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A MATHEMATICAL MODEL TO PREDICT ACTINOMYCETES GROWTH IN BUILDING MATERIAL

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Abstract: **To predict the mathematical model for simulation of actinomycetes growth in building wood material. Actinomycetes growth is one of the first signs of biological growth linked to relative humidity and temperature condition in buildings materials. The numerical growth model was based on several models are found in literature. Quantification of actinomycetes growth in the model is based on mould index used in the experiments for visual inspection. This model consists of differential equations describe the growth rate of the actinomycetes index in vary fluctuating conditions including the effect of exposure time, temperature, relative humidity and dryness. Up to now the mathematical model to assess the actinomycetes growth which is based on steady boundary conditions. This study presented new results for modeling of actinomycetes growth on the surface of building materials such as wood, cement, concrete.**

Keywords: **Actinomycetes, building material, modeling and relative humidity.**

1. INTRODUCTION

The word "Actinomycete" is used to describe a link between bacteria and fungi, so called ray fungi [16]. Actinomycetes play important functional role in natural and man-made environments. In nature, these play a crucial role in the decomposition of organic compounds and environmental pollutants [4]. In buildings, actinomycetes cause problems in different structure and materials like basements, floors, roofs and walls. Surfaces of many other materials support the growth of microbs viz., bacteria, actinomycetes and fungi which are more common for material decay damages. Typical actinomycetes found in moisture damaged buildings are Actinomadura, Kitasatospora, Pseudonocardia, Spirillospora, Saccharomonospora, Rhodococcus, Streptococcus [6] Nocardia, Micromonospora, Streptomyces [5].

The ambient relative humidity (RH, relative humidity of microclimate) above 75%–80% or water activity (a_w) above 0.75-0.80 is critical for the development of actinomycetes on the surface of wood, but the critical humidity level is also dependent on temperature and exposure time [13]. It has been found that the actinomycetes growth on other building materials may not be equal to that on wood based materials [10]. These microorganisms produce aesthetic or technical effects and the requirements for repairing the problems and damages are different. Also the exposure time needed for the microbial growth to begin may be longer. Moisture damage buildings may lead to the growth of microorganisms which damage to building materials after a critical exposure time.

A numerical actinomycetes growth model is used for the evaluation of the effect of humidity, temperature, and exposure time for actinomycetes growth on wood material [7,10]. This model was based on comprehensive laboratory studies with Northern wood species [13]. Many other types of models were presented by Adan[1] and Clarke et al.[3]. According to Brischke and Fruhwald [2] research on modeling moisture and microbial problems in building has been more active over the past few years. In 2006 Vinha et al.[15], adapt the model for analysis of structures made of various building materials

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for different relative humidity and temperature. Consequently, a different conclusion may be drawn depending on the used prediction model.

This paper presents a mathematical index model for the growth of actinomycetes and discuss some of its predictions, the main purpose being to report results of some experiments that were designed to the theory. The growth of actinomycetes in this model was evaluated using "actinomycetes index" scale as shown in Table 1. On the basis of pre exiting models [9] this model can be used to evaluate the bacteria and actinomycetes in different exposure conditions.

2. ACTINOMYCETES PREDICTION MODELS

2.1 Temperature Ratio

To evaluate mould risk, the IEA-Annex 14 [8] proposes a mold growth evaluation based on the temperature ratio :

$$\tau = \frac{\theta smin - \theta e}{\theta i - \theta e} \qquad (1)$$

Where, $\theta smin$ = minimum surface temperature (°C)

θi = inside temperature (°C)

θv = outside temperature (°C)

A temperature factor of 0.7 is related to an acceptable microbial risk of 5%. A lower temperature factor will introduce an unacceptable high microbial risk. This criterion is often used in combination with a critical RH threshold for actinomycetes growth, which is according to the IEA Annex 14 recommended to be set at 80%.

2.2 Pre-existing Growth Model

The pre existing growth for pine and spruce sapwood material and its application has been presented in several papers e.g., Hukka and Vitannen, [7]. Although, it is required to know the threshold conditions for the simulation of actinomycetes growth where their growth occur on different building material. Therefore, minimum and maximum levels for relative humidity or temperature of materials and surrounding environment. The mathematical model growth of mould growth was developed by Hukka and Viitanen[7] was based on regression analysis of the measured data [11,13,9]. In this model different mixed actinomycetes species are used. The actinomycetes growth development is expressed by actinomycetes index (A). An index value between 0-6 to be used as a design criterion that mean evaluation of mould growth on a substrate surface e.g. often A=1 expressed as the maximum tolerable value since from this point the germination process starts and the mould growth can be detected visually in between index 3-6 (Table 1).

Table 1: Actinomycetes Growth Index

Index Values	Growth Rate	Description
0	No growth	Spores not activated
1	Mould growth in small amount occurs on surface	Initiation phase
2	<10% Coverage of mould on surface	-
3	10-30% or <50% Coverage growth on surface	New spores produced
4	>50% Coverage of mould growth	Moderate growth
5	>70% Coverage growth on surface	Plenty growth
6	Very high and dense growth about 100% coverage surface	

According to Hartley *etal*.,[7] moisture content of wood depends on ambient humidity, temperature, exposure time, dimensions and moisture absorption capacity of wood; water can exist in wood as free water content in capillaries or bound water with in the cell walls. Being a hygroscopic material, the equilibrium moisture content of wood is easily affected by the ambient humidity. There are certain maximum and minimum levels of water activity of substrate or temperature at which mould can grow on or in substrate. The mould growth model is based on laboratory experiments on pine, spruce sapwood, fiber, gypsum and concrete screed in which the influence of temperature, relative humidity surface and time is taken into account. In this model a critical relative humidity RH_{crit} (%) can be found which is defined as the lowest humidity under mould growth can occur if the substrate is exposed to it for a long period. For substrate RH_{crit} is given by:

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

RH_{min} is 80% for wood and wood based products. The mould index value either increase or decrease can be calculated by the use of differential equation in which different temperature and relative humidity conditions taken into account. Mould growth model equation 3 was presented by Hukka and Viitanen [6].

$$\frac{dA}{dT} = \frac{1}{7.\exp(-0.68\ln T - 13.9lnRH + 0.14W 0.33SQ + 66.02}k_1 k_2 \qquad (3)$$

Where k_1 = intensity of mould growth, k_2 = mould growth coefficient, W = timber species (0= pine; 1= spruce) and

SQ = surface quality (SQ =0 for swan surface; SQ = 1 for kiln- dried quality).

For other materials than wood, SQ value = 0. In equation 2, time unit used in days , due to relatively long monitoring period used in the mould growth model development. Numerically simulation is carried out using time (h) steps in new model. The factor k_1 defines the growth rate under favorable conditions and is given below:

$$\frac{dA}{dt} = \frac{k_1 k_2}{7tA = 1} \qquad (4)$$

The factor k_1 defined the growth rate under favourable conditions and are given below:

$$k_1 = \frac{tA=1,\ Pine}{tA=1} \qquad when\ A < 1 \qquad (5)$$

$$k_2 = \frac{tA=3,\ Pine - tA=1, Pine}{tA=3 - tA=1} \qquad when\ A \geq 1 \qquad (6)$$

In equation 5 and 6, the factor t_A = 1 and t_A =3 respectively, the time required to start mould growth A =1 and macroscopically appearance of actinomycetes growth A = 3. For pine sapwood t_A=3 is about two times higher than t_A =1and k_1 is 2 when *A*>1 (Table 2). The subscript pine refers to the value with reference material pine. By interpreting the results of the model all values of *M* below 1 indicated no growth. The retardation of the model growth in the later stage is defined by coefficient k_2 (Equation 7). That represents the moderation of growth intensity when the actinomycetes index (*A*) level approaches the maximum peak value in the range of 4 to 6.

$$k_2 = \max[1 - exp[2.3(A - Amax)], 0] \qquad (7)$$

Where the maximum actinomycetes index level A_{max} depends on the Equation 8.

$$Amax = 1 + 7\left(\frac{RHcrit - RH}{RHcrit - 100}\right) - 2\left(\frac{RHcrit - RH}{RHcrit - 100}\right)^2 \qquad (8)$$

In Equation 8 , RH_{crit} is the limit relative humidity level to start the mould growth [2]. This curve is presented in Figure 2.

A mathematical description of degradation of mold growth on wooden and other material surface of building material was modeled based on cyclic changes between two humidity conditions. This delay of mold index is presented by the following Equation.

$$\frac{dA}{dt} = \{-0.0013, when\ t - t1 \leq 6h$$

$$0, \quad when\ 6h \leq t - t1 \leq 24h \qquad (9)$$

$$-0.000667, \text{ when } t\text{-}t_1 > 24h\}$$

Where *A* is actinomycetes index and t is the time (h) for the moment t_1 when conditions on the critical surface changed from growth to outside growth conditions [7]. Under the long periods (week, months), gives practically linear decrease of mold index. The decline stage of mold index for other material was presented using a relative coefficient for each material as Equation (10). So that the decline model for wood could be applied using these additional factors.

$$\left(\frac{dA}{dt}\right) mat = Cmat(dA/dt)0 \qquad (10)$$

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Where $(dA/dt)_{mat}$ =actinomycetes decline intensity for each material, $(dA/dt)_0$= pine in orogonal model, $C_{mat=}$ relative coefficient for mold index decline used in the simulation model.

3. RESULTS AND DISCUSSION

The results were expressed as accordingly to mold index level 1to 6 (Table 1). Experiments were done to take better accounts the different mold growth types with different surface and wood material (Figure). The main differences compared with the version for wood surfaces was in the area that is not visible to naked eye (microscopic). It was found out that with some substrates the mold growth coverage could be quite high in the microscopic level. Therefore, the mold growth index determination was updated with initiation of mold growth equivalent to index level 1. Model index level 3 and higher equates with visible mold growth coverage (macroscopic).

The various building materials showed varying tolerance against mold growth under the test conditions. The results of wood substrate and other material surfaces fitted best with pine sapwood. At the 15˚C temperature, there was a lag phase for the initiation of mold growth, So this was no well fitted with this model. The second evaluation of the mold growth model with the new material sensitivity class factors was done by producing mold index levels under constant temperature and relative humidity.

Table 2: Different sensitivity class of the substrates actinomycetes model based onVTT model[14]

Sensitivity Class	Material	k_1		K_2 (max)			RH min(%)
		A<1	A>1	A	B	C	
Very sensitive	Pine sapwood	1	2	1	7	2	80
Sensitive	Wooden board, spruce	0.578	0.386	0.3	6	1	80
Medium resistant	Concrete, glasswool polyester	0.072	0.097	0	5	1.5	85
Resistant	PUR unpolished surface	0.033	0.014	0	3	1	85

The maximum level of mold index for different materials under different temperature and relative humidity are presented in Table 3. The resulted values are based on steady state conditions and are valid for the set of products used in the tests. Using these experimental data, the approximation for the maximum actinomycetes index levels could be determined for different temperature, RH and test materials.

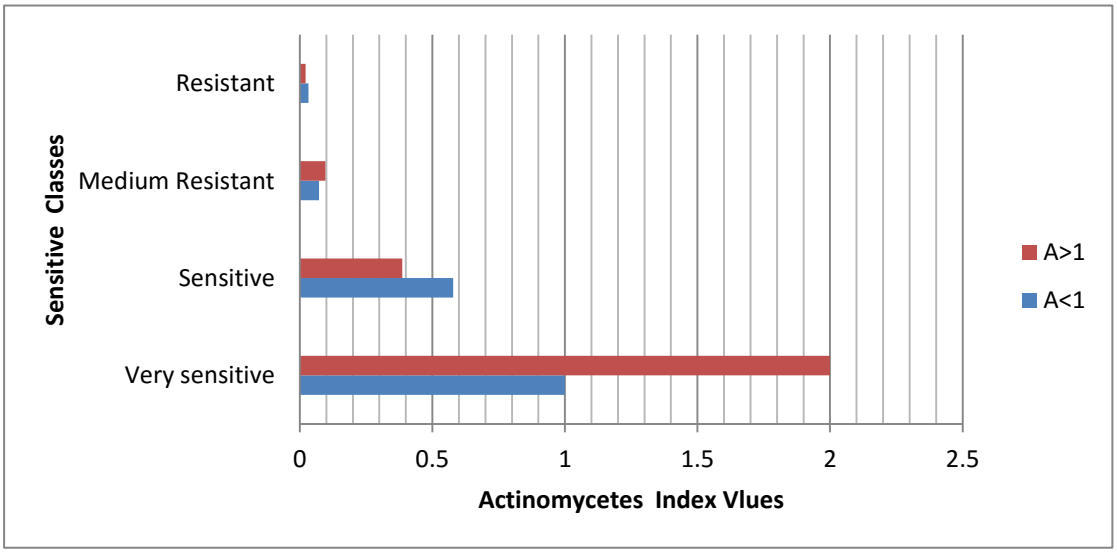

Figure 1: Actinomycetes growth intensity factors k_1 sorted into four sensitivity classes.

Therefore, by the simplify use of these factors, which were also classified to be used as material sensitivity groups. The result of this categorization is presented both for actinomycetes growth intensities and maximum actinomycetes index levels in Table 2. These data gives the values for the actinomycetes growth intensity parameter (k_1) and for the coefficient

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of the max. Actinomycetes index factors (A_{max} and k_2) and RH_{min} indicates the minimum level of relative humidity, where actinomycetes growth is possible on specific material group. All data of Tables (2 and 3) determined the best approximation based on different numerical post processing of the experimental results.

Table 3: Maximum actinomycetes growth index for different material under using steady state conditions

Material	25˚C, 97% RH	10˚C, 97% RH	25˚C, 90% RH	10˚C, 90% RH
Pine sapwood	6	5	4	3
Spruce sapwood	5	5	3	2
Fiber board	4	3	1.5	1
Gypsum	2.0	1.7	1	1
Concrete	2.5	2	0.5	0.5

All building materials tested were susceptible to actinomycetes growth in humidity higher than 90% RH at temperature above 10˚C **(Figure 2).** Actinomycetes were not found at lower humidity (below 80%) condition. Although, wood based materials needed lower critical humidity and exposure period for actinomycetes growth initiation (lag phase; A=1) and all tested material seemed to be most susceptible to biological attack or contamination.

At the varying exposure period, actinomycetes growth begin in substrate material after one, three,five,….weeks from the start of incubation period of inoculums on substrate material, depending on relative humidity and temperature. The initiation of the actinomycates growth on concrete and gypsum was observed to be slower than the pine sapwood, spruce plywood and fiber board(Figure 2). As data shown in Figure 3, based on the exposure condition in the constant condition 97% RH, 25˚C and 90% RH, 15˚C. The actinomycetes growth was restarted due to low temperature and low relative humidity. This is because, this effect was also found in the modeled data for pine sapwood, but it was best fitted in tests using 97% relative humidity at 25 ˚C. This study is based on the experimentally detected actinomycetes index values on the critical interface of wall assemblies exposure under controlled relative humidity and temperature.

The actinomycetes index values were determined for substrate material surfaces on each critical interface. Figure1 showing the relative actinomycetes decline values (C_{mat}) solved from observations in the experiments. The results include the detected mean, minimum and maximum actinomycetes index values. The retarted intensity of actinomycetes on building material surfaces favourable growth conditions could be presented as decline classes (Table 2). This classification is based on few measurements with relatively large scattering classes.

Table 5: Maximum actinomycetes indexes for different materials under different steady state conditions

Material	RH 90%, t 25˚C	RH 90%, t 15˚C	RH 97%, t 25˚C	RH 97%, t 15˚C
Pine sapwood	6	5	4	3.5
Spruce plywood	5.5	4	3	2
Fiberboard	4	2	2	3
Gypsum	3	3	2.5	1
Concrete	3.5	3	2	2

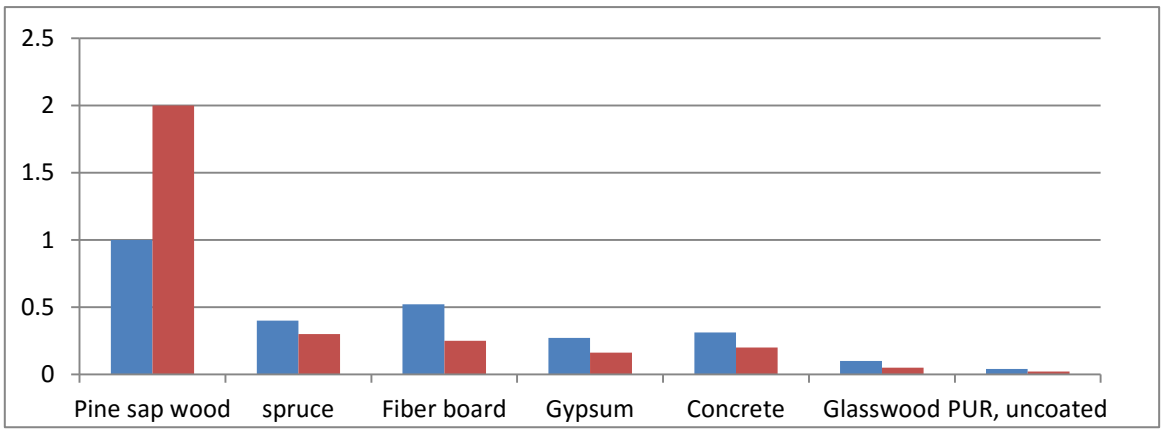

Figure 2: Actinomycetes growth factors (k_1) for different materials used in experiments.

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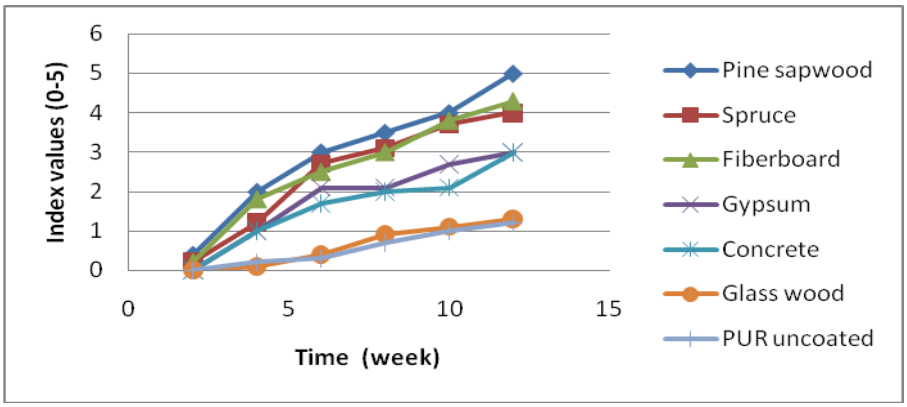
3.1 Numerically Simulation of the Updated Actinomycetes Decline parameter

This model index study is based in the experimentally detected actinomycetes index values on the critically interfaces of wall substrates being exposed to high moisture under controlled conditions. The exposure conditions had four different phases (Table 4) for actinomycetes growth. The actinomycetes growth intensity and rate of microbial consortia growth depends on the nutrition and pH level of material substrates, relative humilities and temperature [12].

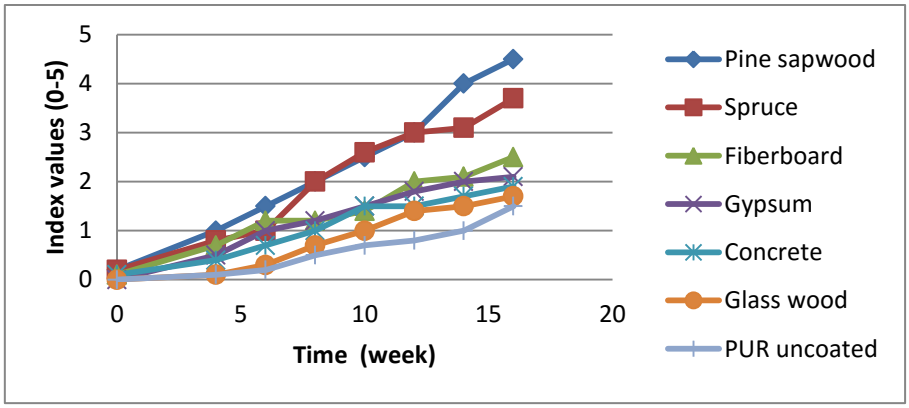
Table 4: Exposure conditions phase

Stage	Season	Time (week)	RH (%)	Temp.(˚C)
1	Summer	8	87…97	25..29
2	Winter	5	90…100	5..10
3	Spring	7	65…97	8..15
4	High Exposure	10	95…100	18..27

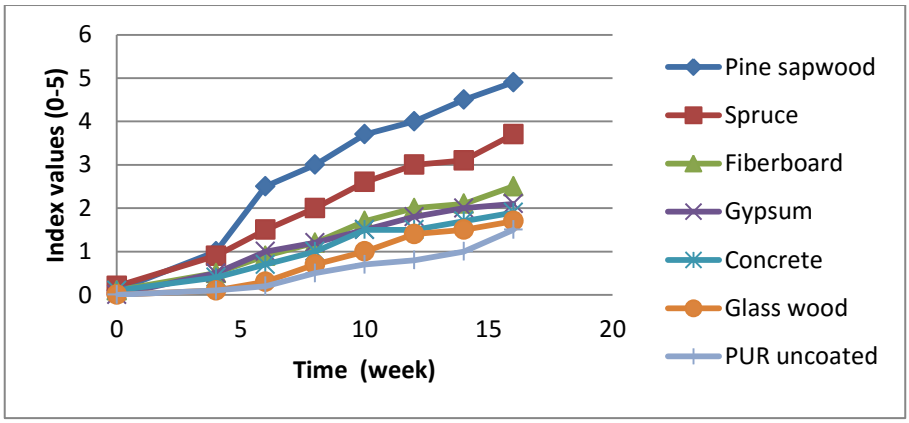
RH 97%, t 25˚C



RH 97%, t 15˚C



RH 90%, t 25˚C



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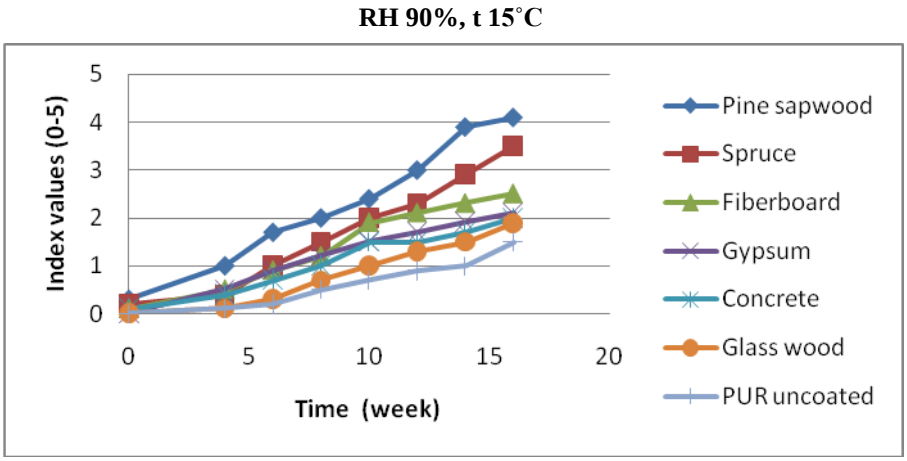

Figure 2 Numerically comparison between experimentally analyzed actinomycetes growth on different wood and other building materials and reference model (Ritschkoff *et al.*,) under monitored conditions 90%RH/25˚C, 90%RH/15˚C, 97%RH/25˚C, 90%RH/15˚C.

3.2 Comparison of Model Results against Experimental Data

The presented mathematical model for actinomycetes growth is based on measured values from steady state and dynamic experiments of building materials. The largest possible value of actinomycetes index Eq. (2) is based on 12 week experiments in constant conditions. Figure 2 shows the values calculated using Eq.(2) versus the experimental observations. All building materials tested were susceptible to actinomycetes growth in humidities higher than 90% RH at temperature in between 15 to 25˚C.

The actinomycetes growth index mathematical model is based on steady state conditions and dynamic experiments of selected building materials: spruce wood, fiber board, gypsum, concrete, glasswool, PUR with paper. Pine sapwood was used as the reference material [11]. The most critical factors for actinomycetes and microbial growth development [10] are the relative humidity, pH, temperature conditions of material surfaces, exposure period (Table 4) and types and age of building materials. Althuogh, the required critical growth conditions of actinomycetes development can start updated the different material classes (Table 2). The decay of actinomycetes growth index level occur during cold or dry period which presents the relative coefficient value (Eq.10) for the decline intensity of different building material classes.

Pure building materials have tolerance for actinomycetes microbial growth performance. The presented research contain results with both pure materials and those having organic and inorganic surfaces. Concrete is the example of a material with a higher pH level. This actinomycetes growth index model is based on mathematical relation for the growth rate of the actinomycetes in different conditions,- exposure time, temperature, relative humidity, pH of substrate material surfaces. The exposure time in constant conditions has been 16 weeks and in fluctuating conditions the period is varied in between 5 to 20 weeks. Through, this approach, the model was compared to data from reference material. The coefficient in actinomycetes growth intensity may need a unique equation to determine for each material. If the substrate materials are exposed to organic substances, the present model will fit the need to predict the actinomycetes growth risks on materials surfaces.

The mathematical model does not make any distinction between actinomycetes growth, but it represents the risk for any possible actinomycetes growth on the material surfaces. The highest growth of actinomycetes in or on building material exists where the relative humidity is about 95 to 97% , temperature 25˚C and required nutrients. However, actinomycetes growth is rapidly occur in moisture damage building materials. The lowest microbial growth occur low relative humidity level for actinomycetes growth in building materials is about 80% RH. The relative humidity of material surfaces at the time of construction is often high and the efficiency and speed of drying is fundamental prerequisites for avoiding humidity and actinomycetes and microbial consortial growth. The humidity limit for actinomycete growth on exposed surfaces is more than 88-92%RH for fibre board, gypsum, concrete and for organic material surfaces are more than78-80%RH [12].

The maximum value of actinomycetes index used in model Equation (2) has been deduced from experiments conducted in constant humidity and tempareture conditions in laboratory. But in the fluctuating humidity and temperature conditions these parameters may be low. In fluctuating conditions will certainly need more experiments or revision as the numerical data proposed by Eq.(9). The actinomycetes or growth in a dense concrete structure is a material layer containing organic material where critical humidity level exceeds 80-90%RH. But for the new and clean concrete and other required building materials, the limit of microbial growth in a dense layer exceeds 97 to 98% RH. PUR with paper and glass wool insulation can also become modeled during long term exposure to relative humidity.

However, it must be kept in mind when the performing the assessment that there is a great uncertainty coupled to this kind of analysis: variation of the material sensitivities is high, estimation of product sensitivity class is difficult without testing, the surface treatments may either enhance or reduce potential growth of actinomycetes. Generally, favourable temperature and nutrients at a given relative humidity, the less time is required for spore germination. The results are limited to new buildings or building materials and cannot be assessed in connection with moisture damage as such.

4. CONCLUSION

This mathematical model is neither based on linear function nor does it provide one exclusive limit state, which might apparently conflict with the ideal preconditions on an engineering approach. Biodegradation of buildings and building materials depending on the, dimension of component, type of decay, Temperature and relative humidity. There are several factors involved with the microbial degradation of buildings and building materials by actinomycetes and other microbial consortia. Due to this mathematical model that may help us to understand the complicated interaction of many factors. The main motive of the actinomycetes growth index model development and application is nevertheless give a tools for better prediction and evaluation of the risk for microbial consortia growth on building material surfaces and capable to find the best solutions to ensure a safe performance for buildings and building materials.

REFERENCES

[1] Adan, O.C.G. 1994. On the fungal defacement of interior finishes. PhD thesis, Eindhoven University of Technology, Eindhoven. pp. 83–185.

[2] Brischke, C. Fruhwald Hansson, E 2011. Modeling biodegradation of timber - Dose-response models for above-ground decay and its climate-dependent variability. Proceeding of the 1st International conference on structural health assessment of timber structures (SHATIS ‟11), Lisbon, Portugal, 16-17 June 2011.

[3] Clarke, J.A., C.M. Johnstone, and N.J. Kelly. 1999. A technique for the prediction of the conditions leading to mould. Building and Environment 34:515–21.

[4] Cross, T. 1982. Actinomycetes: A continuing source of new metabolites. Journal of Devlopment and Industrial Microbiology, 23: 1–18.

[5] Arya, Garima and Kaushik, P. 2013. Bio-aerosols as exposure agents in the biodegraded building indoor environment in relation to asthma and allergy. World journal of pharmacy and pharmaceutical sciences Volume 2, Issue 5, ISSN 2278 – 4357, 4005-4018.

[6] Hassan, E. G. ; Alkareem, A. M. A. ; Mustafa, A. M. I., 2008. Effect of fermentation and particle size of wheat bran on the antinutritional factors and bread quality. Pakistan J. Nutr., 7 (4): 521-526.

[7] Hukka, A., and H. Viitanen. 1999. A mathematical model of mold growth on wooden material. Wood Science and Technology 33(6):475–85.

[8] IEA-Annex 14. 1990. Condensation and energy, Source Book, Acco, Leuven.

[9] Ojanen, T., Viitanen, H., Peuhkuri, R., Lâhdesmäki, K., Vinha, J., Salminen, K. 2010. Mold growth modeling of building structures using sensitivity classes of materials, Proceedings Building XI, Florida.

[10] Ritschkoff, A.C., H. Viitanen, and K. Koskela. 2000. The response of building materials to the mould exposure at different humidity and temperature conditions. Proceedings of Healthy Buildings, Espoo, August 6–10, 1:317–22.

[11] Viitanen, H. 1996. Factors affecting the development of mould growth and brown rot decay in wooden materials and wooden structures, effect of humidity, temperature and exposure time, PhD thesis, Uppsala, The Swedish University of Agricultural Sciences, Departement of Forest Products.

[12] Viitanen, H. 2004. Betonin ja siihen liittyvien materiaalien homehtumisen kriittiset olosuhteet—Betonin homeenesto. (Development of mould on concrete). VTT Working Papers 6, p. 25 (In Finnish).

[13] Viitanen, H, and A. Ritschkoff. 1991. Mould growth in pine and spruce sapwood in relation to air humidity and temperature. Report no. 221. Uppsala, The Swedish University of Agricultural Scienses, Department of Forest Products.

[14] Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., Lähdesmäki, K. 2010. Moisture and bio-deterioration risk of building materials and structures, Journal of Building Physics, Vol. 33, No. 3.

[15] Vinha, J., K. Salminen, H. Viitanen, and T. Ojanen. 2006. Mathematical analysis of mould growth risk in building envelopes. CIB W 40 Building Science Forum 2006, September 5–6, Syracuse, USA.

[16] Williams, S. T., Goodfellow, M., Alderson, G. 1989. The Actinomycetes. Waksman and Henrici 1943, 399AL. In: Williams, S. T., Sharpe, M. E., Holt, J. G. (Eds) Bergey's Manual of Systematic Bacteriology, Williams and Wilkins, Baltimore, 4: 2452-2492.