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Analysis of the suitability of mould growth models for the risk assessment of woodfibre internal wall insulation

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Abstract

The UK has pledged to reduce its carbon emissions by 80% by 2050. This translates into improving, among other measures, the energy efficiency of solid wall buildings, which requires the use of challenging measures such as internal wall insulation. Internal wall insulation can lead to moisture accumulation and mould growth at the interface between the insulation and the existing wall, if incorrectly designed and installed. Consequently, a thorough risk assessment is crucial for the design and specification of measures such as internal wall insulation. This paper presents the evaluation of mould growth models for the risk assessment of woodfibre internal wall insulation. The hygrothermal conditions within internally insulated solid walls were monitored and three models compared. The suitability of the models was assessed in relation to the risk of mould growth at the interface.

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Keywords: Mould growth models; risk assessment; internal wall insulation

1. Introduction

Mould is one of the major issues in buildings across Europe, with 86 million people living in dwellings affected by dampness or mould [1]. Mould growth in buildings is a physiological and visual hazard causing discoloration of building surfaces or weathering of stone; it has also been linked to the development of asthma [2] and upper respiratory tract symptoms [3] in building occupants. Dampness (i.e. excessive moisture accumulation) is a prerequisite for mould growth; however, it is not the only factor causing it as mould growth is a very complex phenomenon.

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Apart from the availability of mould spores in air, the nature of mould species and the ability to compete with other microorganisms, factors such as temperature, humidity, nutrients, pH, oxygen, carbon dioxide and light have to be considered when assessing the development of mould. A number of models have been developed for the evaluation of mould growth risk on surfaces, mainly considering relative humidity, temperature, time of exposure and nutrients (i.e. substrate); however, none of them have considered the risk of mould growth at the interface between a solid wall and an internal wall insulation system.

The aim of this study was to evaluate the suitability of existing mould growth models in the assessment of mould growth risk of internally insulated solid walls, where the critical layer is at the interface between solid wall and insulation. Three mould growth models were considered in the study: the bio-hygrothermal model, the VTT model and the dose-response model. Results were compared and discussed, considering the critical relative humidity curves, the description of mould growth and decline, the pre-processing of environmental data and the failure criteria (i.e. thresholds) used in the risk assessment of mould growth.

2. Methodology

The suitability of existing models was assessed considering monitored data from three case studies; the case studies represent a range of conditions occurring in solid walls that have been internally insulated with woodfibre insulation. In-situ monitored temperature and relative humidity within the insulated walls were used in the analysis and the likelihood of mould growth risk was estimated applying three existing mould growth models. The three models used in the analysis are the bio-hygrothermal, the VTT and the dose-response models; all of them were developed for mould growth assessment at surfaces and consider relative humidity, temperature and substrate as main factors for growth:

- The steady state bio-hygrothermal model stems from the combination of an isopleth system proposed by Sedlbauer with the moisture balance of a spore [4]. The critical relative humidity, above which favourable environmental conditions for mould germination and growth are found, is described by the Lowest Isopleths for Mould (LIM), developed for a number of substrates. The curves were defined as the interpolation of the minimum values of relative humidity and temperature of several mould species studied on specific substrates.
- The VTT model is an empirical model based on Viitanen's regression analysis of measured data [5], considering steady state conditions of temperature and relative humidity, and a number of substrate types [6]. The critical relative humidity in the model is an isopleth that describes the lowest humidity for mould growth on wood, as a function of temperature. When the RH is below the critical relative humidity curve, there is a delay in mould growth, represented in this model by a decline of *mould index*, a measure for mould growth that describes the mould coverage on a surface.
- The dose-response model is designed for predicting the onset of mould growth on building materials under transient conditions [7]. It considers daily mean values of relative humidity and temperature for the calculation of a daily dose for mould growth, which represent the time required for mould to reach a mould index of 1 (small amount of mould on surfaces, at microscopic level) at constant relative humidity and temperature conditions, and depending on a specific substrate. The daily dose for mould growth (and its delay) is based on Viitanen's regression analysis [5]. The model also proposes a critical relative humidity of 75%, independent of temperature.

Mould growth (in mm) is calculated by the bio-hygrothermal model and converted into the mould index (M) using a transfer function [7]. On the other hand, the other models use the mould index directly to describe the extent of mould growth. The failure criteria used with the bio-hygrothermal and the VTT models are based on the traffic light classification for interfaces described in Table 1; for the dose-response model the failure criterion is $M = 1$.

Table 1. Failure criteria for mould growth risk assessment: traffic light classification [8]

	Green (no risk)	Amber (the user decides whether to accept this risk)	Red (unacceptable risk)
Mould index – surface	$M < 1$	$1 \leq M < 2$	$M \geq 2$
Mould index – interfaces and surfaces without direct contact with indoor environment	$M < 2$	$2 \leq M < 3$	$M \geq 3$

2.1. Method of analysis

The three models for mould growth risk assessment were compared considering the choice of critical relative humidity curves, the description of mould growth and delay, the pre-processing of environmental data and the failure criteria. The models were used to assess the risk of mould growth at the interface between a woodfibre insulation board and the existing wall, bonded to the insulation by means of a lime-based plaster. The assessment considered a biological substrate since, of the three materials present in the case studies, the most favourable substrate for mould growth is the insulation board, made of spruce and fin fibres from sawmill waste.

One year of hourly data was used for the analysis, and pre-processed according to the models' requirements (i.e. daily means of temperature and relative humidity in the dose-response model); the year starts in autumn, covering the wetting period and the drying period. The insulation was installed using a wet process; the initial drying of the render occurs in an alkaline environment, which creates unfavourable conditions for mould growth [8]. Therefore, the initial conditions were discarded and the analysis started from the first wetting period (i.e. autumn) after construction. A piecewise cubic Hermite interpolation was used in case of missing data.

2.2. Case studies

Three case studies were assessed, which present various conditions that can occur with capillary active woodfibre insulation, ranging from high exposure to internal vapour pressure to high exposure to external climate. The locations of the case studies are characterized by a fairly low exposure to wind driven rain (WDR areas 1-2) and high solar radiation.

Case study 1 has two different woodfibre-based insulation systems on external walls with a south orientation; the sensors were located in walls of the living room (sensors L1, L2, L3), the bedroom (sensor B) and the staircase (sensors SC1, SC2, SC3, SC4). In case study 2, two walls of the same room were assessed: a north oriented wall (sensors N1, N2) and a south oriented wall (sensors S1, S2) [9]. In case study 3, walls in the kitchen, south oriented (sensor K) and the entrance, north oriented (sensor E), were assessed.

3. Results and discussion

3.1. Critical relative humidity curves

The critical relative humidity curves defined by each model identify levels of relative humidity and temperature that constitute favourable conditions for mould growth. Fig. 1 shows the critical relative humidity curves for the three models, alongside the recorded hourly relative humidity (RH) and temperature (T) at the wall-insulation interface for the three case studies. The recorded relative humidity varied considerably between 45% and 95%. In many cases the recorded relative humidity exceeded the critical curves (especially in Fig. 1a, 1c, 1d), meaning that mould growth was likely to occur in all case studies.

The bio-hygrothermal and VTT models use critical relative humidity curves that were constructed considering temperature as a key parameter in the development of mould, also reflecting the fact that mould growth is unlikely to occur under lower temperatures. On the other hand, the dose-response model uses a constant critical relative humidity of 75%, without considering temperature as critical parameter. In all case studies, temperatures at the interface were as low as 2 ºC, considerably lower than the ones usually found at surfaces. Therefore, critical curves must consider temperature alongside relative humidity for the mould growth risk assessment at interfaces; a constant critical relative humidity should not be accepted for the assessment, as it would not consider that mould growth is inhibited at the lower end of the temperature range found at the interface.

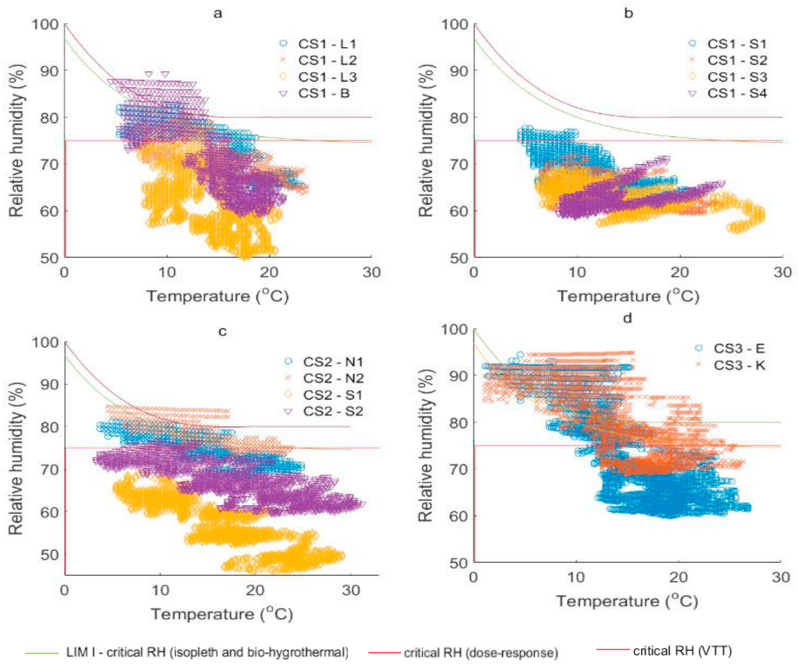

Fig. 1. Hourly data points against the critical relative humidity curves defined for each model, case study 1 (a, b), 2 (c) and 3 (d)

3.2. Mould growth risk assessment: mould growth and delay

The risk of mould growth also depends on the time of exposure to favourable conditions (above any of the critical curves); models that consider the time of exposure to such conditions are required to quantify the mould growth risk. The mould growth risk assessment was performed with the three models; two decline rates for the mould index were used for the VTT model: the original decline rate, based on short term experiments on pine, and a more conservative rate that considers almost no decline.

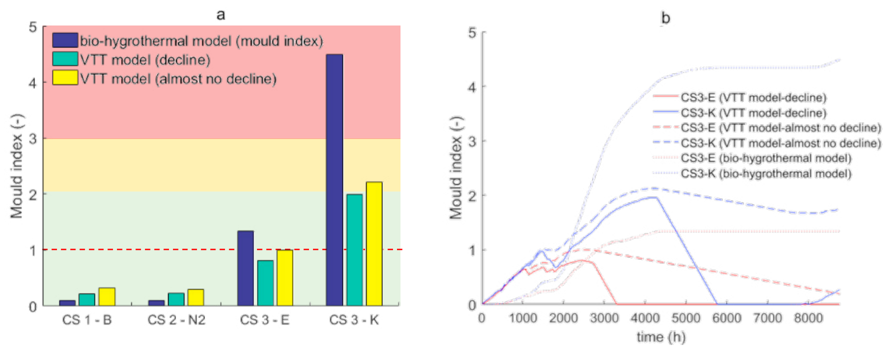

Fig. 2. Mould index (a) according to bio-hygrothermal and VTT models.
Comparison of mould index as function of time for CS3-K (b).

In Fig 2a, the maximum mould index was calculated for the bio-hygrothermal and the VTT model, and the results were evaluated against failure criteria for interfaces (see the traffic light classification in Fig 2a); the dose-response model is presented separately, because the output of the model, relative dose, is different to the mould index. Fig. 2a shows that models performed similarly in the cases with low mould index; however, for higher mould indices, the bio-hygrothermal model showed much higher values than the VTT model. Among the differences between the two models, the VTT model considers a lower growth rate for mould indices higher than 1 and considers mould index decline (Fig. 2b), causing a decrease of mould index under unfavourable conditions. On the other hand, the mould index from the bio-hygrothermal model is monotonic ascendant, and the conversion from mould growth to mould index does not consider the decline of mould index.

Fig. 3a shows the relative dose according to the dose-response model. A relative dose of 1 means that the cumulative sum of the daily dose has reached the number of days required for a mould index of 1 (with spruce as a substrate, the reference number of days to reach M=1 is N_{ref} = 38 d), according to Viitanen's regression function. The dose-response model considers a mould index decline rate based on the VTT model with decline; therefore, as in the VTT model, the cumulative sum of the dose can be lower than the maximum dose reached during the year of monitoring (see Fig. 3b). Using a cumulative sum rather than the maximum value leads to an underestimate of mould growth risk; for example, CS3-E reached a relative dose of 1.04 which then declined to the final relative dose of 0.16. Evaluating the cumulative dose against the threshold for the relative dose, CS2-N2 and CS3-K exceeded a mould index of 1; if the maximum dose was evaluated against the threshold, also CS3-E would have exceeded M=1.

The three models describe mould growth and its delay in different ways; although mould growth has been extensively investigated for steady state and transient conditions, there is a lack of information on the delay of mould growth in unfavourable conditions. Therefore, a conservative mould index decline rate is preferred for the analysis. Also, there is a positive relationship between a delay in mould growth and convection at the surface assessed [10]; no

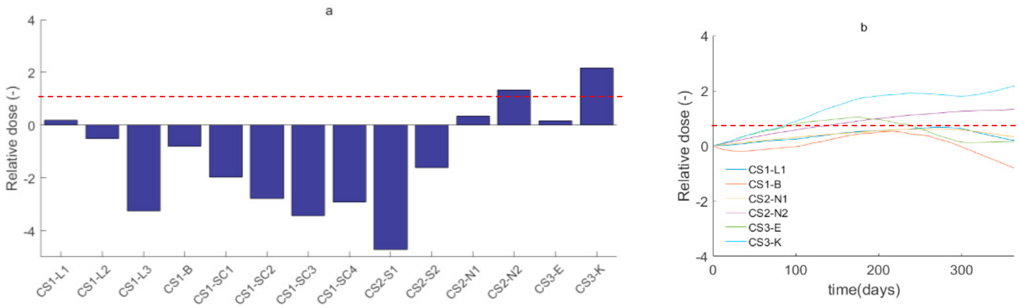

Fig. 3. Cumulative sum of relative dose (a), and relative dose as function of time (b)

research has considered materials interfaces, where convection does not occur. Therefore, a conservative decline rate would be more appropriate for the risk assessment at interfaces.

3.3. Remarks on critical relative humidity curves

Fig. 3a shows positive values for the relative dose in CS1-L1 and CS2-N1; in the other models, which use a non-constant critical relative humidity curve, there was no mould growth at these locations. Also, a comparison between the results of the dose-response model and the results in Fig. 2b, where M=1 is represented with the dashed red line, shows that CS2-N2 exceed M=1 only in the dose-response model. Most data points of CS2-N2 fell between the critical relative humidity curve for the dose-response model and the LIM I (see Fig. 1c); this discrepancy could be caused by the choice of the critical relative humidity curve. These results proved that the selection of critical relative humidity curve can significantly affect the assessment.

3.4. Consideration of transient conditions

The bio-hygrothermal and VTT model were developed as steady-state models and require hourly data for the analysis, even when transient conditions are used; however, mould requires a fairly stable favourable environment to grow. On the other hand, the dose-response model requires pre-processed data of daily averages of temperature and relative humidity. In transient conditions, it has been shown that moving averages would describe better the growth behaviour [11] than hourly data.

4. Conclusion

This paper described the evaluation of the suitability of using existing mould growth models for the assessment of mould growth risk at the interface between a solid masonry wall and woodfibre internal wall insulation systems. Three models were assessed; the type of substrate representing woodfibre, spruce, was considered in the analysis.

It was found that the choice of critical relative humidity curves had an influence on the number of hours at favourable conditions for mould growth. Since mould growth is inhibited at low temperatures, common at interfaces, acceptable critical curves should consider temperature as well as relative humidity. The assessed models describe mould growth and its delay in different ways; currently there is no information on mould delay at interfaces, therefore the risk assessment should consider a conservative mould index decline (e.g. almost no decline) or no decline. If decline is considered, the use of maximum values for the mould index or relative dose should be preferred over the use of cumulative sum. Failure criteria related to interfaces [8] should be used; models such as the bio-hygrothermal and VTT can adapt to represent failure, whereas the dose-response model only considers a more conservative threshold of M=1. Regarding the consideration of transient conditions, using moving averages of temperature and relative humidity would allow a better description of growth under transient conditions.

Models were developed to predict mould growth at surfaces; however, a combination of the assessed models, considering their advantages and disadvantages with regards to the particular conditions at interfaces, can be useful for the mould growth risk assessment at the interface between solid masonry walls and woodfibre internal wall insulation systems.

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