An Evaluation of WUFI-Bio to Predict Mold Growth in Straw Bale Walls in Japan

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Abstract

The greatest challenges facing straw bale building in Japan, and many other countries with high humidity and precipitation, are moisture and the susceptibility of straw to microbial decay. WUFI-Bio, developed by the Fraunhofer Institute for Building Physics, is a computer program that assesses the risk of mold growth in buildings based on measured or computed climatic conditions. Researchers in Japan have monitored the hygrothermal conditions of six straw bale buildings in Japan and evaluated the risk of mold growth based on an interstitial temperature and relative humidity guideline. The purpose of the present study is: (one) reevaluate the potential for mold growth in the six buildings using WUFI-Bio and (two) evaluate the accuracy of Holzhueter and Itonaga's interstitial temperature and relativity guideline vis-à-vis WUFI-Bio. As a result of the study, the potential for mold growth was found to vary by structure. Buildings utilizing rainscreens were found to have a lower risk of mold growth. Holzhueter and Itonaga's interstitial temperature and relativity guideline was found to over exaggerate the potential for mold growth. Also, although Holzhueter's guideline does indicate a potential for mold growth, the number of hours above the guideline alone is not a sufficiently accurate indication of severity.

Keywords: straw bale building; WUFI-Bio computer program; hygrothermal environment; mold growth; interstitial temperature and moisture

1. Introduction

Straw bales are blocks of compressed straw. In straw bale construction, bales are stacked to create bearing or infill walls.

Straw bale building has numerous ecological advantages. Straw bales are low in embodied energy (Centre for Building Performance Research, 2010). Since straw consists of approximately 36% carbon, straw bale walls function as a carbon sink, sequestering carbon during the life of the building (Wihan, 2007). Straw bale walls are also highly insulative, reducing energy use and CO_2 emissions due to heating and cooling (Bigland-Pritchard, 2005). And lastly, upon deconstruction, straw bales can safely decompose without becoming landfill.

Straw bale building is relatively new to Japan. According to the Japan Straw Bale House Association (2009), the first straw bale home in Japan was completed in 2001 in Tochigi Prefecture. The greatest challenges facing straw bale buildings in Japan, and many other countries with high humidity and precipitation, are moisture and the susceptibility of straw to microbial decay.

However, controlling moisture to reduce microbial decay and improve building durability is an issue common to conventional construction and particularly buildings utilizing organic insulations such as straw, rice hulls, etc. (Lee *et al.*, 2013).

Holzhueter and Itonaga of Nihon University (2015) have monitored the indoor, outdoor and interstitial hygrothermal environment of six straw bale buildings in Japan. The potential for interstitial mold growth was evaluated given a temperature and relative humidity guideline. Holzhueter (2011) found hygrothermal conditions of 80% relative humidity and 10ºC to be a safe guideline for straw bale walls. Above 80% relative humidity and 10ºC, mold growth was predicted. At and below 80% relative humidity and 10ºC, some biological activity may be present, but was not believed to impact the life of the building.

Given this guideline, Holzhueter and Itonaga (2015) found that rainscreens were an effective means to control interstitial moisture. That is, buildings utilizing rain screens were found to have lower interstitial relative humidity and a lower risk of mold growth.

Klaus Sedlbauer (2001) of the Fraunhofer Institute for Building Physics developed a bio-hygrothermal procedure for evaluating the potential of mold growth based on three prerequisites: temperature, relative

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humidity, and substrate. Based on these variables, the boundary conditions (Isopleths) of spore germination and mold growth were identified. Sedlbauer reviewed over 250 sources regarding mold development and synthesized the data creating isopleths which represent mold development on various building materials. Sedlbauer's predictive model corresponded well with the literature review of experimental results and case studies.

Led by Sedlbauer, the Fraunhofer Institute for Building Physics developed WUFI-Bio, a transient prognosis model to assess the risk of mold growth on and in building components.

Using WUFI-Bio, the present study evaluates the potential for mold growth in the same six straw bale buildings investigated by Holzhueter and Itonaga in 2015.

The purpose of the present study is to (one) reevaluate the potential for mold growth in the six buildings using WUFI-Bio and (two) evaluate the accuracy of Holzhueter's interstitial temperature and relativity guideline vis-à-vis WUFI-Bio. By doing so, the authors hope to show the potential to use WUFI-Bio in future studies examining the potential for mold growth in straw bale walls.

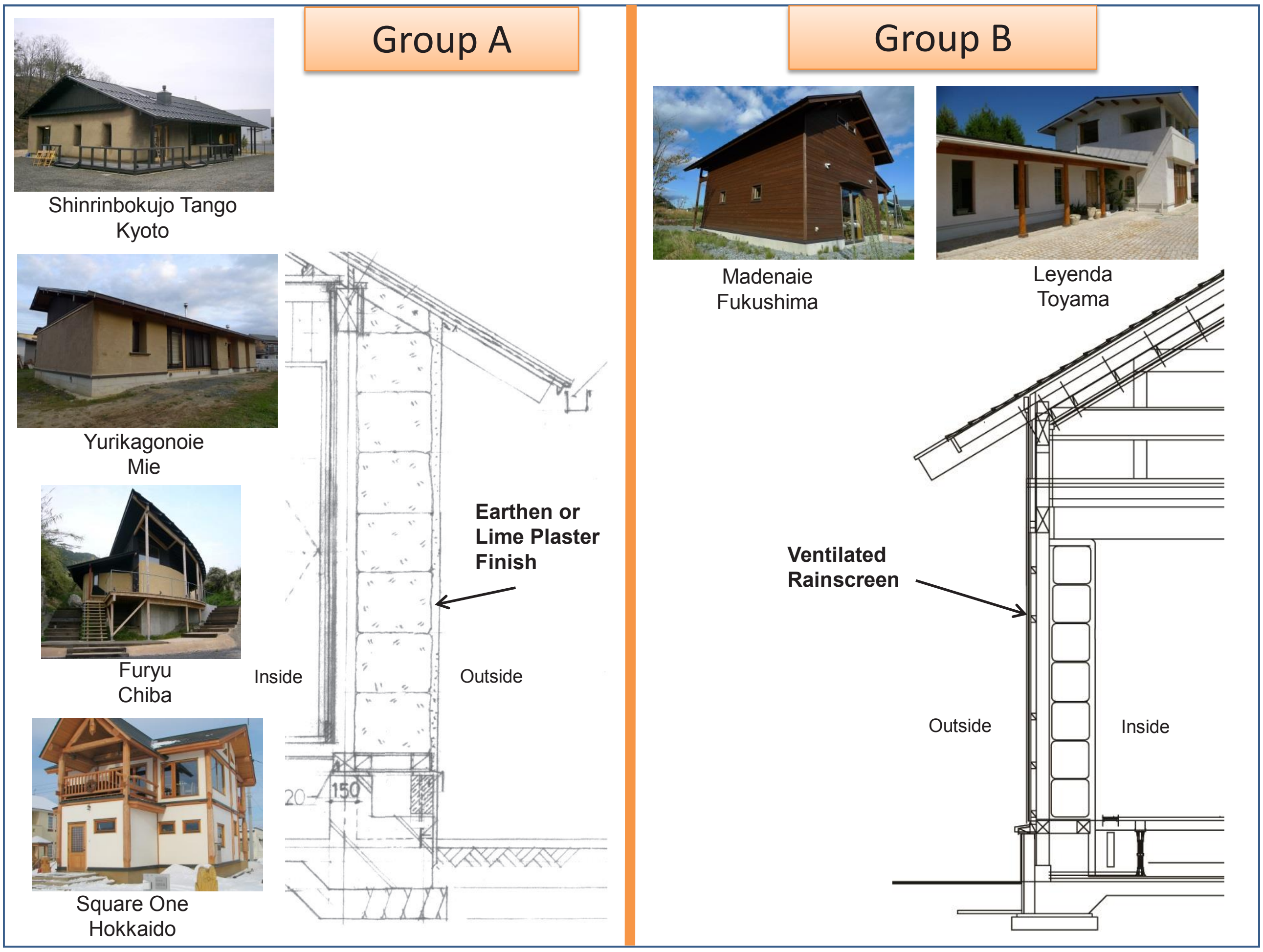

Fig.1. Six Straw Bale Buildings Divided into Two Groups

Table 1. Details of Each Building

Group	Building Name	Prefecture	City	Architect	Principle Builder of Straw Bale Walls	Construction		One Year Observation Period	
						Start	Finish	Start	Finish
A	Shinrinnobokujo Tango	Kyoto	Kyotango	Goichi Oiwa	Takao Kobayashi	Oct-07	Jun-08	Sep-08	Aug-09
	Furyu	Chiba	Minamiboso	Goichi Oiwa	Takao Kobayashi	Mar-08	Nov-08	Feb-09	Jan-10
	Yurikagonoie	Mie	Tsu	Masatoshi Sakamoto	Hideto Oshima	Feb-09	Jul-09	Jul-10	Jun-11
	Square One	Hokkaido	Asahikawa	Mikio and Masami Sakai	Stefan Bell	May-09	Jun-10	Nov-11	Oct-12
B	Madenaie	Fukushima	Itate	Yoshiyuki Toyoto	Kyle Holzhueter, Koji Itonaga	Nov-09	Mar-10	Dec-11	Nov-12
	Leyenda	Toyama	Toyama	Shoko Yoshimoto	Hiroaki Yoshimoto, Kyle Holzhueter	Aug-10	Sep-11	Apr-12	Mar-13

2. Materials and Methods

2.1 Monitoring the Hygrothermal Environment

The indoor, outdoor and interstitial hygrothermal environment of six straw bale structures in Japan have been monitored. These six straw bale buildings are organized into two groups according to construction details (Fig.1., Table 1.). The first Group A includes buildings consisting of straw bale walls with an earthen or lime plastered exterior finish applied directly to the bale walls. The second Group B includes buildings consisting of straw bale walls utilizing ventilated rain screens. Further details regarding the buildings can be found in Holzhueter and Itonaga, 2015.

T and D Corporation's Thermo Recorder sensors monitor the indoor, outdoor and interstitial hygrothermal conditions of the six straw bale structures. These sensors measure temperature and relative humidity, and data is recorded at one-hour intervals by data loggers.

In Group A buildings, a "stack" of nine interstitial sensors have been installed at various heights and depths perpendicular to the plane of the wall in each building (Fig.2.). Each interstitial sensor is given a name consisting of multiple letters. The first letter designates the height: "L" stands for low, "M" for middle, and "H" for high. The second letter describes the sensors depth: "I" stands for interior, "N" for interstitial and "E" for exterior.

In Group B buildings, a "stack" of six interstitial sensors have been installed at various heights and depths perpendicular to the plane of the wall. The nomenclature of the sensors follows Group A. Due to funding limitations, interstitial sensors were not installed. Previous research by Holzhueter and Itonaga (2010, 2014, and 2015) and the results of the present study suggest that a thorough investigation of the interstitial hygrothermal environment is possible with the sensor arrangement of Group B.

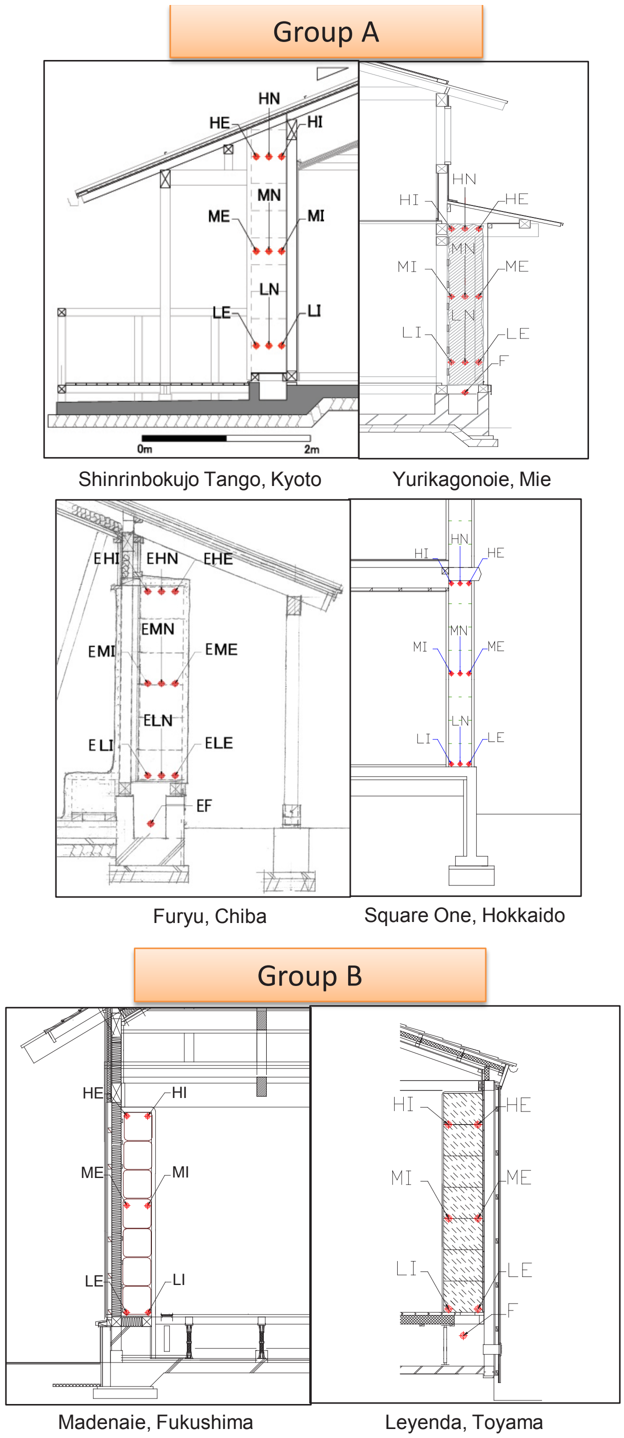

Fig.2. Wall Section and Sensor Locations for Each Building

2.2 Predicting Mold Growth

Holzhueter (2011) found that hygrothermal conditions of 80% relative humidity and 10ºC are understood to be a safe guideline for straw bale walls. Above 80% relative humidity and 10ºC, mold growth is predicted. At and below 80% relative humidity and 10ºC, some biological activity may be present, but is not believed to impact the life of the building.

WUFI-Bio uses three parameters, temperature, relative humidity and substrate, to evaluate the potential for mold growth. In addition to relying on temperature and relative humidity, WUFI-Bio takes into consideration the influence of the substrate (and the probability of contamination) on the formation of mold. Based on research by Sedlbauer (2001), WUFI-Bio divides substrates into four categories:

(0) Optimal culture medium.
(I) Biodegradable building materials such as wallpaper, wood, etc.
(II) Building materials with a porous structure such as plaster, mineral building materials, insulation, and some species of wood not covered by I or possible contamination by mold fungus.
(III) Building materials that are neither degradable nor contain any nutrients.

Assuming a worst-case scenario, for purposes of this study, straw bales are assumed to be in the substrate category (I).

Based on a review of the literature, Sedlbauer developed an isopleth model for each substrate category. For a given substrate, isopleths are three-dimensional diagrams using temperature, relative humidity, and time as variables to depict iso-lines that indicate spore germination time or growth per time unit. Isopleths visually depict the hygrothermal prerequisites for fungal growth and germination on a specific substrate. The isopleth for spore germination and mycelium growth on substrate category I are seen in Fig.3.

In Fig.3., LIM stands for Lowest Isopleth for Mold, and represents the limit of fungal activity below which spore germination and mycelium growth is excluded. For spore germination (left), the other lines represent the hygrothermal conditions and time needed for spore germination. And for mycelium growth (right), the other lines represent the hygrothermal conditions and rate of mycelium growth in mm/day.

Given a specific substrate category and temperature and relative humidity data over a one-year period, WUFI-Bio calculates the mold growth rate (Fig.4.). Fig.4. is the results of Shinrinnobokujo Kyotango's LI sensor. According to WUFI-Bio, the straw in the location of the LI sensor is calculated to have a mold growth rate of 110 mm/year.

WUFI-Bio classifies mold growth rates into three categories:

Green Light - Mold growth is below 50 mm/year, which is usually acceptable.

Yellow Light - Mold growth is between 50 mm/year and 200 mm/year. Additional criteria or investigations are needed for assessing acceptability.

Red Light - Mold growth exceeds 200 mm/year, which is usually not acceptable.

The signal light presents a general assessment of the mold growth risk and the severity of the infestation.

With a mold growth rate of 110 mm/year, Shinrinnobokujo Tango was given a yellow signal

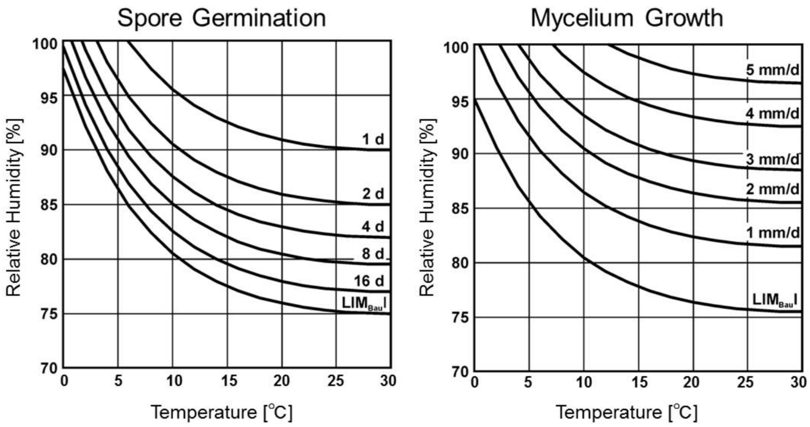

Fig.3. Generalized Isopleth System for Spore Germination (Left) and Mycelium Growth (Right) Valid for All Fungi of Substrate Category I (Sedlbauer, 2001)

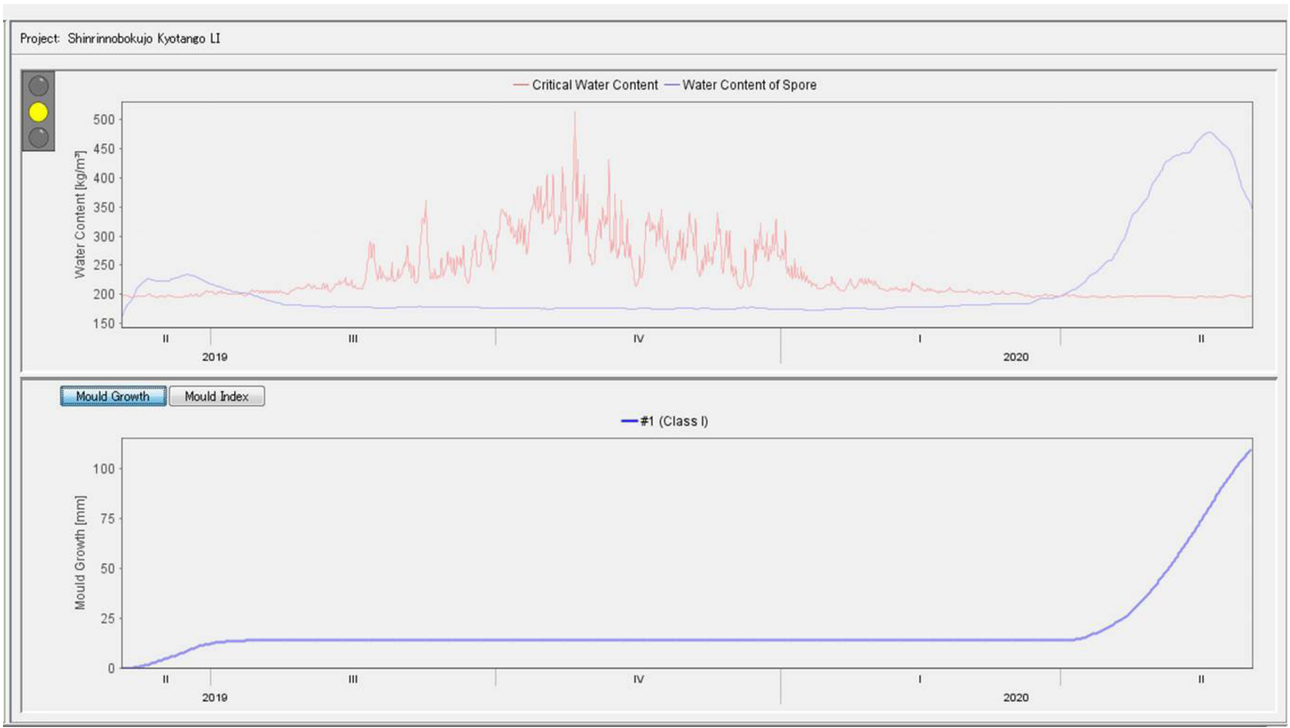

Fig.4. WUFI-Bio Results for Shinrinnobokujo Tango's LI Sensor Location

light. That is, additional criteria or investigations are needed for assessing acceptability.

2.3 Comparing Holzhueter's Guideline and WUFI-Bio

Holzhueter and Itonaga (2015) never confirmed the presence of mold in the six buildings they monitored. Practical limitations prohibit the opening up of walls and extraction of straw from the walls of private homes. On the other hand, Sedlbauer's predictive model corresponded well with the literature review of experimental results and case studies.

The results of Holzhueter and Itonaga's 2015 study are compared to the results of using WUFI-Bio to evaluate the same data.

Table 2. Results of the Study Using Holzhueter's Guideline and WUFI-Bio

Group	Building	One Year Observation Period	Sensor Location	Interstitial Hours Surpassing Guideline	Mold Growth Rate (mm/year)	WUFI-Bio Signal Light
A	Shinrinnobokujo Tango	2008/09-2009/08	LI	1705	110.00	Yellow
			LN	15	6.29	Green
			LE	0	0.00	Green
			MI	169	13.80	Green
			MN	0	0.00	Green
			ME	33	0.00	Green
			HI	34	2.46	Green
			HN	50	1.47	Green
			HE	303	6.07	Green
	Furyu	2009/02-2010/01	LI	2682	264.00	Red
			LN	2849	296.00	Red
			LE	2730	284.00	Red
			MI	1093	65.40	Yellow
			MN	1165	69.10	Yellow
			ME	1227	75.10	Yellow
			HI	961	54.60	Yellow
			HN	1512	104.00	Yellow
			HE	1387	91.40	Yellow
	Yurikagonoie	2010/07-2011/06	LI	105	12.70	Green
			LN	0	0.00	Green
			LE	6	0.00	Green
			MI	0	0.00	Green
			MN	0	0.00	Green
			ME	0	0.00	Green
			HI	0	0.00	Green
			HN	0	0.00	Green
			HE	0	0.00	Green
	Square One	2011/11-2012/10	LI	0	0.00	Green
			LN	0	0.00	Green
			LE	0	0.00	Green
			MI	0	0.00	Green
			MN	0	0.00	Green
			ME	4177	428.00	Red
			HI	0	0.00	Green
			HN	0	0.00	Green
			HE	1158	339.00	Red
B	Madeinaie	2011/12-2012/11	LI	0	0.00	Green
			LE	0	0.00	Green
			MI	0	0.00	Green
			ME	0	0.00	Green
			HI	0	0.00	Green
			HE	0	0.00	Green
	Leyenda	2012/04-2013/03	LI	0	0.00	Green
			LE	4	0.00	Green
			MI	0	0.00	Green
			ME	0	0.00	Green
			HI	0	0.00	Green
			HE	0	0.00	Green

3. Results and Discussion

Table 2. summarizes the results of the monitoring. Of the six buildings monitored, the interstitial hygrothermal environment of five buildings surpassed the 80% relative humidity and 10ºC guideline.

20 sensors surpassed Holzhueter's guideline, ranging from 4 hours to 4,177 hours. According to WUFI-Bio, sensor locations surpassing the guideline for 303 hours were found to be acceptable. 961 to 1,705 hours above the guideline was found to be uncertain with additional criteria or investigations needed for assessing acceptability. More than 1,158 hours above the guideline was found to be unacceptable.

Shinrinnobokujo's LI sensor surpassed the guideline for 1,705 hours, and was given a yellow signal light by WUFI-Bio. Square One's HE sensor surpassed the guideline for 1,158 hours and was given a red signal light by WUFI-Bio. The results show that although Holzhueter's guideline does indicate the potential for mold growth, the number of hours above the guideline alone is not a sufficiently accurate indication of mold growth.

According to WUFI-Bio, even sensor locations surpassing the guideline for 303 hours were found to be acceptable. This suggests that Holzhueter's guideline over exaggerates the potential for mold growth.

A discussion of building details and hygrothermal performance can be found in Holzhueter and Itonaga, 2015, 2014, and 2010.

4. Conclusion

The hygrothermal conditions of six straw bale structures in Japan were monitored. The purpose of the present study was to (one) reevaluate the potential for mold growth in the six buildings using WUFI-Bio and (two) evaluate the accuracy of Holzhueter's interstitial temperature and relativity guideline vis-à-vis WUFI-Bio. (1) The potential for mold growth was found to vary by structure. Buildings utilizing rainscreens were found to have a lower risk of mold growth. (2) The results show that although Holzhueter's guideline does indicate the potential for mold growth, the number of hours above the guideline alone is not a sufficiently accurate indication of mold growth. Also, the results suggest that Holzhueter's guideline over exaggerates the potential for mold growth.

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