Predicting mould growth on building materials- the PJ-model

Pernilla Johansson^{1,*}, Thomas Svensson²

¹RISE Research Institutes of Sweden, Built Environment, Box 857, S50115 Borås, Sweden

²Thomas Svensson-Ingenjörstatistik, Boviksvägen 21, S50493, Borås, Sweden

Abstract. Mould growth in buildings is a complex process, affected by moisture and temperature, the properties of the building material as well as characteristics of the mould fungi. The complexity poses challenges when assessing the risk of mould growth in buildings. Mathematical models are often used to predict whether mould will grow in a part of building with expected RH and temperature conditions. The models can be described as static or dynamic. In a previous round-robin study, comparing results from models with observations from field studies, the outcome of the dynamic models evaluated depended on the user of the model. Also, the models often underestimated the risk of mould growth. A better agreement was found for static models, especially for the PJ-model. It is a part of a standardised technical specification (SIS-TS 41:2014) and has not previously been described as a model. The critical moisture level (RH_{crit}), determined by tests according to the method, is used as input. Thus, the subjectivity in the predictions is reduced. RH_{crit} is the lowest moisture level at which mould can grow and is temperature-dependent. The PJ-model provides an equation to estimate RH_{crit} at typical temperatures in buildings. If RH in a building section exceeds the limit values at the current temperature, growth is predicted. This paper describes the PJ-model version 1.0, some of the extensive work performed during the development and validation of the model and the ongoing work to refine the model to include considering transient conditions and measurement uncertainties.

1 Introduction

Different materials vary in their susceptibility for mould growth. One way to describe this is by critical moisture level/limit, RH_{crit} , the lowest RH at which mould can grow on a specific material. RH_{crit} depends on the temperature; the lower the temperature, the higher the RH_{crit} .

Mould growth is expected to occur on a building material if the RH conditions exceed the critical limit for mould growth at the current temperature. To avoid mould growth in a building, the RH should be kept below the critical limits for the building materials that have been used, or materials should be chosen that will withstand the RH and temperature conditions and so not have mould growing on them.

RH and temperature are seldom constant within the different parts of a building, varying both in the long term, because of factors such as seasonal variations, and in the short term because of human activity or local climatic conditions. As a result, the critical limit may be exceeded only occasionally. Over time, conditions fluctuate between being favourable and unfavourable for mould growth. The length of these periods also varies, see for a schematic illustration.

Fig. 1. A schematic illustration of variations of RH and temperature over time in part of a building. When the RH is above RH_{crit} (A), the conditions are favourable for mould growth. When RH is below this limit, the conditions are unfavourable (B). RH_{crit} varies over time because it is dependent on the temperature and periods of unfavourable and favourable conditions replace each other by time.

There is always a time before mould growth is initiated. The length of time depends, for example, on the substrate (building material) and the levels of RH and temperature [1-4]. The length of the periods with unfavourable or favourable conditions also affects mould growth [5, 6] with the long-term cycling affecting it more than the short-term cycling. It is therefore expected that the risk of mould growth occurring is low if the variation

* Corresponding author: pernilla.johansson@ri.se

is such that the moisture levels are substantially lower than the critical limits over a sufficiently long period and the critical limits are exceeded for only short periods.

To estimate the risk for mould growth, given the fluctuating RH and temperature, mould prediction models can be used. Static models consider the conditions if the actual RH values exceed the limit values for mould growth or not, while dynamic models also attempt to consider the length of varying favourable and non-favourable conditions. All models require the users to - choose values of some input parameters, such as material classification.

In a round-robin study [7, 8], the output from commonly used mould growth prediction models, based on choices made by different end-users, were compared with the results of mould growth under real conditions. Measurements of RH and T from one crawlspace and four attics were used as input data in the models. Mould growth data consisted of results from an analysis of mould growth on six different building materials exposed in the building parts where the measurements were performed.

The results showed that dynamic models often used to assess the risk of mould (the VTT model, WUFI®-bio, MRD model and m-model) may underestimate the risk of mould growth when temperature and moisture levels fluctuate much over time. The study also showed that different end-users make different choices of input parameters for the same product for example, to which material class a specific product belongs and this also affected the outcome of the comparisons between predicted and found mould growth.

One model that performed better in the study was the PJ-model. One identified reason is that the material data for each product was known from laboratory tests, and no “guessings” were made on to which material group the tested products belonged.

In this paper, the PJ-model is described, together with information and data used to develop and verify the model. The model is described in Annex C of a test method for determining the critical moisture level for mould growth on building materials [9], also published as a standardised technical specification [10]. It has not, however, previously been described as a model.

The PJ-model is currently a static isopleth model. It is under development, and a later version may be published. The present version is therefore denominated as PJ-model version 1.0. In this paper, however, the PJ-model version 1.0 is referred to as the PJ-model. It is expected that extended results from the development of the model will be presented at the NSB conference in September 2020.

2 General description of the model

2.1 Input to the model-RH_{crit}

The material parameter input to the model is the critical moisture level, RH_{crit}, at 22°C. RH_{crit} for the specific product is determined according to a standardised test method [9, 10]. The method is presented

and discussed in [9]. In short, specimens of the product to be tested is sprayed with a water solution containing spores from mould fungi and are then incubated at four different levels of RH at 22°C. After 12 weeks of incubation, the specimens are analysed for mould growth.

RH_{crit} is determined by considering the lowest RH at which mould growth is established on the test specimens and the next lower RH where no growth was detected during analysis. The actual critical moisture level is then considered to be somewhere between these two values, or at the RH when the test pieces failed, according to expression in equation 1.

$$RH_{low} < RH_{crit} \leq RH_{up} \quad (1)$$

In the PJ-model, a product can belong to one out of five material classes, see Table 1. These classes are not described in the original test method.

Table 1. Material classes in the PJ-model. A product is put into a class based on results from testing, according to the test method [10] [9]

Class	RH _{crit} at 22°C
Class A	75% ≤ RH _{crit} ≤ 80%
Class B	80% < RH _{crit} ≤ 85%
Class C	85% < RH _{crit} ≤ 90%
Class D	90% < RH _{crit} ≤ 95%
Class E	95% < RH _{crit}

As it is not possible to estimate the RH_{crit} of a specific product, it must be tested. If RH_{crit} is not known, i.e. test is not performed or communicated; it is recommended to use Class A. This is in line with recommendations from the Swedish National Board of Housing [11].

2.2 Growth limit curves

Because RH_{crit} is temperature-dependent, the values of RH_{crit} for the different material classes are valid for 22°C. In the PJ-model, RH_{crit} is assessed for other temperatures by using equation 2.

$$RH_{crit(T)} = 105 + c(T^2 - 54 \cdot T) \quad (2)$$

where T is the temperature in °C and c is the value according to Table 2. A value is produced for the lower, as well as the higher, level in the RH_{crit} expression in equation 1. RH_{crit} can never be higher than 100 %, so the final RH_{crit} from equation 2 will be expressed as in equation 3.

$$RH_{crit} = \min(100, RH_{crit(T)}) \quad (3)$$

If the calculations are repeated for a series of temperatures common in buildings (0-30 °C), the critical moisture levels can be expressed as growth limit curves see Fig. 2.

Table 2. Values of c in equation 1 for each material and the lower and upper limit value respectively

Class	RH_{low}	RH_{up}
Class A	0.043	0.036
Class B	0.036	0.028
Class C	0.028	0.021
Class D	0.021	0.014
Class E	0.014	-

For defining equation 2 and determine the values in Table 2, we used the same technique as Hofbauer et al. [16]. Material-specific isopleths were constructed from the closest approximation to Sedlbauer's LIM0 curve for mycelial growth [5]. Input to the curve fitting came from laboratory tests at two temperatures [3]. In [12], the procedure is described more in detail.

Fig. 2 Growth limit curves the different material classes.

2.3 Prediction of growth

To predict possibility for mould growth the RH in the building part at different temperatures are compared to the upper and lower value of RH_{crit} in (1) at the specific temperatures, see (3) and (4).

$$Ratio_{up} = RH(T)/RH_{critup}(T) \quad (3)$$

$$Ratio_{low} = RH(T)/RH_{critlow}(T) \quad (4)$$

In building parts where the relative humidity at a specific temperature is expected to be below the lowest growth limit curve, i.e. $Ratio_{low} < 1$, no mould growth is expected. If it exceeds the upper limit, i.e. $Ratio_{up} \geq 1$, mould growth is possible. In between the two values, there is a zone in which the critical moisture level may fall. If the actual relative humidity is in this zone, mould growth is also regarded as possible to be on the safe side. The procedure is described visually in Fig. 3.

Fig. 3 Illustration of how the prediction of mould growth is performed. The measured value of RH is plotted as a function of the measured temperature. Mould growth is predicted on materials belonging to Class A as the values are above the upper growth limit curve. Also, to be on the safe side, mould growth is considered possible at materials belonging to Class C, as the values are in the zone between the upper and lower curve. No mould growth is predicted on materials belonging to Class D as the values are below the lower growth limit curve.

3 Validation of the model

The model has been validated in two ways. In field studies, predictions were compared to the real outcome. Laboratory tests were performed to verify the values of RH_{crit} at different temperatures.

3.1 Field studies

Test pieces of the same materials tested in a laboratory environment, and therefore with known RH_{crit} , were placed in crawl spaces, attics and one garden shed for up to 3 years. A data logger with internal sensors (Testo 175H1) was placed close to the specimens. The temperature and RH were registered hourly and varied by time.

The field test was performed on two occasions; the first at the development of the test method for determining critical moisture levels [12] and the other one some years later, after this method was standardised [13]. In the first study, samples of 10 different building materials were exposed in 6 different test sites; in the second study five different materials were included, 4 of them was the same as in the first study. This field test comprised 12 different test sites.

The test specimens were analysed for mould growth at intervals of 3-6 months. At the end of the test period, predictions of mould growth, according to 0, was performed. The results from the prediction were compared to the real outcome of mould growth. The procedure is shown in Fig. 4.

Table 3 Interrelation of predicted growth by the PJ-model and observed mould growth on test specimens from field tests[12] [13]. The figures refer to the number of cases, with percentages within the brackets. Each case represents the median rating of growth on seven or six (depending on study) samples of each material at each test site. Green numbers show correct predictions and red numbers incorrect.

Predicted mould growth	Observed mould growth	
	Yes	No
Yes	58 (51 %)	15 (13 %)
No	-	40 (35%)

Fig. 4 Comparison of the prediction of the PJ-model and presence of mould growth on test specimens. In the left graphs, each dot is an hourly measurement of temperature and RH. Prediction is made according to Fig. 3. The graphs on the right of describes mould growth analysis at the end of the field study. The mould growth was assessed and rated according to a five graded rating scale. Each dot represents the rating on one test piece. The median is represented with a blue diamond. If the median is at or above 2 (represented by the dotted horizontal line), mould is established. In (a) mould growth is predicted, and there was established growth at test specimens. In (b) no mould growth was neither predicted or found. Therefore, the predictions were correct.

In 86 % of the cases, the model predicted mould growth correctly. When predicting wrong, the model was conservative; mould growth was predicted when there was none at the test specimens. In all these cases, the total time which RH was above the curves were short, or the RH values were very close to the limit values.

The time for mould growth to establish on a building material is shorter at constant favourable conditions than if the favourable and non-favourable conditions vary by the time [5, 6]. Therefore, it expected that the time to mould growth to appear in real conditions, where both RH and temperature vary a lot, cannot be shorter in constant, favourable conditions. In the cases where there was no mould growth while the model predicted growth, the time was always shorter than the shortest time before the critical moisture level was achieved in the laboratory. There was, therefore, consistency between actual and

expected mould growth when both criteria (a) conditions exceeding the limits for growth and (b) cumulative time over the limits being lower than the time before mould growth was established in the laboratory were considered, and the agreement between predicted (non) growth and actual (non) growth was 100%. However, in the present version of the model, the time above the curves are not considered.

3.2 Validation of calculation of RH_{crit}

During the development of the test method for determining RH_{crit} , several laboratory tests were performed. Ten different building materials were tested for mould growth at different levels of RH at 22°C and 10°C [3]. Critical moisture levels were determined for both these temperatures and the curve fitting to develop the curves as described above considered both temperature. Equation 2 was tested for 22°C and 10°C and the result was in agreement with determined RH_{crit} at each temperature respectively temperatures.

In a later laboratory study, RH_{crit} at 5°C was determined for five of the previously tested materials belonging to different classes, according to Table 1. Ten specimens were incubated at RH at 95 %, 90 % and 85 % at 5°C. Material classes in the test belonged to Class A, Class B, Class C, Class D; one product from each class except for Class D, where two products were represented.

For each material class, RH_{crit} at 5°C was calculated according to equation 2. It was then expected that there would be mould growth only on specimens belonging to Class A in the 95% chambers and that there should be no growth on any materials in 90% or 85 %. When comparing actual growth on specimens, the prediction for Class A was correct; however, there was also growth on Class C in this chamber, showing that the prediction was false negative in this case. Also, mould growth was found on specimens of group A in the 90 % chamber. In Table 4, this is summarised. The results indicate that RH_{crit} , as estimated by equation 2, might be a few percentages too high for material class A and B at 5°C.

Materials with known RH_{crit} were also tested at 15°C at 90 %, following the routines in the method. Materials represented all material classes in Table 1. As only one level of RH was used, it was not possible to determine RH_{crit} at this temperature. However, it was evaluated if the predictions at this temperature agreed with found results. At 15°C, mould growth is expected on specimens from Class A and Class B, but on no other materials tested. The findings agreed with the predictions, see Table 4.

The lowest possible RH_{crit} of the most sensitive materials is in the PJ-model assumed to be 75 % RH. This assumption is based on results from the laboratory tests during the development of the test method, as there was mould growth at 75 % on the most sensitive material, and literature data. It is sometimes argued that mould growth is possible even at 70 % at room temperature. To test whether RH_{crit} of the most susceptible materials may be lower than 75%, specimens of materials belonging to

Class A and was tested at 71,5 % and 22°C. Also, a glass fibre filter dipped in agar solution was used as a test material. This nutrient media is an optimal substrate for mould growth. No mould growth was found on any of the materials or the filter even after 32 weeks of incubation. Therefore, we conclude that 75 % RH at room temperature is a reasonable lowest value for mould growth on the most susceptible materials.

Table 4 Results from laboratory test at different temperature or RH to validate equation 2.

Set RH and Temp	Material classes on which mould growth was predicted	Material classes on which mould growth was present
95 %, 5° C	A	A and C
90 %, 5° C	None	A
80 %, 5° C	None	None
90 %, 5° C	A and B	A and B
71,5 %, 5° C	None	None

4 Development of the model

Development of the model is ongoing. The work is based and tested on extensive data from previous studies and ongoing tests. Both laboratory test in constant and varying conditions of RH and temperature and results from field tests are being used in this work.

One limitation of the present model is the use of two curves, as it is not intuitive to interpret the results if RH values are only in between the upper and lower curve. One aim of the development is to replace these with just one curve and adding an uncertainty interval. Another aim is to determine the minimum cumulative time RH must be over the curve in order for the model to predict mould growth. This duration may be especially important when periods of favourable conditions are short, as the results from the field tests indicate.

Also, the work aims to consider the measurement uncertainty of RH and temperature measurements or simulations. The measurement uncertainty is especially significant when the values of RH is close to the limit values.

The model was initially developed to be used as a practical tool where the RH_{crit} values could be used to choose the most suitable material to a building part with known RH and temperature in order to avoid mould growth. The aim was not to determine when mould growth is expected if the conditions are favourable. Sometimes, however, the information on when mould growth is expected and how long time RH can be exceeded without mould growth is needed. Examples of such situations are when defining indoor climate control systems or when the materials are exposed to certain climate conditions during the construction of a building. The ongoing work is also including an attempt to include also the time until mould growth.

5 Conclusions

Although not perfect, the PJ-model is useful to predict mould growth in buildings where the RH and temperature are known. The model has been validated in both laboratory and field studies.

If the expected temperature and RH in a building part are known, the PJ-model may be used as a tool when choosing the materials for the construction to minimise the risk of mould growth.

Work is ongoing to refine the model to the extent which can be motivated from existing data, and to customise the parameters to make safer predictions.

In comparison to other mould prediction models, the subjective influence of the PJ-model is low, as the input material parameter is from laboratory tests. Other models assume that the end-user need to estimate to which material class a specific material belong.

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