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Original Article

Analysis of Hygrothermal Performance of Wood Frame Walls according to Position of Insulation and Climate Conditions[1]

Yujin Kang[2] · Seong Jin Chang[2] · Sumin Kim[2,†]

ABSTRACT

The insulation of a building envelope influences the hygrothermal performance as well as the thermal performance of the building. While most of Korean wood frame houses have an interior insulation system, the exterior insulation system with high thermal performance has recently been applied. While it can be effective in energy savings for better insulation performance, without consideration of the moisture, condensation and mould growth can occur. Therefore, in this study, hygrothermal behaviour, water content, and mould growth were analyzed using hygrothermal simulation of an exterior wall of a wood frame house with which the interior insulation and exterior insulation systems were applied. The wall layer included Wall A (Interior insulation) and Wall B (Exterior insulation). The U-values were identified as 0.173 and 0.157 W/m^{2}K, respectively. The total water content and OSB absolute water content of Wall A were confirmed to be higher than those of Wall B, but the absolute water content did not exceed the reference value of 20%. The moisture content of the two walls was determined to be stable in the selected areas. However, mould growth risk analysis confirmed that both Wall A and Wall B were at risk of mould growth. It was confirmed that as the indoor setting temperature decreased, the mould index and growth rate in the same area increased. Therefore, the mould growth risk was affected more by indoor and outdoor climate conditions than by the position of the insulation. Consequently, the thermal performance of Wall B was superior to that of Wall A but the hygrothermal performances were confirmed to be similar.

Keywords : hygrothermal performance, wood frame walls, WUFI simulation, climate conditions, position of insulation

1. INTRODUCTION

The world's CO_2 emissions have increased by about 40% since the mid-1800s, with an average increase of 2 ppm a year during the last ten-year period (IEA, 2015). International environmental issues, such as global warming and climate change, have been caused by the continued increase in greenhouse gas exhaustion. Accordingly, the Climate Change Convention assumed the responsibility of reducing of greenhouse gases in both leading and developing

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[2] Building Environment and Materials Lab, School of Architecture, Soongsil University, Seoul 06978, Korea

[†] Corresponding author: Sumin Kim (e-mail: skim@ssu.ac.kr)

countries. In each country, this has been managed by presenting greenhouse gas reduction targets. In the case of Korea, a 26.9% reduction of emissions in the building sector has been set as a target by 2020. In addition, it make mandatory that the Passive house level from 2017 and the Zero-energy house level from 2025 for reduction of the main cause energy use of greenhouse gas emissions (Kwon, 2012).

In Korea, the demand for detached houses has increased with the changing culture and its focus on indoor comfort. wood framed construction is actively being applied as a form of passive house construction because their construction processes and techniques are simple and economical. In addition, the level of CO_2 emissions occurring in the construction, operation, and process is low in wood frame house. In addition, the excellent insulation and humidity control performances of wood are beneficial for the occupants. Indeed, wood frame houses have been spotlighted as green buildings (Kim *et al*., 2013; Winistorfer *et al*., 2005). Research in wood frame houses has recently been carried out to improve the heat insulation property. Especially, the envelope performance of residential buildings has a significant effect on the energy consumption and comfort level because the envelope comprises a relatively large proportion of the heating load due to the lower internal heat generation (Yu *et al*., 2013). The interior insulation system is usually applied to domestic detached houses. However, common issues with the interior insulation system are the discontinuity of insulation and the occurrence of thermal bridges. On the other hand, in the case of the exterior insulation system, continuous insulation can be installed to block the thermal bridges, thus reducing the building energy consumption.

The building envelope performance is an important factor in moisture behavior as well as thermal behavior. Indoor temperature and humidity not only influence surface condensation, mould growth, and the occupant's health such as allergies, skin disease, and respiratory disease but also structural problems such as heat and moisture behavior inside the structure (Fedorik *et al*., 2015; Richardson *et al*., 2005; Mudarri and Fisk, 2007). Therefore, in this paper, a simulation was used to analyze the hygrothermal performance of the wall according to the position of internal and external insulation in wood frame houses. Also, the simulations of the inside and outside climatic conditions were carried out differently with consideration for the different climatic conditions that occur depending on the national geography. In addition, we analyzed the water content and mould growth risk of the wall.

2. SIMULATION and VARIABLE CONDITIONS

2.1. Simulation program

This study used the WUFI Pro 5.3 and WUFI Bio simulation programs developed by Fraunhofer IBP (Institute in Building Physics) for hygrothermal performance analysis of walls by variable conditions. WUFI simulation models are heat and mass transfer models used for evaluating the extensive heat and moisture distribution of building materials and climatic conditions. The program was composed of a one-dimensional cross-section of buildings. It calculates hygrothermal behavior with consideration of moisture, rainfall, solar radiation, longwave radiation, capillarity, and condensation, and evaluates the hygrothermal performance of a component according to the setting conditions (Budaiwi and Abdou, 2013). In addition, the effectiveness of the program was verified through comparison analysis between simulation result and outdoor testing under natural climatic conditions (Kuenzel and Holm, 1999).

2.2. Wall layer composition of wood frame houses

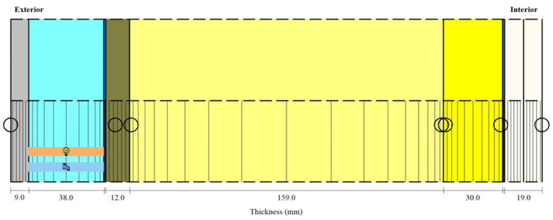
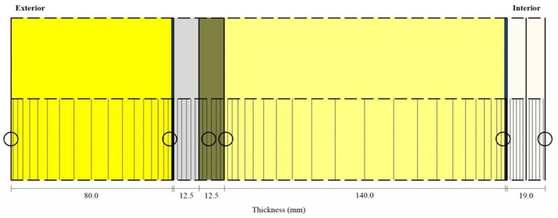
In this study, the envelopes insulation system for a detached house was selected for the interior insulation and exterior insulation. The interior insulation system of Wall A was selected from a residential construction standard established by the Korea Rural Community Corporation, while the exterior insulation system of Wall B was sourced from the plan of the Exterior Insulation Finishing System (EIFS) by reviewing the existing study (Pasztory *et al.*, 2012). The compositions of the two types of wall layers and thermal properties are shown in Table 1. The material properties were set to be the same for the comparison of the hygrothermal performance of the two wall type. The total thickness and U-value of Wall A were confirmed to be 0.267 m and 0.173 W/m^{2}K respectively, and those of Wall B were 0.264 m and 0.157 W/m^{2}K, respectively.

2.3. Climatic and simulation conditions

Indoor climatic conditions were based on EN 13788. The indoor moisture load profile was set to Humidity Class 3 for the case where the average relative humidity reaches 50% when the indoor temperature is at 25℃ in the Seoul climate. The indoor setting temperature was applied to increase in 1℃ increments, from the winter optimal temperature of 18℃ to the summer optimal temperature of 26℃ depending on energy saving standards.

Outdoor climatic conditions used were the modified Meteo norm 7.2 climate data applicable to the WUFI simulation by Passive House Institute Korea (phiko) and Institute for Passive Zero energy Building (IPAZEB). This climate data included hourly dry bulb temperature, solar radiation, humidity, wind speed and direction, and rainfall for one year. Table 2 shows the selected areas. The areas were selected by dividing into a central district, southern district, and Jeju; Icheon (Area a), Namwon (Area b), and Seogwipo (Area c). In addition, the Tabeak (Area d), located in the highland area of the Taebaek Mountains, was selected to confirm the effects of high-level climate. The four selected areas of this paper excluded an urbanized area because the simulation targets the detached

Table 1. Assembly and thermal properties of Wall A and Wall B

<table>
<tr><th colspan="5">Wall A</th><th colspan="5">Wall B</th></tr>
<tr><td colspan="5">
</td><td colspan="5">
</td></tr>
<tr><th>Material</th><th>Thickness (mm)</th><th>Thermal conductivity (W/mK)</th><th>Heat capacity (J/kgK)</th><th>U-value (W/m^{2}K)</th><th>Material</th><th>Thickness (mm)</th><th>Thermal conductivity (W/mK)</th><th>Heat capacity (J/kgK)</th><th>U-value (W/m^{2}K)</th></tr>
<tr><td>Cement board</td><td>9</td><td>0.255</td><td>840.0</td><td rowspan="9">0.173</td><td rowspan="2">EPS</td><td rowspan="2">80</td><td rowspan="2">0.04</td><td rowspan="2">1500.0</td><td rowspan="9">0.157</td></tr>
<tr><td>Air layer</td><td>38</td><td>0.23</td><td>1000.0</td></tr>
<tr><td>Weather resistive barrier (sd = 0.1 m)</td><td>0.1</td><td>2.3</td><td>2300.0</td><td>Weather resistive barrier (sd = 0.1 m)</td><td>0.1</td><td>2.3</td><td>2300.0</td></tr>
<tr><td rowspan="2">OSB</td><td rowspan="2">12</td><td rowspan="2">0.13</td><td rowspan="2">1500.0</td><td>Interior gypsum board</td><td>12.5</td><td>0.16</td><td>870.0</td></tr>
<tr><td>OSB</td><td>12.5</td><td>0.13</td><td>1500.0</td></tr>
<tr><td>Fiber glass</td><td>159</td><td>0.035</td><td>840.0</td><td rowspan="2">Fiber glass</td><td rowspan="2">140</td><td rowspan="2">0.035</td><td rowspan="2">840.0</td></tr>
<tr><td>EPS</td><td>30</td><td>0.04</td><td>1500.0</td></tr>
<tr><td>Vapour retarder (sd = 100 m)</td><td>0.1</td><td>2.3</td><td>2300.0</td><td>Vapour retarder (sd = 100m)</td><td>0.1</td><td>2.3</td><td>2300.0</td></tr>
<tr><td>Gypsum board</td><td>19</td><td>0.2</td><td>850.0</td><td>Gypsum board</td><td>19</td><td>0.2</td><td>850.0</td></tr>
</table>

* Wall A : Rural houses standard plan ’14
* Wall B : EIFS

house. The average temperature and relative humidity increased from Area a to Area c due to latitude. While Area d has a lower latitude than Area a, the temperature and relative humidity are lower due to the highland characteristic.

Also, we set the value of the surface heat transfer coefficient according to the existing domestic law (energy saving design standards of the buildings) for carrying out the simulation according to the domestic conditions. The exterior surface heat transfer coefficient (R_o) is 0.043 m^{2}K/W, and the interior surface heat transfer coefficient (R_i) is 0.11 m^{2}K/W. The surface radiation properties used the WUFI database depending on the exterior surface material of the selected wall layer. Simulation was set to three years for evaluating to long-term hygrothermal performance.

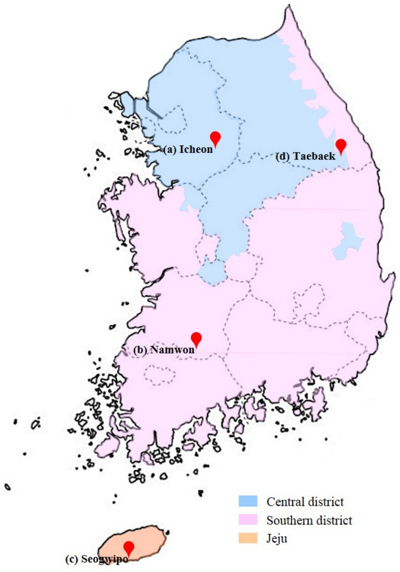
3. ASSESSMENT and ANALYSIS

3.1. Water content

The hygrothermal behavior of the composed

Table 2. Location of selected regions

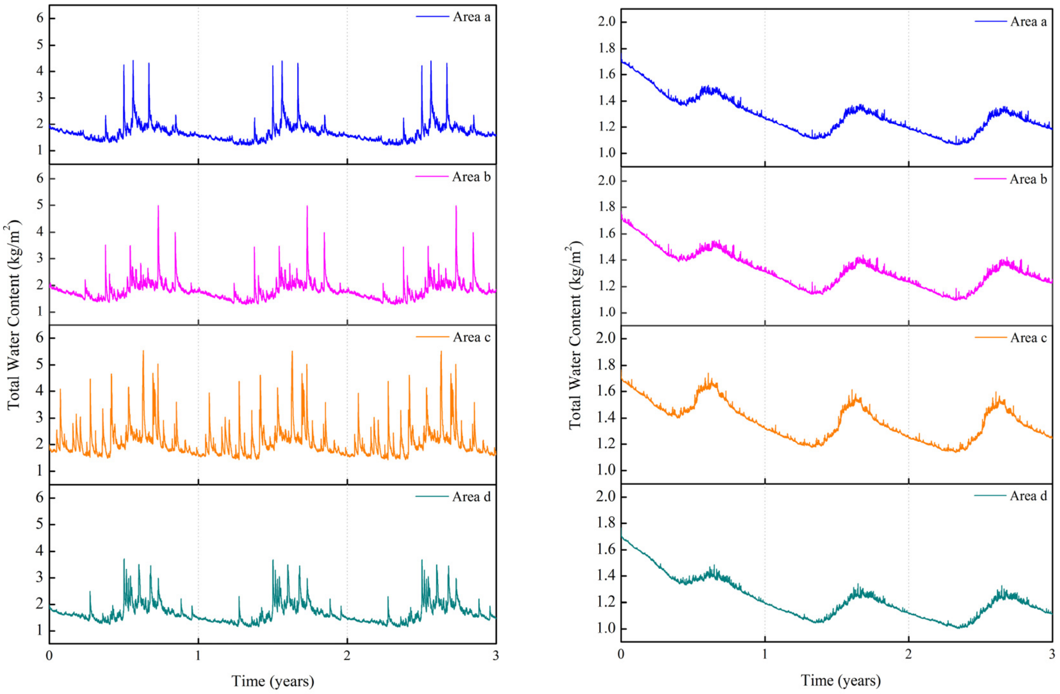
Location



	Area	Longitude (°)	Latitude (°)	Altitude (m)
a	Icheon	127.48 E	37.25 N	92
b	Namwon	127.32 E	35.40 N	91
c	Seogwipo	126.55 E	33.23 N	0
d	Taebaek	128.98 E	37.17 N	734

wall layer is confirmed using the WUFI simulation, and the water content can be quantitatively analyzed. The results of simulation, showing the change of total water content for three years in the four areas is shown in Fig. 1 when the indoor setting temperature was 25℃. Figs. 1(a) and 1(b) show the total water content of Wall A and Wall B, respectively. The graphs show a tendency for the total water content to increase in summer and decrease in winter. Also, the change of total water content was decreased and was maintained from the second year. In the total water content graphs of Wall A and Wall B, the value of the water content increased when the latitude is lower. Area d has the lowest value in all cases.

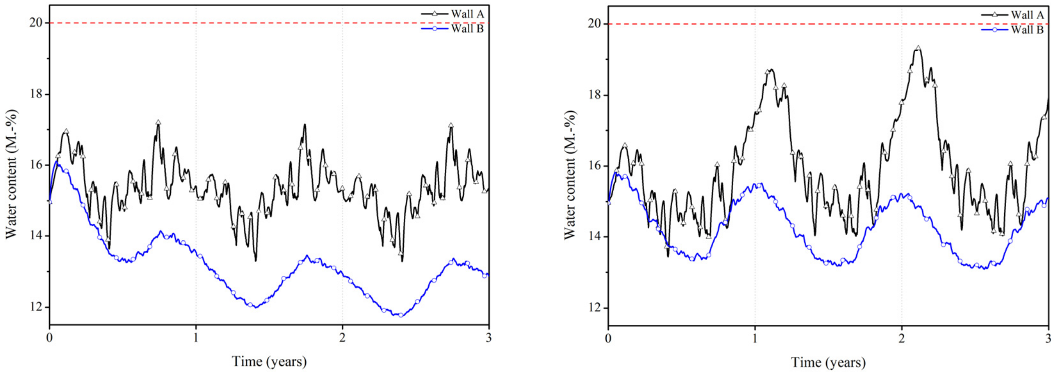
The numerical values of the total water content is not meaningful. However, the moisture behavior was determined to be in a dynamic steady state if the graphs of the total water content did not show an increase, and have a tendency to remain unchanged or decrease for the measurement periods. When in the dynamic steady state, the absolute water content of the materials of each layer can be analyzed. Otherwise, the layers need to be reconstituted because problems can occur such as decomposition, corrosion, mould, frost, and heat loss. The absolute water content refers to the water content compared to the bulk density of the material (M. -%), which should not exceed 20% in the case of wood based materials. A high water content for wood based materials can cause corrosion and mould growth, and can reduce the insulation efficiency because the moisture is transferred in closed insulation. The total water content of both wall layers moves to a dynamic steady state for the measurement periods, so we analyzed to the absolute water content of OSB (Oriented Strand Board) as the wood based materials. Fig. 2 shows the absolute water content in OSB when the indoor setting temperatures in Area c are 18℃ and 25℃, the highest values in the total water content assessment. The water content value of Wall A was higher than that of Wall B as can be seen in the results of the total water content. However, the absolute water content in the



(a) Wall A

(b) Wall B

Fig. 1. Total water content of (a) Wall A and (b) Wall B in Areas a, b, c, and d.



(a) 18℃

(b) 25℃

Fig. 2. Absolute water content of OSB layer according to indoor setting temperatures of 18℃ and 25℃.

OSB layer of both walls did not exceed the standard 20%. The indoor setting temperature decreased, the numerical value of the water content increased, but did not exceed 20% at 18℃. Therefore, it was determined that for Wall A and Wall B, the problems occurred due

Table 3. Mould index level (Ojanen and Airaksinen, 2015)

Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or, < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10-50% coverage, or, > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

to the increased water content of wall layer in the four areas.

3.2. Analysis of mould growth risk

In this study, the mould index and mould growth of Wall A and Wall B were evaluated using the WUFI Bio program for the mould growth risk of the interior surface according to the regional climate and indoor setting temperature. The mould index indicated 0 to 6, calculated according to the temperature, humidity, time, and substrate, as shown in Table 3 (Ojanen and Airaksinen, 2015). The interior surfaces of Wall A and Wall B are composed of gypsum board and wallpaper, so the substrate condition of the simulation was set as Class I.

When the mould growth rate exceeds 200 mm/year which corresponds to a mould index of 2, the mould value is not usually acceptable. If the mould growth rate is between 50 mm/year and 200 mm/year, the mould is considered to have a necessary values for assessing acceptability. Table 4 shows the mould index and growth rate, appearing on the interior surface of Wall A and Wall B, according to all indoor and outdoor climatic conditions. The mould growth risk levels are marked in red. At the lower indoor setting temperature, the mould growth rate increased. The risk of mould growth increases at an indoor setting temperature below 21℃, except in Area d. In addition, it was confirmed that the standard temperature of mould growth risk increased in Area a and Area c. Because the outdoor relative humidity is higher toward Area c, the water content of the wall increased. Consequently, the mould growth rate increased despite having the same temperature and substrate as that of Area a because the humidity of the indoor wall surface increased. We also determined that the position of insulation did not affect the risk of mould growth, since the mould index and growth rate of both wall layers appear to be similar at the same indoor and outdoor climatic conditions.

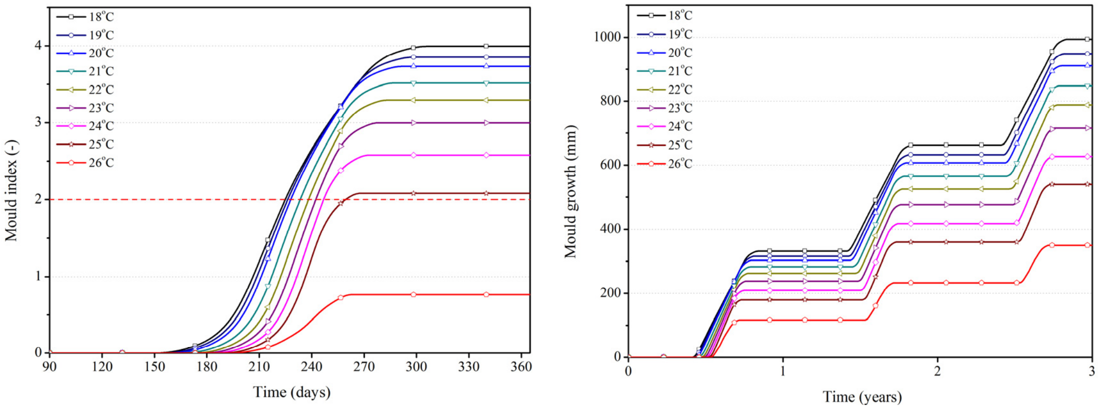
The mould index and mould growth of Wall A in Area c, which has a high mould risk level, are shown in Fig. 3, in order to compare the mould index with the indoor setting temperature. Fig. 3(a) shows the mould index,

Table 4. Mould index and mould growth rate

Wall	Indoor setting temperature (℃)	Area a		Area b		Area c		Area d	
		Index (-)	Growth rate (mm/year)	Index (-)	Growth rate (mm/year)	Index (-)	Growth rate (mm/year)	Index (-)	Growth rate (mm/year)
A	18	3.31	264	3.55	286	3.99	331	2.42	199
	19	3.11	247	3.35	268	3.85	316	1.67	159
	20	2.88	230	3.15	250	3.73	304	0.388	90.2
	21	2.49	203	2.93	233	3.52	283	0.060	29.5
	22	1.91	171	2.51	205	3.23	263	0.002	0.996
	23	0.63	108	1.91	171	3.00	239	0	0
	24	0.101	43.1	0.39	90.4	2.58	209	0	0
	25	0.011	6.46	0.065	31.2	2.08	180	0	0
	26	0	0	0.001	0.676	0.764	117	0	0
B	18	3.31	264	3.55	286	4.00	332	2.40	198
	19	3.11	246	3.34	267	3.85	316	1.65	158
	20	2.88	229	3.14	250	3.73	303	0.380	89.3
	21	2.49	202	2.91	232	3.51	282	0.058	28.8
	22	1.91	171	2.50	204	3.29	262	0.001	0.833
	23	0.615	108	1.89	170	2.98	238	0	0
	24	0.099	42.5	0.382	89.5	2.57	208	0	0
	25	0.010	6.14	0.063	30.5	2.06	179	0	0
	26	0	0	0.001	0.552	0.744	115	0	0

🟥 : Mould growth exceeds 200 mm/year

🟨 : Mould growth exceeds 50 mm/year



(a) Mould index (b) Mould growth

Fig. 3. Mould index and mould growth on Wall A according to the indoor setting temperatures of 18 to 26℃ in Area c.

and Fig. 3(b) shows the mould growth that occurs during the measurement for three years. It was confirmed that as the indoor setting temperature is reduced, the mould index and mould growth increased. If the indoor setting temperature is set to below 25℃, the mould index was 2 and over. It was confirmed that when the temperature is 18℃, the mould index was 4. If the mould index is 4, then a 10% - 40% level of mould was observed on the surface. Therefore, the difference in the mould growth risk was greatly influenced by the climatic conditions of the indoor and outdoor setting rather than by the difference between Wall A and Wall B.

4. CONCLUSION

The exterior walls of wood frame houses are composed of an interior insulation system and an exterior insulation system; the hygrothermal performance evaluated of these walls was evaluated in four selected areas according to the indoor setting temperature. The water content was evaluated and mould growth risk was analyzed, using the WUFI simulation program. The U-value of Wall A (Interior insulation) and Wall B (Exterior insulation) was 0.173 and 0.157 W/m^{2}K, respectively; which confirms the superior thermal performance of Wall B.

The areas were determined as being in a dynamic steady state because the total water content of Wall A and Wall B did not increased in the four comparison areas for 3 years and there was no change after two years. After confirming the dynamic steady state for the study areas, we evaluated the absolute water content. The absolute water content analysis result showed that the wood based material OSB in Area c had the highest total water content, Wall A, was higher than Wall B but it did not exceed 20% of the standard. The problems mentioned above, however, will not occur since the water content of both walls in that indoor setting temperature did not exceed the standard value at 18℃. We analyzed the mould index and mould growth rate on an occurring indoor surface of Wall A and Wall B according to mould growth risk analysis. In the same area, as the indoor setting temperature is increased, the mould index and growth rate decrease. The results of analysis by region confirmed that the risk of mould growth for the indoor setting temperature range increased at the lower latitude. In Area c, the risk occurred within the range of indoor setting temperatures of 18 - 26℃, and the risk was higher compared to that in another areas. On the contrary, in Area d, the mould growth risk level was low, within the range of the setting temperature. Therefore, it was confirmed that the mould growth was mostly affected by the indoor and outdoor climatic conditions rather than by the position of insulation.

While the thermal performance of an exterior insulation wall is superior to that of the interior insulation wall, the results of hygrothermal performance evaluation were approximately the same. Moreover, it was confirmed that the moisture behavior and mould growth levels appear to differ according to climatic conditions. Therefore, it was determined that different indoor and outdoor setting temperatures are needed according to the regional climatic conditions.

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