isopleths for mould (LIM) from available information in the literature.

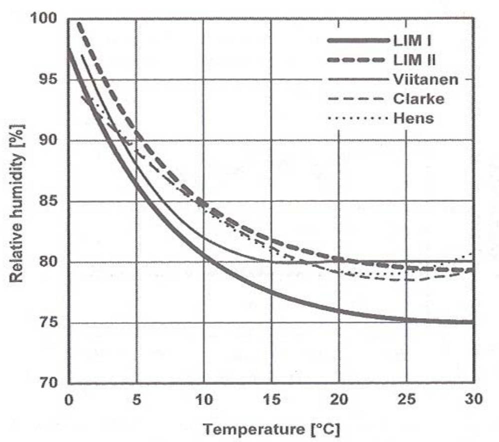

Figure 5: Comparison of the LIM's of substrate class 1 (LIM I, biodegradable materials) and substrate class 2 (LIM II, porous materials) after Sedlbauer (2001) with data from results of building materials after Viitanen et al (2000), Clarke et al. (1998) and Hens (1999).

The following case study shows an example on how to use a mathematical model for predicting mould 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 with the mould index calculation according to the VTT-model and using field measurements. Also the biohygrothermal model implemented in WufiBio was used for some of analyses 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 mould growth for pine. These tests are part of a larger project "Modelling of mould growth", which is still on-going (Lähdesmäki *et al*. 2008). The 48-hour-average values are shown in Figure 8. The detected mould growth level of pine samples were compared to those solved using different approaches for the mould index calculations. The results are found in Figure 9. The period shown is almost a year, starting in June.

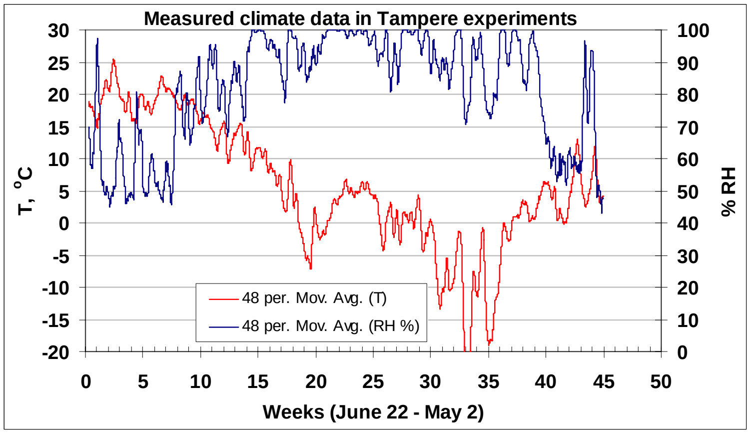

Figure 6. Measured climate data presented using 48 hour moving average values. The simulations use the original hourly measured data.

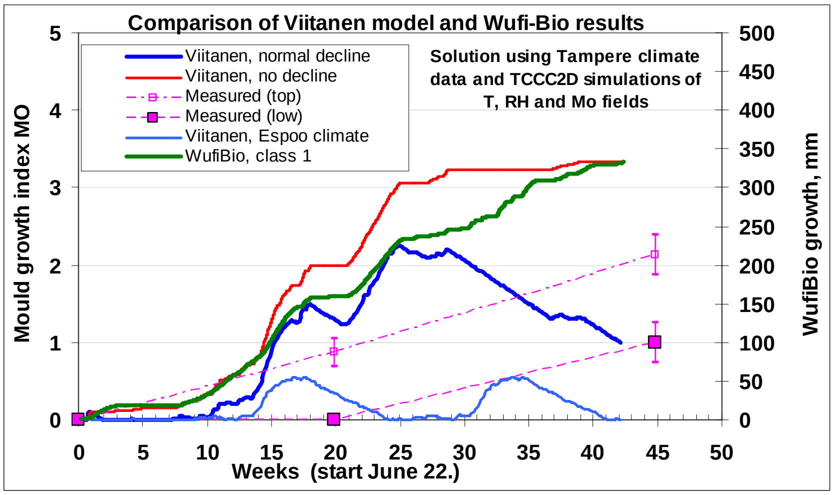

Figure 7. Comparison of VTT Model and WufiBio – and measured mould index – on pine sap wood. Results with VTT Model has been calculated under several assumptions. Viitanen, no decline is assumed to most comparable with the biohygrothermal model behind WufiBio.

Prediction of mould growth, however, should be thought of as an attempt to predict the risk of mould 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. Figure 9 presents a comparison of two totally different models – WufiBio and the VTT Model – as well as the influence of weather and the effect of assuming a decline of mould growth under unfavourable conditions. The samples of pine sap wood were exposed to outdoor conditions in a storage room almost a year. With the VTT model the result was calculated with and without a decline in mould growth assumed when conditions were unfavourable for that growth. The governing limit for mould growth in these comparisons was pine sapwood for the VTT model and LIM I for the WufiBio model. The plots show how sensitive the results are to the assumptions. The development of decay, however, should be evaluated using different models.

6 DISCUSSION

The most critical factors for mould 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 mould 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, 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 mould 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. 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 the delay in biological activity. The simulation of mould 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 mould growth can vary strongly depending on the properties of the materials.

When applying the 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 ageing 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 mould fungi mainly depends upon the water activity and nutrient content of the substrate. During manufacturing of different wooden products, the properties of materials and also 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 a less susceptible to mould 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 2001) and this may promote the mould 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 micro-organisms 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 mould growth levels. In the real life, the humidity conditions will vary and the ambient humidity conditions and microclimate conditions will not be equal. Under **dynamic tests** the conditions at the interface of the air and test sample are typically different than 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 reduced from the measured data. Under dynamic conditions the thermal and moisture **capacity** of material and the heat and mass **transfer coefficients** on the surface may cause a severe delay in the change of surface conditions, differences in the humidity level and in the mould growth when compared to the adjacent conditions. Dynamic simulation that solves the surface conditions should be used both in the analysis of dynamic mould experiments and when predicting the mould growth in structures under real climate conditions.

The use of full simulation enables to separate the delay in the actual mould growth from the delay in the surface conditions. In practise this means that short high humidity excursions cause no risk for mould growth, if the moisture of a structure is not increased for longer time. For example an RH of 95 % for 2 hours in each day will cause no harm, if the continuous microclimate condition of a material is below RH 75 %. Temperature fluctuations can cause condensation of water or a high RH near the surface, if RH of inside air is high (e.g. above 50 % during winter time). 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 will also tolerate the cold periods. Some findings show, that some mould 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 organisms will also affect the humidity conditions of the material. The most active effect is for rot fungi; the mycelia of mould fungi growing on the surface will also affect on the moisture condition of the surface. However, the effect is not prevalent in varying humidity conditions, where the moisture behaviour of material (hygroscopicity, water vapour and water permeability) is the most important factor.

The existing VTT-model has **declination of mould** index when the conditions are not suitable for growth. The original attempt was to model the delay of mould growth during the short period dynamic conditions (in the order of days). This declination seems to be artificial and is probably not proper to adopt for seasonal conditions. New seasonal experiments showed provide information about the mould growth during and after too dry or cold conditions, which will enable improved modelling of the phenomena.

Within the pending project, the analysed existing VTT –model will also be extended to other building materials than pine and spruce sapwood. However, the existing model is based on experiments on these materials – pine and spruce sapwood – that are understood as being relatively sensitive to mould growth. Therefore, using the existing model will give one safe guidelines for the risk of mould growth. The present model is not intended to evaluate decay development, and separate model for this purpose is needed.

7 CONCLUSIONS

There are several factors involved with the biodeterioration of materials and buildings, and mathematic modelling that may help us to understand the complicated interaction of many factors. The mathematic modelling, however, will not give the answers for all problems and users should be aware on 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.

8 ACKNOWLEDGEMENTS

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