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Critical conditions for onset of mould growth under varying climate conditions

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ABSTRACT

A performance-based service life design format based on climatic exposure on one hand and "resistance" of materials against mould growth on the other hand, is presented in this paper. A limit state for onset of mould growth is defined as the occurrence of traces of mould observed by microscopy. A dose–response model is proposed by which onset of mould growth can be predicted for an arbitrary climate history of combined relative humidity ϕ and temperature T. The model is calibrated and verified against a comprehensive set of experimental data published by Viitanen et al. [Viitanen H, Ritschkoff A-C. Mould growth in pine and spruce sapwood in relation to air humidity and temperature. Uppsala: Swedish University of Agricultural Sciences, Department of Forest Products; 1991. Report No. 221, 49 p.; Viitanen H. Modelling the time factor in the development of mould fungi – effect of critical humidity and temperature conditions in pine and spruce sapwood. Holzforschung 1997;51(1):6–14; Viitanen H. Modelling the time factor in the development of brown rot decay in pine and spruce sapwood – the effect of critical humidity and temperature conditions. Holzforschung 1997;51(2):99–106; Viitanen H, Bjurman J. Mould growth on wood under fluctuating humidity conditions. Material und Organismen 1995;29(1):27–46] describing mould development on spruce and pine sapwood as a function of climatic exposure. The model is applied to predict time to onset of mould growth under natural outdoor climate (under shelter) as well as mould development in building attics and in crawl space foundations. The predicted response shows reasonable agreement with experimental observations and proven experience, although biological processes of this type display great variability. The results show that a generally applicable, quantitative model can be used as a powerful tool for moisture safe design in practice. The model is designed to facilitate continuous improvement of prediction capability by further laboratory testing of various materials under specified climate conditions. In combination with currently available building physics software the model is suitable for moisture safe design of wood-based components in the building envelope.

1. Introduction

One of the key issues in building construction is durability. A modern definition of durability is: *The capacity of the structure to give a required performance during an intended service period under the influence of degradation mechanisms*. For design of components in the building envelope an important requirement is to limit the risk for mould growth under the intended service life of the building. Traditionally, durability design of building components and structures is based on a mixture of experience and adherence to good building practice, sometimes formalised in terms of implicit prescriptive rules. Therefore, the expected performance can seldom be specified in quantitative terms. As a result, the design cannot be optimised and any change of design will be associated with uncertain risks.

The development of performance-based service life design methods requires that models are available to predict performance in a quantitative and probabilistic format. This means that the relationship between product performance during testing and in service need to be quantified in statistical terms and the resulting predictive models should be calibrated to ensure that they provide a realistic measure of service life, with reasonable degree of certainty.

Attempts have been made to develop empirical models for service life prediction. One example is the so called factor method which is intended as a tool for predicting the service life of components and structures. This concept has been introduced in the standard ISO 15686-1 [5]. The method is based on a reference service life (*RSLC*) which is multiplied by a series of empirical factors taking into account various aspects of material

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characteristics, environmental conditions and operation conditions. The standard itself contains some general remarks regarding the method. Among other things it states that the method does not provide an assurance of a service life in quantitative terms. It merely gives an empirical estimate based on available information and may serve as a guide when choosing between different components.

The factor method has so far not been used in practice. This is quite understandable as its appearance is very different from other design methods in the construction process, such as structural design in the ultimate limit and serviceability state. Also, the lack of reliable quantification of the factors in the equation makes it more or less impossible to use this method in its present state. A state-of-the-art on the factor method is given in a report by Hovde and Moser [6]. They summarize the need for development of the factor method as follows:

- Determination and collection of data for the reference service life (RSL) and the individual factors.
- Development of sound engineering methods that combine the benefits of more sophisticated probabilistic methods and simple deterministic methods, i.e. describe the factors as random variables.
- Practical use of the method in case studies of specific building materials, components or buildings.
- Application of methods in life cycle assessment of building materials and components and environmental evaluation methods for buildings.
- Application of the methods in integrated life cycle design and design for durability of buildings.

Marteinsson [7] applied the factor method in a case study of wooden windows in Iceland. The conclusion was that the method requires knowledge which is rarely available, at least not for practical design situations. Empirical type service life design models for wood have also been developed in a national research program in Australia, see e.g. Wang et al. [8]. It is mainly based on a large field testing programme at different sites in Australia with wood species typical for Australia. Compared to organic materials like wood, methods for performance-based durability design is much more developed for e.g. concrete with a firm foundation on physical models; see e.g. Sarja and Vesikari [9].

2. Proposed approach to service life design of building components

A proposed principle for a performance-based service life design model is illustrated in Fig. 1. The problem is here described in terms of climatic exposure on one hand and resistance of materials on the other hand. The design model should be based on a clearly defined limit state, which in this context could be onset of mould growth or decay alternatively a specified acceptable degree of mould growth or decay. The performance requirement in a certain situation could e.g. be that onset of mould growth is not accepted during a specified service life. Most factors affecting the performance are associated with uncertainty. This means that the probability of non-performance must be assessed so that it can be limited to an accepted maximum level. The advantage with the approach displayed in Fig. 1 is that exposure can be described as a function of global climate, component design and surface treatment in a general way independent of the exposed material. Likewise, the resistance of different types of materials can be expressed in terms of response to quantified micro-climate conditions independent of practical design situations.

As illustrated in Fig. 1, the criterion for acceptable performance is that the resistance of the material is sufficient to withstand the exposure in a given situation. This has to be verified by a performance model, which in turn is related to a specified performance criterion. The performance criterion may be associated with requirements of different types such as load-bearing capacity of a structure, serviceability requirements or aesthetics. A key element in such a design approach is a reliable performance model, which must be available if a quantitative evaluation shall be possible.

In the present paper a performance model is proposed for onset of mould growth under exposure to climate conditions varying in time. This situation is typical for materials in the building envelope (external walls, attics and foundations). Computer programs in

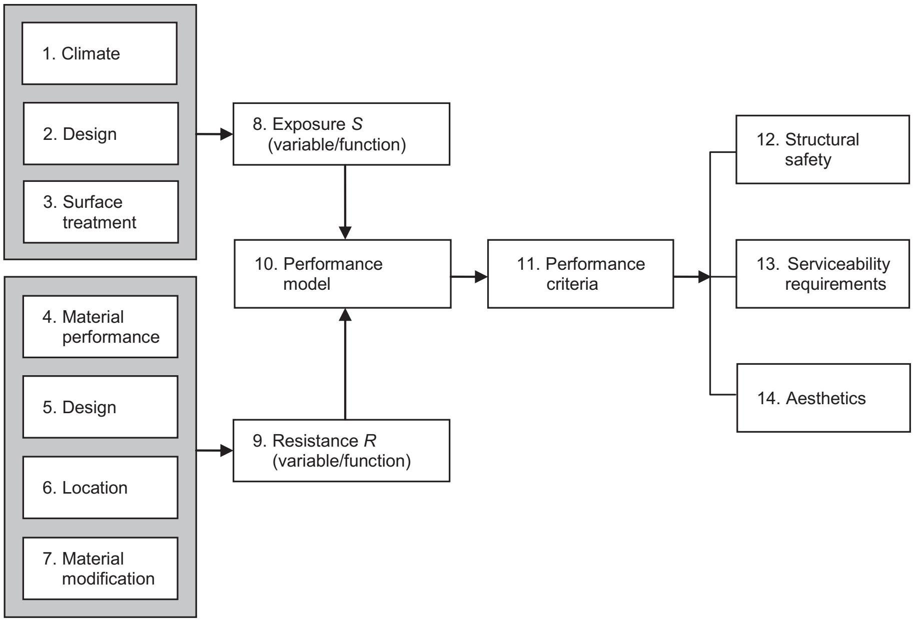

Fig. 1. Principle for performance-based service life design.

building physics are nowadays available to predict microclimatic conditions in the form of continuous time series for relative humidity and temperature at different locations in the building envelope components, see e.g. Sedlbauer [10,11]. The main issue is then to interpret such results in terms of risk for onset of mould growth, which normally is not accepted in building components in contact with the indoor environment.

According to Sedlbauer [10,11], the three most important growth conditions temperature, humidity and substrate must exist simultaneously over a certain period of time to enable fungal growth. Using mould isopleth graphs Sedlbauer developed a prediction method to estimate the risk of mould fungus formation for different combinations of relative humidity and temperature, see Fig. 2. The figure presents the general principle that there is a safe area (low values of temperature and relative humidity) with no risk of mould and an unsafe area (higher humidity and temperature). The lines separating safe and unsafe regions depend on

- the duration of the climatic conditions
- if spore germination or mycelium growth is considered
- type of building material (substrate)
- type of mould fungi

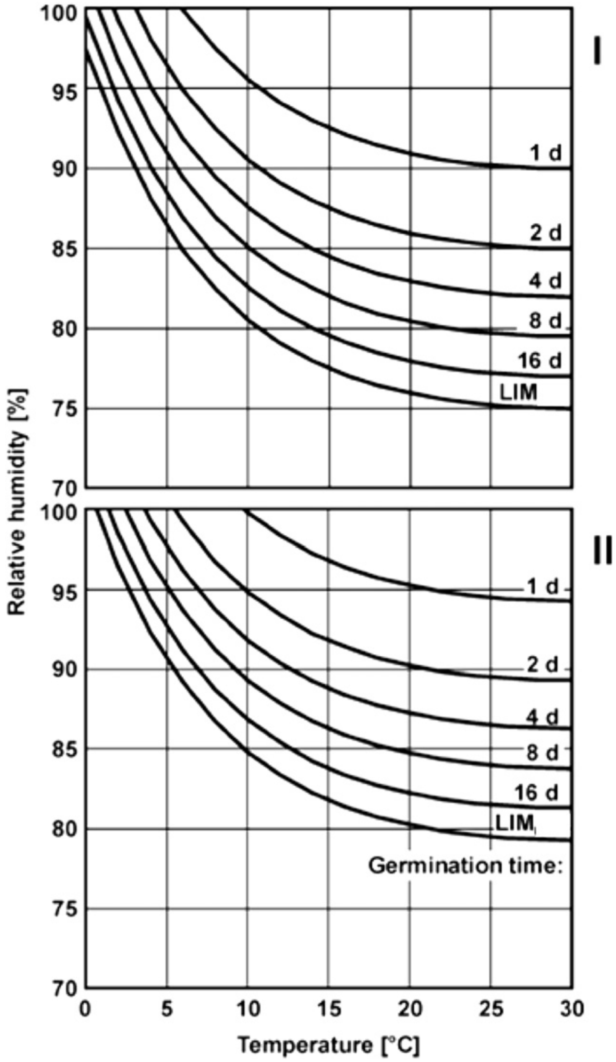

Fig. 2. Generalized isopleth system for spore germination valid for all fungi of substrate categories I (bio-utilizable substrates) and II (substrates with porous structure) Sedlbauer [10].

Sedlbauer [10] presented this type of graphs over growth conditions based on experimental validation. Spore germination times and growth rates are specified for three different substrate categories in dependence on temperature and relative humidity. All fungus species occurring in buildings were considered and the shortest germination times and highest growth rates for the group of species were used. Fig. 2 shows examples of isopleths for two different substrates. The lowest isopleth LIM is shown together with curves indicating the number of days required for spore germination to start. The higher the temperature and relative humidity the quicker germination starts.

An operational performance model for unique verification of limit states requires, however, a mathematical formulation, by which the onset of mould growth can be evaluated for a general climate history of combined relative humidity and temperature. Such a model is proposed below and calibrated against experimental data for mould growth on wood from Viitanen [1–3]. The model is used to assess whether mould growth will occur when the material is exposed to global climate at different locations as well as to micro-climate in building attics and crawl spaces.

3. Performance model based on dose–response functions

A possible way to describe the impact of a general time variation of relative humidity ϕ and temperature T on the potential for mould growth is to use a so called dose–response relation, see e.g. Brischke and Rapp [12], who applied this for rot decay.

The total daily dose D is assumed to be the product of a component D_ϕ dependent on daily average of relative humidity ϕ and a component D_T dependent on daily average temperature T.

$$D = D_\phi(\phi) \cdot D_T(T) \tag{1}$$

For exposure during n days the total dose is given by

$$D(n) = \sum_1^n D_i = \sum_1^n D_\phi(\phi_i) \cdot D_T(T_i) \tag{2}$$

where ϕ_i is average relative humidity and T_i is average temperature for day i. The dose can be defined in relation to a specified reference climate (ϕ_{ref}, T_{ref}). For a substrate where mould is initiated under constant exposure to this reference climate after N_{ref} days, the dose is defined so that

$$D\left(N_{\mathrm{ref}}\right) = \sum_1^{N_{\mathrm{ref}}} D_\phi\left(\phi_{\mathrm{ref},i}\right) \cdot D_T\left(T_{\mathrm{ref},i}\right) = N_{\mathrm{ref}} \tag{3}$$

This means that the dose is expressed in days and is equal to 1.0 for a day with reference climate (ϕ_{ref}, T_{ref}). Mould growth is initiated when the accumulated dose becomes equal to N_{ref} and is expressed in days. For other relative humidities and temperatures than the reference values the dose will be less than 1.0 if growth conditions are more unfavourable and greater than 1.0 if conditions are more favourable than the reference conditions.

Under dry conditions and at low temperatures (corresponding to the safe regions) some recovery or set-back for the germination/growth process can be expected, which then can be described as a negative daily dose, i.e. $D < 0$. A condition is that the total accumulated dose can never be negative, i.e. $\sum_1^n D_i \geq 0$ is always valid.

4. Experimental data on mould growth as a function of climate conditions

The model outlined above will be quantified on the basis of comprehensive experimental data presented by Viitanen [1–3]. The tests were performed in laboratory conditions using kiln dried pine and spruce sapwood. The material was exposed to mould fungi in different constant or fluctuating humidity and temperature conditions. The test specimens were inoculated initially with a mixture of spores from typical fungi growing on wood. Thereafter the specimens were stored in a climate chamber with controlled relative humidity ϕ and temperature T, and examined in microscope once a week. In Viitanen's tests, the evaluation of mould growth was made with the following scale

0: no growth
1: some growth detected with microscope (trace)
2: moderate growth detected with microscope (coverage 10–25%)
3: some growth detected visually (coverage below 10%)
4: moderate growth detected visually (coverage 10–50%)
5: plenty of growth detected visually (coverage above 50%)
6: very heavy growth (coverage 100%, very thick growth)

Based on the test results the response time for growth of mould fungi to these various levels was derived. In the present paper, level 1 is assumed to correspond to the limit state: "Onset of mould growth". Viitanen [2,3] derived expressions for response time as a function of relative humidity ϕ and temperature T based on fitting against test results. An example is given here for resawn spruce sapwood exposed to *constant humidity* ϕ *and constant temperature* T. The critical time t_{ms} for onset of mould growth (level 1) under different climate conditions (constant in time) is given by

$$t_{ms} = \exp(-0.74\ln T - 15.53\ln \phi + 75.736) \tag{4}$$

with t_{ms} in days, T in °C and ϕ in %. According to [2,3] this formula is valid for relative humidities in the interval $75 \leq \phi \leq 100$ and temperatures $0.1 \leq T \leq 40\,^{\circ}\mathrm{C}$. The substrate material is resawn spruce sapwood, which means that 8 mm thick specimens were cut out from boards 7 mm below the originally kiln dried surface. This may be seen as representative for planed wood, which is most common in building construction. The regression formula (4) is presented in the form of isopleths in Fig. 3. A comparison with the isopleths from Sedlbauer in Fig. 2 reveals that these results show a slower attack rate. Possible reasons are that the rating scales are not directly comparable and that the substrates are different. Sedlbauers porous structure is probably more favourable to mould growth than Viitanen's planed wood specimens.

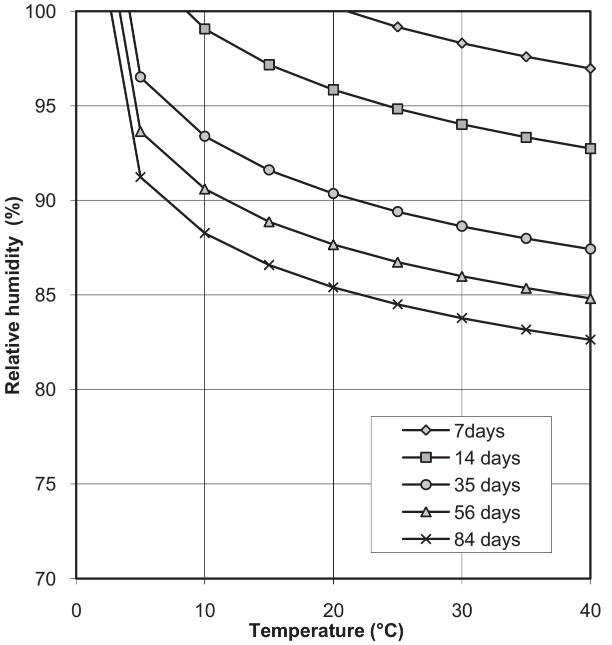

Fig. 3. Graphical illustration of Eq. (4) in terms of isopleths.

5. Calibration of performance model for spruce sapwood

The results from laboratory exposure under constant moisture conditions, described in Section 4 for resawn spruce sapwood as substrate, and expressed by Eq. (4) are used here to calibrate the performance model presented in Section 3. The reference climate is chosen to

$$\phi_{ref} = 90\%$$
$$T_{ref} = 20\,^{\circ}\mathrm{C}$$

From Eq. (4) it is found that mould is initiated after $N_{ref} = 38$ days when exposed to these conditions. The following relations can be derived from Eq. (4) describing the data

$$D_{\phi} = \exp\left[15.53 \cdot \ln\left(\frac{\phi}{90}\right)\right] \quad \text{for } 75 < \phi \leq 100\% \tag{5a}$$

$$D_{T} = \exp\left[0.74 \cdot \ln\left(\frac{T}{20}\right)\right] \quad \text{for } 0.1 < T \leq 30^{\circ}\mathrm{C} \tag{5b}$$

These relations are graphically displayed in Figs. 4 and 5. Note that D_{ϕ} has the dimension days, while D_T is a dimensionless factor.

A "safe" region with dry conditions and low temperatures with unfavourable conditions for germination and mould growth is also defined in the model. This region is defined as all states where

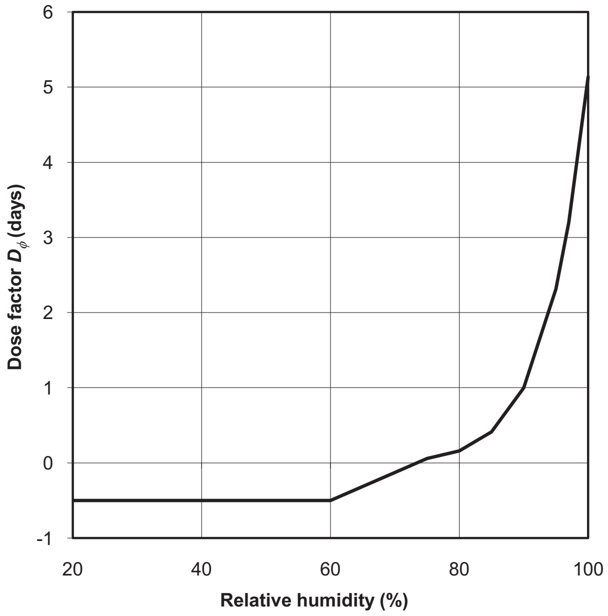

Fig. 4. Dose factor D_{ϕ} derived from test data.

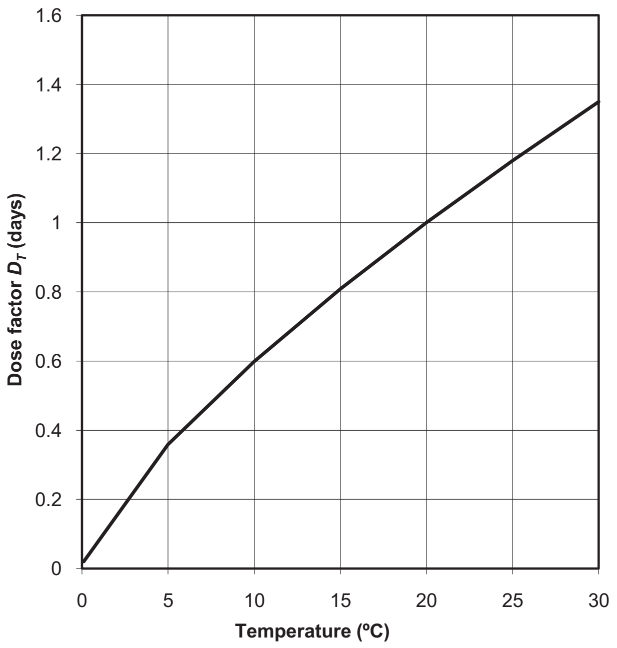

Fig. 5. Dose factor D_T derived from test data.

$\phi < 75\%$ or $T < 0.1$ °C. For conditions in the safe region the following "negative" doses are assumed

$$D_\phi(\phi) = (-2.7 + 1.1\phi/30) \quad \text{for } 60 < \phi < 75\% \tag{6a}$$

$$D_\phi(\phi) = -0.5 \quad \text{for } \phi < 60\% \tag{6b}$$

with ϕ in %. This is also illustrated graphically in Fig. 4.

Likewise, when the temperature is below zero the total dose D is assumed to be

$$D(\phi, T) = -0.5 \quad \text{for } T < 0.1\ ^\circ\text{C} \tag{7}$$

The interpretation of a negative value −0.5 of D is that a total recovery from a situation where onset of mould growth is immediately imminent, will be achieved after $2 \cdot N_{\text{ref}}$ days in a climate with $\phi < 60\%$ or $T < 0.1$ °C. The estimated recovery behaviour here is based on examination of Viitanen's test results under variable climate conditions, but it should be noted that the empirical basis for this is rather uncertain with the information presently available.

The model may now be used for general climatic exposures with arbitrary variations of $\phi(t)$ and $T(t)$. In the absence of experimental data it may also be used for prediction of mould on other substrates if test data for the reference conditions (constant $\phi = 90\%$ and constant $T = 20$ °C) is available to predict the value of N_{ref} for a given substrate material.

6. Verification of the model for varying climate conditions

Viitanen and Bjurman [4] investigated mould initiation/growth under varying climate conditions. The temperature was held constant at 20 °C and the relative humidity was cycled between a lower and a higher value. The cycles in the tests ranged from 6 h to 4 weeks. The model described in the previous sections can to some extent be validated against these experimental data. The material used in [4] was in this case pine sapwood which means that Eq. (4) changes to

$$t_{\text{mp}} = \exp(-0.67\ln T - 13.15\ln\phi + 64.546) \tag{8}$$

The dose–response functions according to Section 5 are modified accordingly with $N_{\text{ref}} = 29$ days.

The test climate conditions were fed into the model and the results are shown in Fig. 6. The continuous lines show the experimental results and the broken lines show the predicted relative dose according to the model. The relative dose is here given as

$$\text{Relative dose} = \frac{D}{N_{\text{ref}}} \tag{9}$$

The relative dose is directly comparable to the experimental results which are evaluated according to the evaluation scale described in Section 4, i.e. level 1 means initiation of mould. The model should in principle not be used for a relative dose above 1, but to visualize the performance of the model and compare with the data the relative dose is shown up to a value of 2. The different curves in Fig. 6 represent the different climates tested, i.e. V 75(36)/97(24) means test results from Viitanen, cycling climate between 75% for 36 h and 97% for 24 h. The time interval given as (2) and (1) is in weeks, the

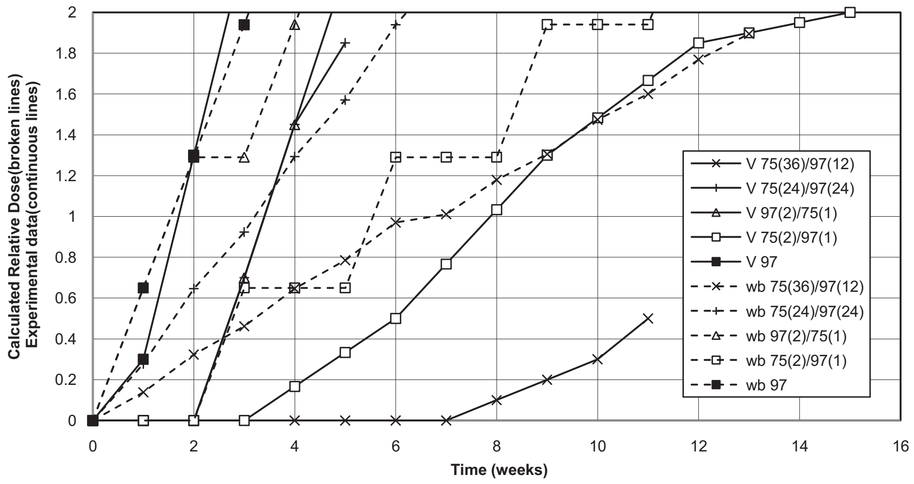

Fig. 6. Experimental data according to Viitanen (1996) together with calculated relative dose using the proposed model. The curves from Viitanen begins with V and the results using the model begins with wb. Results for pine sapwood.

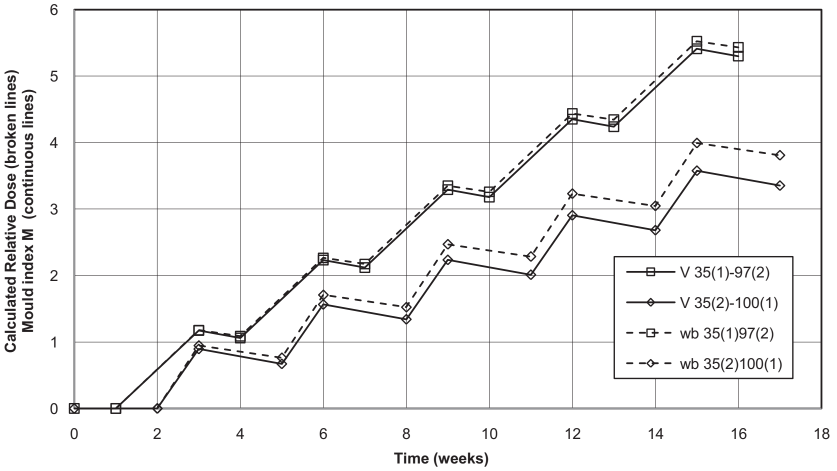

Fig. 7. Comparison between a Mould index (M) model proposed by Hukka and Viitanen [13] (V) and the relative dose using the proposed model (wb). Results for spruce sapwood.

rest in hours. Wb is the corresponding model response. Generally, the time till index 1 is reached is shorter according to the model which means that the model in its present form appears to be conservative. The model shows better agreement with the test results for longer cycles, i.e. with a week or more in a constant climate. Cycling where the duration for each wet/dry period was only 6 h is not included in Fig. 6, since the model using daily averages is not applicable for such a case, and it is uncertain whether equilibrium relative humidity is actually reached in the test for such rapid cycling. The tests show however that mould initiation is delayed quite significantly under these rapidly cycling conditions. For cycles with durations of 6 h at each humidity level the accumulated time at the high humidity level 97% before mould was initiated, was 8 times longer than the time to mould initiation under continuous exposure to the high humidity level 97% [4]. It can be noted that the test results shown in Fig. 6 in some cases show contradictory results. The case with constant exposure at 97% reached level 1 after 12 days, whereas in the test with cycling between 97% and 75%, gave results at level 0 after the initial 2 weeks at 97%. This shows the large variability in the mould growth process.

A mathematical model of mould growth on wooden material was proposed by Hukka and Viitanen [13]. The model is based on the same data from [1–3] as discussed above and it was shown that their model gives good predictions of the above described tests under variable moisture conditions. A mould index *M* was defined as a function of temperature, relative humidity and material. In dry/cold conditions their model can account for a decreasing mould index, but the model format cannot be applied for general climate variations. In Fig. 7 the response of the mould index model is shown together with the response of the dose–response model proposed here. As mentioned before, in this paper we are focusing on the behaviour of mould initiation, i.e. a mould index or relative dose–response equal to or below 1. In Fig. 7 the whole scale up to 6 is shown. As expected the results are very similar, the dose–response model being slightly more conservative. For other time cycles the

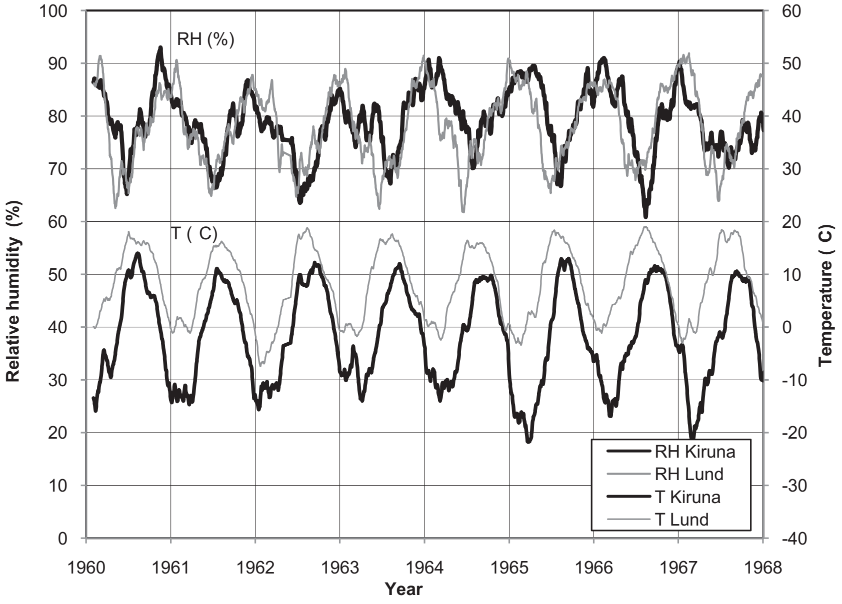

Fig. 8. Monthly averages of temperature and relative humidity for Lund and Kiruna during 8 years.

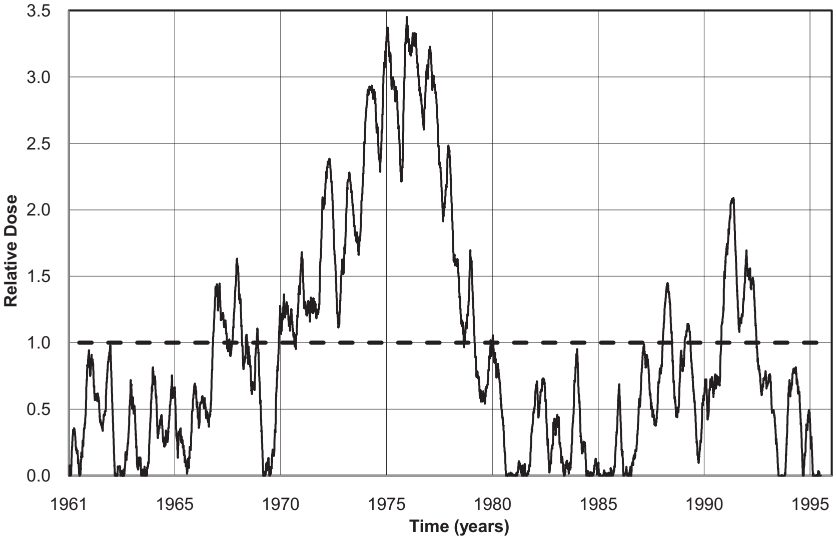

Fig. 9. Relative dose–response for mould initiation on spruce sapwood exposed to outdoor climate (under shelter) in Lund, South of Sweden.

results may differ more since the recovery part is modelled somewhat differently.

7. Model response for wood exposed to outdoor climate

Using today's Swedish building regulations regarding allowable climate conditions for wood it may be hard to even handle wood under shelter exposed to outdoor climate for shorter periods. A critical relative humidity of 75% (independent of temperature) shall be used if no other information is available. Using the dose–response model for mould initiation the risk of exposing wood to outdoor climate (under shelter) in different geographical areas can be evaluated. In this case two very different climates are used; the more warm and humid conditions of Lund in southern Sweden and the more cold and dry conditions of Kiruna in northern Sweden. The climate data were provided by the Swedish Meteorological and Hydrological Institute (SMHI). Fig. 8 shows the monthly averages of temperature and relative humidity for the two areas from 1961 to 1968 to illustrate the difference in climate. For both locations the periods of high relative humidity coincides with low temperatures.

Climate data from 1961 to 1996 in terms of diurnal averages for Lund and Kiruna are used as input to the dose–response model. The outcome is the relative dose where values > 1 indicate initiation of mould, i.e. non-performance. Figs. 9 and 10 show the results for Lund and Kiruna, respectively. For Lund a relative dose of 1 is reached after 7 years, see Fig. 9. However, initiation of mould is very close already after one year. The striking effect of recovery in the late 1970's–early 1980's coincides with years with a more dry and cold climate. For Kiruna, see Fig. 10, the maximum relative dose during the 36 years is around 0.5. i.e. the model predicts very low risk for mould at this site, which is in line with generally known experience.

8. Model response for exposure in building envelope

In an ongoing project, samples from 10 different building materials are placed in three outdoor ventilated crawl spaces and

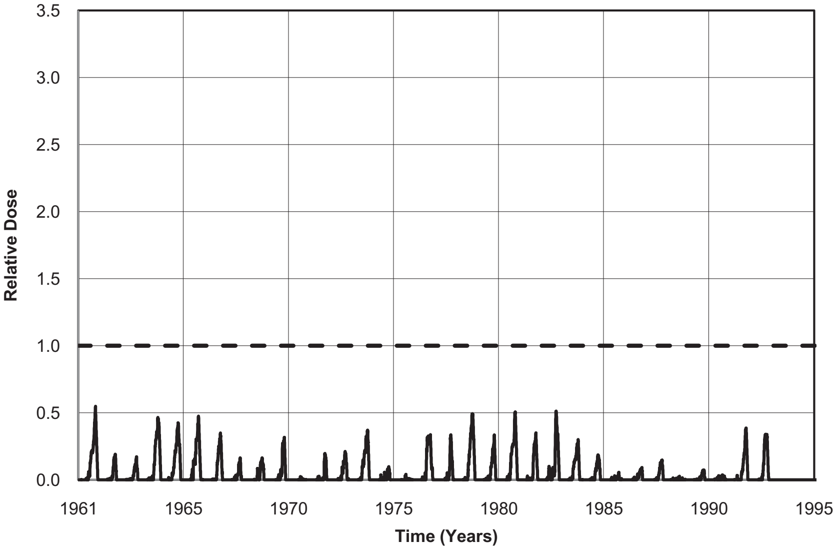

Fig. 10. Relative dose–response for mould initiation on spruce sapwood exposed to outdoor climate (under shelter) in Kiruna, North of Sweden.

Table 1
Evaluation scale of mould growth in the SP project CRAM.

Extent of mould growth	Classification	Description
None	0	No surface growth
Trace	1	Little, or very scattered, growth
Light	2	Slight mould growth, spread over the surface
Medium	3	Substantial growth distributed in patches on the surface
Heavy	4	Substantial growth across the entire surface
Very heavy	5	Very substantial growth across the entire surface

three outdoor ventilated attics. The purpose is to study mould growth under natural circumstances and to compare this growth with test results from laboratory testing. The study is part of a larger, ongoing, project at SP Swedish Technical Research Institute, where critical moisture levels for different building materials are studied and a test method is developed. The attics and crawl spaces are representative for Swedish single family houses, and are situated within a radius of about 30 km from Borås, in western Sweden. The climate in the constructions is expected to be favourable for fungal growth, at least during part of the year.

Although there are ten different building materials, only the results from pine sapwood and wood-based panel products (plywood, thin hardboard and chipboard) are reported here. Five test pieces, 50 × 100 mm, of each building material are placed in racks made of stainless steel and mounted on the blind floor surface of the crawl spaces and on the inside of the pitched roofs of the attics. The surfaces are then exposed to naturally occurring mould spores and climate variations within the constructions.

Along with the building materials, a logger (Testo 177-H1) is mounted in each crawl space and attic. Temperature and relative humidity are logged every fourth hour. The loggers were calibrated before being placed in the constructions. Data from the loggers are dumped every sixth month. The sampling started in April 2007 and will continue until October 2009.

Observations of mould growth are made every sixth month. The test pieces are then removed and the exposed surfaces are analysed in a stereomicroscope (40× magnification). The extent of growth is assessed according to the scale described in Table 1. The scale used in the model (Viitanen [1–3]) is assumed to be comparable to one in Table 1.

Both discoloration visible to the naked eye and mould growth only detectable in microscope are assessed in the analysis. After the analysis the pieces are mounted at the same place as they were removed from.

The climate in these two environments is quite different. For the outdoor ventilated attic the climate variation follows the outdoor climate, i.e. cold nights with high humidity followed by warmer days with lower humidity. The variation in the crawl space is more seasonal, i.e. during the summer the temperature is still low but the humidity is high.

Using the climate measurements of the six different locations the mould situation can be evaluated using the dose–response model and compared with the visual inspection of the mould status. The material used is in this case pine sapwood.

Fig. 11 shows the calculated relative dose for the crawl spaces using the climate measurements as input. For crawl spaces 1 and 3, non-performance (relative dose equal to 1) is reached during the first summer while the second crawl space performs well. The calculated and observed mould status for crawl space 1 indicates similar status while the other two show significant difference between calculated and observed status. As can be seen in the figure, the climate in the crawl space is often more severe with respect to mould growth than outdoor conditions (under shelter).

Fig. 12 shows the calculated relative dose for the ventilated attics using the climate measurements as input. All three attics perform well during the test period. In this case the outdoor conditions are more favourable for mould growth. The observed status so far for all test sites is no mould.

Table 2 shows comparisons between the model predictions and observations for both attics and crawl spaces. The mould status was observed every 6 months for pine sapwood as well as other wood-based materials (plywood, particle board and fibre board) placed in the attics and crawl spaces respectively. For each type of material, 5 specimens were used and the mould status was evaluated according to Table 1. The experimental values given in Table 2 for pine sapwood as well as plywood are median values of 5 estimates using this scale.

A direct comparison between test and model is only valid for pine sapwood, since the model is calibrated for this material. For all

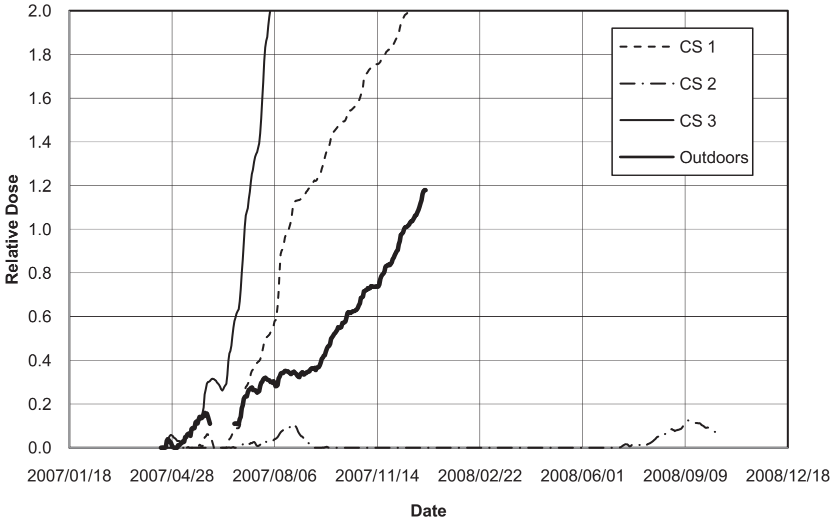

Fig. 11. Relative dose for three different crawl spaces (CS 1–3) and for outdoors under shelter. The material is pine sapwood.

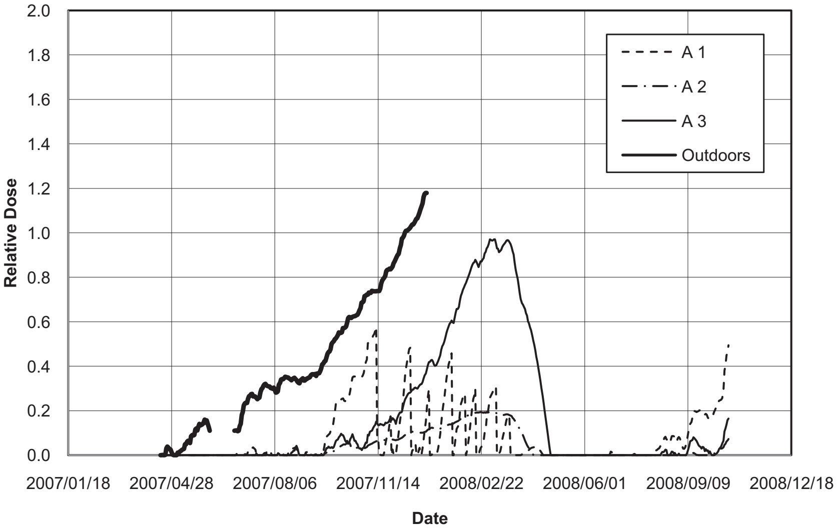

Fig. 12. Relative dose for three different attics (A1–3) and for outdoors under shelter. The material is pine sapwood.

three attics the model predicts that no mould growth is initiated during the test period which completely agrees with the observations. The agreement is not so good for the three crawl spaces (CS). For CS 1 and CS 3 the model predicts onset of mould growth after 3–5 months. For CS 3 onset of mould occurred in the test between 6 and 12 months, while no mould was detected for CS 1 on the pine sapwood samples. For crawl space 2 the model predicts no mould growth, but traces of mould were detected after 18 months in the tests. The comparison is however somewhat shaky since the actual extent of mould growth is generally quite limited for the pine samples. The test results for plywood, which is more sensitive to mould growth, are also given in Table 2 even if a direct comparison is not relevant. Looking at the extent of mould on plywood, however, shows that the relative ranking of the mould risk delivered by the model for the different spaces is as a whole correct.

The rather poor correlation for the crawl space could also be explained by the fact that the specimens are placed close to the ground which means that the natural biological exposure can be quite different from the spore concentration used in the laboratory tests which the model is derived from.

Table 2
Mould growth status for material in crawl spaces and attics observed experimentally compared to the model prediction. Median value rating of five specimens for each material.

Component	Material	Month 6		Month 12		Month 18	
		Test	Model	Test	Model	Test	Model
Crawl space 1	Pine sapwood	0	1.2	0	>2	0	>2
	Plywood	0		3		1	
Crawl space 2	Pine sapwood	0	0	0	0	1	0
	Plywood	0		0		1	
Crawl space 3	Pine sapwood	0	>2	1	>2	1	>2
	Plywood	4		5		4.5	
Attic 1	Pine sapwood	0	0.3	0	0	0	0.2
	Plywood	0		4		5	
Attic 2	Pine sapwood	0	0	0	0	0	0
	Plywood	0		0		0	
Attic 3	Pine sapwood	0	0	0	0	0	0.2
	Plywood	0		0		0	

9. Discussion and conclusions

A dose–response model is proposed for predicting onset of mould growth when wood is exposed to a dynamic and arbitrary climate exposure described in terms of time variation of coupled relative humidity ϕ and temperature T. The model is quantified on the basis of comprehensive test results for spruce and pine sapwood published by Viitanen [1–3]. The test data covers relative humidities in the range 75–100% and temperatures in the range 5–40 °C. For efficient application in building design, the model has been extended to drier conditions as well as to lower temperatures, also below zero. In dry conditions and at low temperatures the model operates with “recovery”, i.e. it is assumed that conditions unfavourable for mould germination and growth will set back the process. The problem here is that experimental verification of such behaviour is lacking, and can only be verified in an indirect sense.

Viitanen and Bjurman [4] and Hukka and Viitanen [13] present some test data for mould development under fluctuating humidity exposure. Applying the model for these tests did show reasonable agreement at least in a qualitative sense and was in general on the conservative side. A crucial aspect is the modelling of retardation of mould development, which is a complex process, which is not well understood. But even at the present state-of-the-art it is evident from qualitative experience that some type of retardation process must be included in the model. If not, the model would predict initiation of mould almost everywhere sooner or later because each period in the unsafe area would give an accumulated effect which inevitably would lead to mould germination also in e.g. normal indoor environments. This is in clear contradiction to what is generally known. Therefore, there is a need for well designed tests which makes it possible to make a more reliable prediction of the set-back of mould development during periods with dry and/or cold climate conditions typical in the building envelope.

When applying the model for different locations in the building envelope in real buildings, it was concluded that mould status predictions for attic spaces seem to correspond quite well with actual observations, while the agreement for locations close to the ground as in crawl spaces is not so good. This indicates that the model predictions should be interpreted with care in environments where the population of mould species might differ from that used in the laboratory tests which are used to calibrate the model.

Generally, the ability of the laboratory methods to represent natural microbiological environments need to be investigated further.

The following main conclusions can be drawn from the present study:

- It is possible to predict onset of mould growth for arbitrary climate exposure with reasonable reliability.
- The prediction model can in general be quantified on the basis of laboratory tests on different substrate materials under controlled climate conditions
- Once quantified for a certain substrate it can be applied in durability design under arbitrary conditions for the tested material.
- The model in its present form seems to be somewhat conservative
- The model predicts responses to outdoor climate at different sites which is in agreement with general experience concerning risk for mould growth
- The model can be used to compare different design solutions and climatic locations in a relative sense even if the absolute results might be uncertain
- The model is also useful as a tool for probability based evaluation of safety against non-performance defined by a limit state.

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