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A mathematical model of mould growth on wooden material

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Summary A mathematical model for the simulation of mould fungi growth on wooden material is presented, based on previous regression models for mould growth on sapwood of pine and spruce. Quantification of mould growth in the model is based on the mould index used in the experiments for visual inspection. The model consists of differential equations describing the growth rate of the mould index in different fluctuating conditions including the effect of exposure time, temperature, relative humidity and dry periods. Temperature and humidity conditions favourable for mould growth are presented as a mathematical model. The mould index has an upper limit which depends on temperature and relative humidity. This limiting value can also be interpreted as the critical relative humidity needed for mould growth depending also on the mould growth itself. The model enables to calculate the development of mould growth on the surface of small wooden samples exposed to arbitrary fluctuating temperature and humidity conditions including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can be reasoned to be valid also for other wood-based materials.

List of symbols

M	mould index [−]
T	temperature [°C]
SQ	surface quality (0 = resawn, 1 = original kiln-dried)
t	time [d]
k_1,k_2	correction coefficients [−]
W	wood species (0 = pine, 1 = spruce)
RH	relative humidity [%]

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Introduction

Mould fungi is a heterogeneous and not a particularly well defined group of fungi. Most of the mould fungi, as also the blue-stain and soft rot fungi, belong to Ascomycotina-(Ascomycetes) fungi. Mould and bluestain fungi are often both called discolouring fungi. Discolouring fungi are often the initial microbial colonisers of wood: logs can be infected in forests and in storage, sawn goods can be contaminated before and during drying, at storage or at the building site if the conditions for fungal growth are favourable. In buildings, mould fungi cause problems in different structures and materials: roofs, basements, floors and walls. Except of wooden substrates, surfaces of many other materials support growth of microbes and mould problems are more common than decay damages. Typical mould fungi found in moisture damaged wood are *Alternaria alternata*, *Aspergillus* species, *Aureobasidium pullullans*, *Cladosporium cladosporioides*, *Chaetomium globosum*, *Paecilomyces variotii*, *Penicillium* species and *Trichoderma viride*.

The growth of mould fungi on wooden material has been the subject of experimental research for a long time, but the knowledge thus gathered has been mostly qualitative in nature (Henningsson 1980; Block 1953; Park 1982). The aim has been to describe the material response and find the critical conditions for mould growth on surfaces of different materials with different treatments. Most of this previous extensive research has been carried out in constant temperature and humidity conditions but even such models are usually not applicable in arbitrarily varying conditions. Concerning fluctuating conditions, no mathematical models seem to be available at all in the literature.

Especially dry periods have posed a problem in the published regression models, as experimental knowledge concerning the effect of non-favourable conditions for mould growth has been very limited. The few results published on this subject are not applicable to humidity histories other than those used in the experiments. From a practical point of view, it has not been possible to analyse real building structures in actual varying climatic conditions.

Recently, Viitanen (1997a) has published comprehensive regression models for mould growth in constant humidity and temperature conditions for pure pine and spruce sapwood. Those regression models along with the experiments in fluctuating conditions are the basis for the present mathematical model. It is a material model describing the response of pure wooden material to arbitrary temperature and humidity conditions and will form an essential part of a more complete structural model simulating the moisture behaviour of building structures in actual measured weather conditions.

Experimental material

The experimental material consisted of small samples (7 × 15 × 50 mm) of pure kiln dried pine and spruce sapwood. Two different surface qualities differing in nutrient content were studied: original kiln-dried and resawn. The experimental results have been presented in detail by Viitanen and Ritschkoff (1991), Viitanen and Bjurman (1995) and Viitanen (1997a).

Certain preconditions must be assumed concerning these experiments:

- The small samples used do describe the mould growth on wooden material reaching the equilibrium moisture content without delay. The finite size of the samples may thus be neglected as well as the delay in the wood cell wall attaining the equilibrium moisture content prescribed by the surrounding relative humidity.

- The growth of mould fungi takes place only on the material surface and it may thus be modelled using only surface temperature and moisture content as input data.
- The existence of mould fungi on the material surface does not influence the moisture behaviour of the material, e.g. sorption properties.

The mould was measured applying an existing standard index based on the visual appearance of the surface under study. Some refinement has been made concerning the scale and as a result this mould index assumes following integer values:

0 no growth
1 some growth detected only with microscopy
2 moderate growth detected with microscopy (coverage more than 10%)
3 some growth detected visually
4 visually detected coverage more than 10%
5 visually detected coverage more than 50%
6 visually detected coverage 100%

The same scale is applied in the present mathematical model, but the index is not limited to integer values.

Model development

Conditions favourable to initiation of mould growth

Moisture content of wood depends on ambient humidity, temperature, exposure time, dimensions and moisture absorption capacity of wood; water can also exist in wood as free water in cavities or bound water within cell walls (Siau 1981; Cloutier and Fortin 1991; Hartley et al. 1992). Being a hygroscopic material, the equilibrium moisture content of wood is easily affected by the ambient humidity. At low moisture content, the most direct measure of water availability is water potential (ψ) defined as the free energy of water in a system relative to that of a reference pool of pure water (Schniewind 1980). Water activity (a_w) is, like water potential, related to actual availability of water and it is determined by both matric and osmotic components. Relative humidity (RH) is a percentage relation of actual vapour pressure (p) and saturated vapour pressure (p_0). The a_w can also be defined as the relative humidity at equilibrium (ERH) divided by 100, i.e. relative vapour pressure (p/p_0) of the atmosphere in equilibrium with the substratum.

The water activity in the ambient air or in the cavities of the material is critical for active stages of mould growth. Growth of mould fungi and time period needed for the initiation of mould growth is mainly regulated by water activity, temperature, exposure time and surface quality of the substrate. The experiments suggest that the possible temperature and relative humidity conditions favouring initiation of mould growth on wooden material can be described as a mathematical diagram in Fig. 1. The favourable temperature range is 0–50 °C, and the critical relative humidity required for initiation of mould growth is a function of temperature. Based on experiments covering the temperature range 5–40 °C this boundary curve can be described using a polynomial function

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

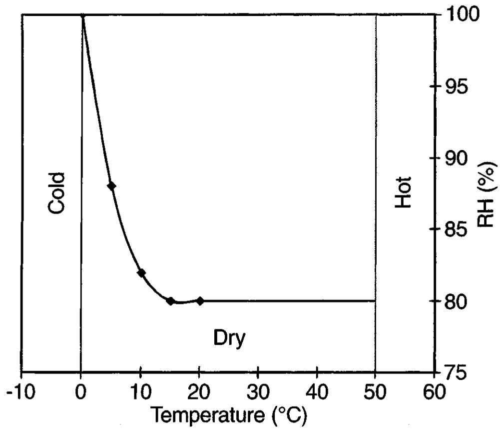

Fig. 1. Conditions favourable for initiation of mould growth on wooden material as a mathematical model

The behaviour of RH_{crit} in the vicinity of the upper end of the temperature range is only an approximation, but it is of only very little importance in practical applications.

The largest possible mould growth

As known from experience, mould growth once initiated does not necessarily lead to visually detectable mould (Viitanen and Bjurman 1995). Also, the final coverage of mould fungi on a surface is dependent on the temperature and humidity conditions suggesting that a certain limiting value exists above which the mould index does not rise irrespective of time available in basically favourable conditions. To construct this limit, it is natural to assume that in conditions critical for the initiation of mould growth, Eq. (1), this upper limit for growth is 1, i.e. just some growth can be detected microscopically no matter how much time passes. In the other extreme it may be concluded that at 100% relative humidity the mould will eventually cover the whole surface regardless of temperature (in the range 0–50 °C) and M thus reaches a value of 6. In between these two fixed points the experiments suggest that the largest possible value of the mould index assumes a parabolic form:

$$M_{max} = 1 + 7\frac{RH_{crit} - RH}{RH_{crit} - 100} - 2\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \qquad (2)$$

The contents of Eq. (2) may also be interpreted by stating that the critical RH needed for mould growth does not only depend on temperature but also on the

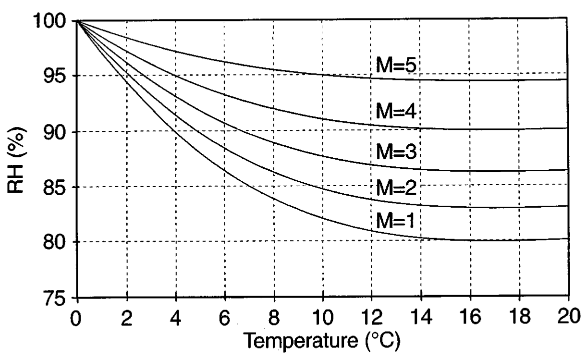

Fig. 2. Temperature-dependent critical relative humidity needed for mould growth at different values of mould index

stage of mould development, i.e. the mould index itself. This result is arrived at by solving Eq. (2) for RH, which now represents the temperature-dependent RH needed for mould index reaching a value of M_{max}. This result is depicted in Fig. 2.

Growth rate in favourable conditions

The present model is based on mathematical relations for the growth rate of mould index in different conditions. The model is purely mathematical in nature and as mould growth is only investigated by visual inspection, so it does not have any connection to biology in the form of modelling the number of live cells. Also, the mould index resulting from computation with the model does not reflect the visual appearance of the surface under study, because traces of mould growth remain on wood surfaces for a long time. The correct way to interpret the results is that the mould index represents the possible activity of the mould fungi on the wood surface.

As a basis for the growth model, Viitanen (1997a) presents a regression equation for the response time (weeks) needed for the initiation of mould growth on wooden material in constant temperature and humidity conditions:

$$t_m = \exp(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02) \tag{3}$$

If the mould index M is presumed to increase linearly in time and time is measured in days, Eq. (3) may be interpreted as a differential relation

$$\frac{dM}{dt} = \frac{1}{7 \exp(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02)}, \quad M < 1 \tag{4}$$

This conversion extends the applicability of Eq. (3) into variable conditions such that the relative humidity is constantly above the critical value defined by Eq. (1) and the temperature is in the range 0–50 °C. Linear growth in the range $M < 1$ is only a mathematical description and in principle any other growth model could be utilised. When interpreting the results of the model all values of M below 1 indicate no growth.

As the growth proceeds above the initial stage ($M = 1$), Eq. (4) is no longer valid. For a larger growth Viitanen (1997a) presents another regression model describing the response time needed for the first visual appearance of mould growth ($M = 3$):

$$t_v = \exp(-0.74 \ln T - 12.72 \ln RH + 0.06W + 61.50)\ . \tag{5}$$

If growth of the mould index is presumed to proceed from $M = 1$ to $M = 3$ on a constant rate in constant conditions, Eqs. (3) and (5) can be combined to give the growth rate on that range. The result is a correction coefficient if Eq. (4) is used as a basis:

$$k_1 = \begin{cases} 1 & \text{when } M < 1 \\ \frac{2}{t_v/t_m - 1} & \text{when } M > 1 \end{cases} \tag{6}$$

Although based on constant conditions, the experiments suggest that Eq. (6) is valid also for mould growth in fluctuating conditions as long as the conditions are continually favourable to growth. Based on data from growth after the visual appearance of mould fungi it may be concluded that the same correction for growth rate applies for the entire range $M > 1$.

Taking into account the upper limit for mould growth defined by Eq. (2) may also be accomplished by using a correction coefficient. Assuming the delay to affect the growth rate by 10% at 1 unit below the maximum value of the index gives this coefficient to the following form

$$k_2 = 1 - \exp[2.3(M - M_{max})] \tag{7}$$

The complete model in conditions favourable for mould growth consists of Eqs. (4), (6) and (7):

$$\frac{dM}{dt} = \frac{1}{7\exp(-0.68\ln T - 13.9\ln RH + 0.14W - 0.33SQ + 66.02)} k_1 k_2 \tag{8}$$

As an initial condition M must be a known value, usually equal to zero immediately after artificial drying of wood in a kiln with wood temperature exceeding 50 °C.

Model during non-favourable conditions

In fluctuating humidity conditions Viitanen (1997a) states that the cumulative time in high-humidity conditions can be used to a limited extent to quantify the response time needed for the initiation of mould growth. This simplification, however, eventually always leads to a large mould activity as humidity cycles are repeated. Instead of remaining on a constant level the activity of mould can be thus regarded as decreasing during dry periods. Of course, the visual appearance of the surface does not necessarily change during the dry period, but a finite delay in growth after the dry period can be clearly observed. This delay does exist as soon as after 6 h in dry conditions, but extending the dry period to 24 h does not seem to significantly affect the delay, if growth will initiate at all. After that the delay is again prolonged. A mathematical description of the delay can be written by using the time passed from the beginning of the dry period $(t - t_1)$:

$$\frac{dM}{dt} = \begin{cases} -0.032 & \text{when } t - t_1 \leq 6\,\mathrm{h} \\ 0 & \text{when } 6\,\mathrm{h} \leq t - t_1 \leq 24\,\mathrm{h} \\ -0.016 & \text{when } t - t_1 > 24\,\mathrm{h} \end{cases} \tag{9}$$

The experimental data behind this equation cover dry periods between 6 h and 14 days, but the functional form of expression (9) is based only on a small number of experiments and thus must not be seen as the best possible one. Knowledge of the influence of longer dry periods on mould growth is very limited as is the data concerning the effect of temperatures below 0 °C. In lack of better information Eq. (9) may be applied also for such situations, although the validity of such an application must be questioned.

Comparing the model results against experimental data

The largest possible value of the mould index, Eq. (2), is based on 12-week experiments in constant conditions. Figure 3 presents the values calculated using Eq. (2) versus the experimental observations. Only points showing a clear limit of mould index have been taken into account. It can be seen that the largest error in

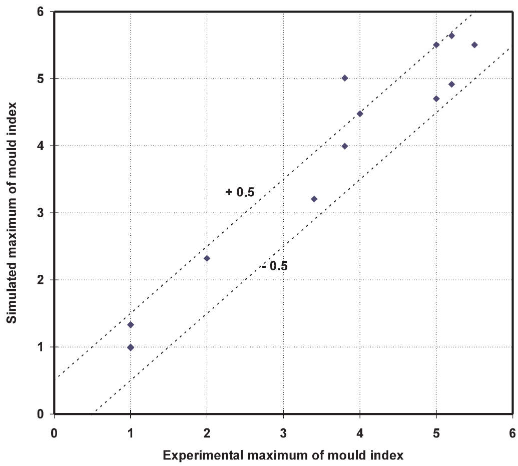

Fig. 3. Comparison of the largest possible value of mould index produced by Eq. (2) against the experimenta

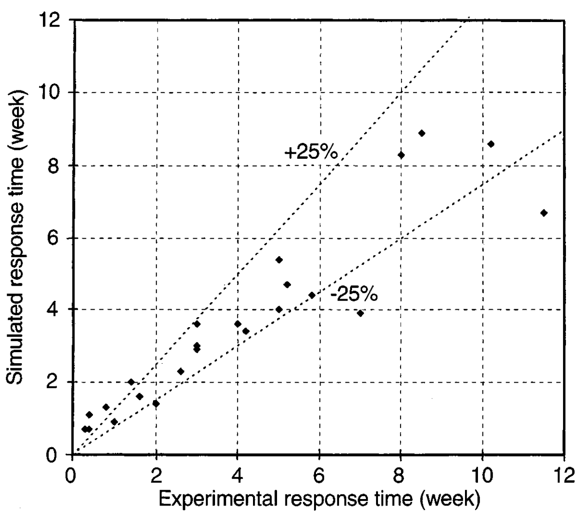

Fig. 4. Comparison of simulated and experimental response times needed for initiation of mould growth on pine sapwood in constant conditions

the maximum value of mould index is 1.2 and that only one point includes an error larger than 0.5 in value.

To compare the model results to the original experimental data, Figs. 4 and 5 present the experimental and simulated response times needed for the initiation and the first visual appearance of mould growth on the surface of resawn pine sapwood. Similar results for spruce are presented in Figs. 6 and 7. The experimental results represent the average of 6 parallel samples. It can be seen that there are no major systematic errors in the model and that in all cases most of the errors in response time are smaller than 25% in numerical value. However, also some points with very large errors can be detected, indicating that a model with only a very few numerical parameters may not be sufficient for describing the phenomenon of mould growth in the whole temperature and RH range, especially in higher temperatures.

Figure 8 presents the results obtained when using the model to predict the response time needed for the initiation of mould growth on pine sapwood in

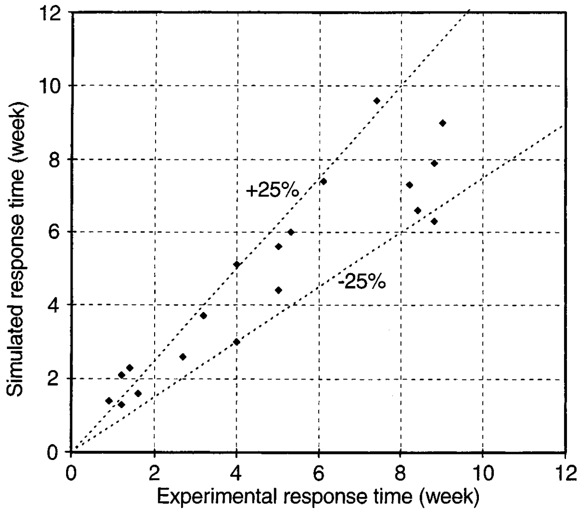

Fig. 5. Comparison of simulated and experimental response times needed for visual appearance of mould growth on pine sapwood in constant conditions

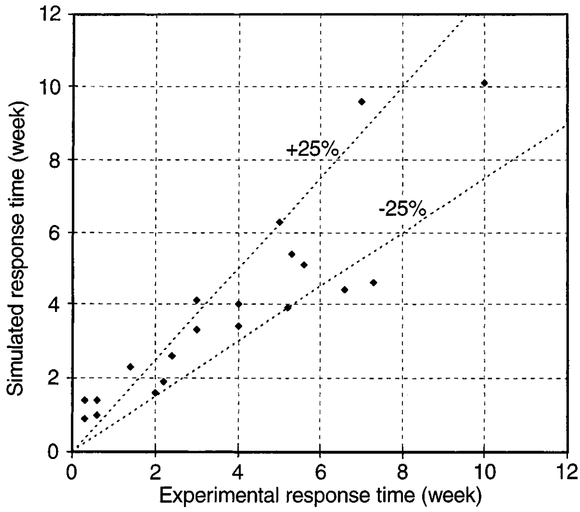

Fig. 6. Comparison of simulated and experimental response times needed for initiation of mould growth on spruce sapwood in constant conditions

fluctuating humidity conditions. The relative humidity has been kept at two constant values, 75% and 95%, the period in each condition varying between 6 and 196 h. The temperature has been constant at 20 °C. It can be seen that most of the simulated points (80%) are such that the error in response time is less than 25%. The average error in simulated response time is only 1%, indicating that there is essentially no systematic error in the model.

Discussion and conclusion

The mathematical model presented is throughout formulated in a differential form. As such it allows to calculate the development of mould growth on a wooden surface exposed to arbitrary temperature and humidity histories including also dry periods. The numerical values of the parameters in the model apply only for pure pine and spruce sapwood and aim at describing the average response of the material based on a small number of parallel samples. The

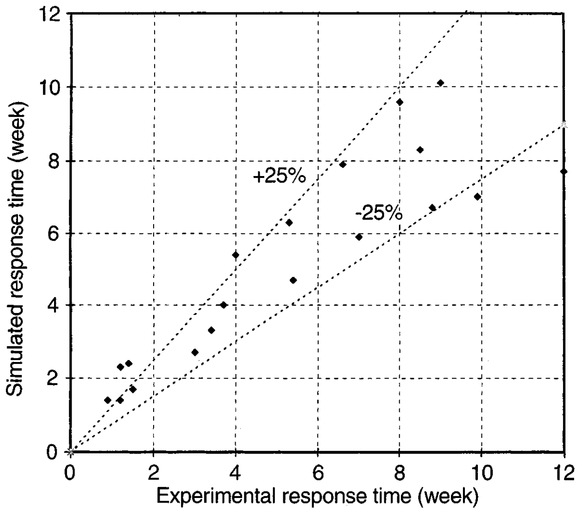

Fig. 7. Comparison of simulated and experimental response times needed for visual appearance of mould growth on spruce sapwood in constant conditions

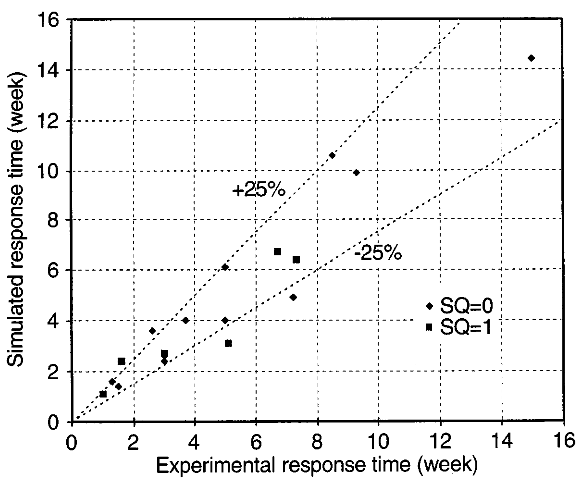

Fig. 8. Comparison of simulated and experimental response times needed for initiation of mould growth on pine sapwood in fluctuating humidity conditions. Values of surface quality SQ correspond to original kiln-dried (1) and resawn (0) surfaces

response does, however, exhibit a very large variation between samples originating from different stems of the same wood species. This variation is of the same order in magnitude as is the variation in results between samples representing different species of wood. Based on this it may be reasoned that the same functional form of the model could be utilised also for prediction of mould growth on other wood-based materials, only the numerical values of the coefficients must be re-evaluated.

The experimental data behind the model covers temperatures between 5 and 40 °C and relative humidities between 75 and 100%. The exposure time in constant conditions has been at least 12 weeks and the time in fluctuating conditions has varied between 6 and 24 weeks. This temporal scale is clearly shorter than will be the application area of the model. This requires an extrapolation of experimental results and causes an uncertainty in the results produced by the model in such situations. Also the nature and range of the experiments conducted in fluctuating conditions will certainly need some revision as the numerical result proposed by Eq. (9) is not totally satisfactory.

The maximum value of the mould index used in the model, Eq. (2), has been deduced from experiments conducted in constant humidity conditions. It is known that this parameter is lower in fluctuating humidity conditions, but the numerical value of the maximum growth in such situations on a general level is not comprehensively known. In this sense the present model obviously needs further development. The same applies for fluctuating temperature conditions with constant RH.

The present model describes mould growth on wooden material surfaces. It is a pure material model trying to quantify the experimental results of mould exposures conducted on small samples. The next natural step in the evolution of the model is to insert the mathematical equations into a simulation program for calculation of mould growth on an actual wooden structure. This would create a new tool for prediction of the service life of a certain structural design in critical temperature and humidity conditions. Another possible direction of further development is to apply the model for quantification of mould growth in materials other than pure wood, which combined to a moisture simulation program would give a powerful tool for analysing the moisture behaviour of a very wide range of structures.

It has been found in laboratory studies and in practice that mould fungi are more rapid invaders than decay fungi in wooden structures subjected to excess moisture stresses (Viitanen 1997a, b). Also, the minimum humidity and temperature requirements are in general lower for mould fungi than for brown rot fungi. Growth of mould fungi and time period needed for the initiation of mould growth are mainly regulated by water activity, temperature, exposure time and surface quality of the substrate. Especially at low water activity and low temperature, the latent period preceding the initial stages of mould growth and the appearance of mould fungi on wood have been found to be several weeks although the equilibrium moisture content of the small samples used was reached in two weeks (Viitanen 1997a). However, Viitanen and Paajanen (1986) found no mould growth at RH 75% and according to recent studies, the lowest humidity condition allowing mould growth is RH 80–85% (i.e. water activity 0.80–0.85) providing that the temperature is above 5 °C (Bjurman 1989; Park 1982; Wang 1992; Adan 1994; Hocking et al. 1994; Viitanen 1997a). Modeling of the critical humidity and temperature conditions, and especially of the critical time required for spore germination and the growth of mould fungi mycelium on pine and spruce sapwood was presented by Viitanen (1997a). Temperature conditions have a minor effect on the water activity and the main effect is concerned with the growth and metabolic activity of the fungi. Often the selection of mould species at high temperatures (above +30 to +35 °C) consists mainly in thermotolerant or thermophilic mould fungi (Henningsson 1980). At fluctuating humidity conditions, the growth of mould fungi is clearly retarded and latent period is even longer than at constant favourable conditions (Adan 1994; Viitanen 1997a).

In general, the higher the temperature and the more favourable the nutrition at a given relative humidity, the less time is required for spore germination. After kiln drying, the concentration of nitrogen and low-molecular hydrocarbon compounds on the surface layers of sawn timber are often higher than inside the wood (Boutleje 1990; Theander et al. 1993). Terziev et al. (1994) and Viitanen and Bjurman (1995) showed, that the growth of mould is clearly more rapid and vigorous on the original kiln dried wood surface than on a resawn surface.

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