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Original Article

Comparison of Hygrothermal Performance between Wood and Concrete Wall Structures using Simulation Program[1]

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ABSTRACT

Owing to an increase in the air tightness of recent buildings, the natural ventilation rate was significantly lowered and the removal of accumulated moisture became difficult in these buildings. The hygrothermal performance of these buildings should be carefully considered to provide comfortable indoor environment by removing the moisture condensation risk and the mold growth potential. In this study, hygrothermal performance of two selected wall structures was investigated based on WUFI simulation program. The results displayed that the indoor temperature had impact on the moisture accumulation in the insulation layer for both modeled walls, showing that lower indoor temperature resulted in higher moisture accumulation, especially in the wood frame structure. Also, the yearly moisture accumulation profile exhibited a downward shift throughout the year by adding a vapour retarder with a lower sd-value. In addition, both of the two walls have condensation risk in winter, due to low temperature level. The wood frame structure has a bigger fluctuation and higher condensation risk than the concrete structure.

Keywords : hygorthermal performance, indoor humidity, WUFI, condensation

1. INTRODUCTION

Moisture control has become a worldwide issue because building operations and construction practices have been changing (Künzel and Karagiozis, 2010). As the buildings have become larger and more airtight, the ventilation rate has decreased more, and the insufficient ventilation leads to moisture problems. Indoor humidity level is closely related to health problems such as skin irritation and respiratory problems (Zhang and Yoshino, 2010). High humidity level can create stuffy odor in a house and a breeding ground for mold, mildew, dust mites, and bacteria, which are harmful to residents' health (Fang *et al*., 1998; Bornehag *et al*., 2004). It also affects the construction durability as dry air makes furniture to shrink,

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warp, and crack. In the case of the high relative humidity level in the environment, thermal bridges can occur, and it lowers the thermal performance of the whole building. Additional energy consumption by air-conditioning may be required to remove excess indoor humidity (Vu *et al*., 2013). Therefore, it is important to keep indoor humidity at the correct level to ensure comfort and sustainability as healthy buildings.

In Korea, the winter is cold and dry, and summer is hot and humid. The condensation and mold occurs due to low ambient temperature and high indoor humidity in winter. It also occurs during the summer as the humidity diffuses into the room. Elimination of condensation within the walls is as important as reducing the heat loss through the wall or the floor. Most wall and insulation materials are porous enough that water vapor will migrate right through them. If the dew-point temperature is reached within the wall section, hidden condensation occurs and a wet wall or insulation results, which reduces the insulation effectiveness and deteriorates these materials. A vapor barrier must be used under the finish covering on the warm side of the wall to block this movement of vapor. However, most of the residential houses in Korea do not have a vapor barrier layer inside the walls. Paint, in general, is not an adequate vapor barrier.

Materials used in construction are affected by the ambient conditions, and if these are favourable to mould fungi, there is a mould growth risk on the materials. Each specific material has a critical moisture level for mould growth (Johansson *et al*., 2013), and when this level is exceeded, there is a risk that mould fungi will develop. Conditions for mould growth include nutrient availability, temperature, pH, and moisture (Johansson *et al*., 2012). In general, the availability of water in the material is regarded as the crucial element for growth to occur. Moisture requirements are also related to temperature; at lower temperatures, the fungus requires more available water to germinate and grow (Ayerst, 1969). In conclusion, the building structure and materials should be considered as a part of the moisture control design (Yu, 2014).

Within a building, the humidity and temperature is expected to vary from one construction to another. To minimize the risk of condensation and microbial growth, materials and components that can tolerate the prevailing conditions should be chosen. The purpose of this study is to investigate the effect of moisture transport on overall building performance, based on hygrothermal simulation. This study investigates the hygrothermal performance of building components, which are wood and concrete wall structures mainly used in Korea. This study also verified the humidity levels in various building layers, the condensation risk, and the mould growth risk. It is expected that hygrothermal simulation will lead to a better understanding of hygrothermal behavior of wall structures and to more accurate predict overall performances of the buildings.

Table 1. Thermal and moisture characteristics for the components of wood frame structure

Material	Thickness (mm)	Thermal conductivity (W/mK)	Heat capacity (J/kgK)	Diffusion Resistance Factor (-)
Plywood board	16.0	0.100	1500.0	700.0
Wood Frame	38.0			
Air layer	38.0	0.230	1000.0	0.4
Vapour retarder	0.1	2.300	2300.0	100.0
OSB	11.1	0.130	1500.0	650.0
Wood frame	184.0			
Fibergalss	184.0	0.035	840.0	1.3
Gypsum board	19.0	0.200	850.0	8.3

Table 2. Thermal and moisture characteristics for the components of concrete structure

Material	Thickness (mm)	Thermal conductivity (W/mK)	Heat capacity (J/kgK)	Diffusion Resistance Factor (-)
Mineral plaster	19.0	0.800	850.0	25.0
Concrete	200.0	1.700	850.0	192.0
Fiberglass	200.0	0.035	840.0	1.3
Gypsum board	13.0	0.200	850.0	8.3

2. MATERIALS and METHODS

2.1. Wall structures

Moisture performance of wall construction systems under the given climatic conditions is dependent on the system composition and thermal and moisture characteristics of comprising elements. In this study, moisture performance of wood frame and concrete wall structures are investigated under the climate conditions of Seoul, Korea. Two of the wall structures, wood-frame and concrete, were selected through residential construction standard established by Korea Rural Community Corporation and by reviewing the existing papers (Sedbauer, 2001).

The first wall, which will be referred to as Wall-A, is a wood frame wall structure which is composed of a 16 mm plywood board for exterior finish, a 38 mm air layer for ventilation, a 0.1 mm vapour retarder, a 11.1 mm OSB, a 184 mm fiberglass, and a 19 mm gypsum board, as shown in Table 1. The corresponding thermal and moisture characteristics are also given in Table 1. The results of the calculations showed that the Wall-A had the U-value of 0.171 W/m^2K or an R-value of 5.67 m^2K/W. The second wall, which will be referred to as Wall-B, is composed of a 19 mm mineral plaster, a 200 mm concrete, a 200 mm fiberglass, and a 13 mm gypsum board. The corresponding thermal and moisture characteristics are given in Table 2. The Wall-B had a U-factor of 0.165 W/m^2K or an R-value of

5.87 m^2K/W. The difference in heat resistance between the Wall-A and Wall-B structures was considerably small, while they had similar thickness of insulation layer.

Most of the houses in Korea have been built with concrete, but wood is one of the most preferred building materials for energy efficient buildings. As it is renewable and has excellent properties such as aesthetical appearance, high strength relative to its weight, easy workability, and good heat insulation capacity. In addition, wooden residential buildings emit less carbon dioxide during their processes of manufacture, operation, and disposal (Winistorfer *et al*., 2005; Salazar and Meil, 2009).

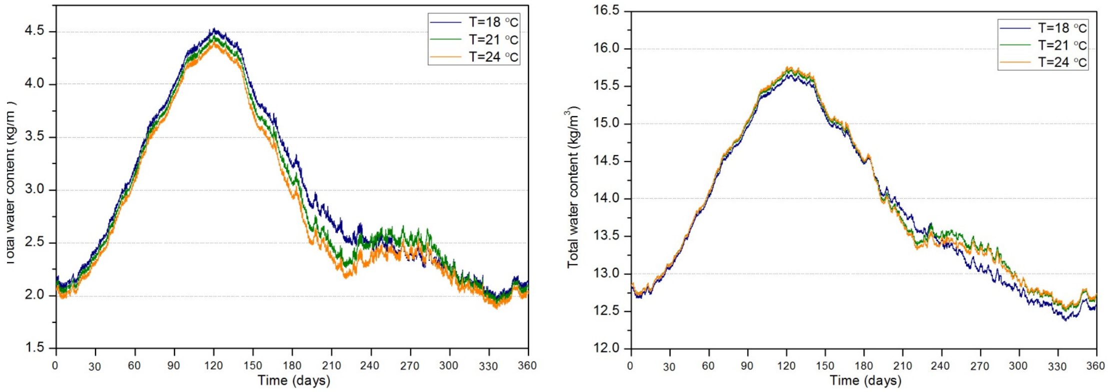
2.2. Modeling technique

WUFI family, a commercial program, is a one or two-dimensional model for heat and moisture transport developed by Fraunhofer Institute in Building Physics. It is validated using data derived from outdoor and laboratory tests, which allows realistic calculation of the transient hygrothermal behavior of multi-layer building components exposed to natural climate conditions (Künzel and Holm, 1999). Five wood-based building elements were chosen, at the campus of the Fraunhofer Institute of Building Physics, for thermal and moisture transfer using WUFI Pro. Simulation results were in agreement with the experimentally measured thermal conductivity values (Joscak *et al*., 2011).

For the purpose of this study, the moisture performance simulation model WUFI PRO 5.3 was selected, which is a windows-based program for the hygrothermal analysis of building envelope constructions. The WUFI simulation model is a transient heat and mass transfer model, which can be used to assess the heat and moisture distributions for a wide range of building materials and climatic conditions. WUFI can provide customized solutions for moisture engineering and damage assessment in the envelope systems of various buildings. It can estimate the drying time of the masonry and lightweight structures with trapped or concealed construction moisture. It can also be used to investigate the danger of interstitial condensation or to study the influence of driving rain on the exterior components of buildings. The software tool can also help to select repair and retrofit strategies, with respect to the hygrothermal response of particular roof or wall assemblies subjected to various climates (Budaiwi and Abdou, 2013). This allows comparison and ranking of different designs according to the total hygrothermal performances.

2.3. Description of modeling parameters

The WUFI simulation software requires hourly weather data for a full year including hourly dry-bulb temperature, solar radiation, humidity, and wind speed and direction. The weather data of Seoul (Alt. 20 m, Lat. 37° N) in Korea was used to represent typical weather variations in the central province of Korea. Seoul's climate is characterized by hot and humid summers,



(a) (b)

Fig. 1. Total water content (a) in Wall-A and (b) in Wall-B at three different indoor temperatures.

and cold and dry winter. Air temperature of Seoul rises above 35.9℃ in July and falls below -13.5℃ in January. In particular, a severe rain storm in July and August can lead to strong driving of rain force. The solar radiation level is the highest in April and the lowest in December.

The indoor climatic conditions were based on EN 13788, which can include high moisture load profiles of the buildings. The indoor temperatures were set to 21℃. The surface radiation properties were set according to the material specification listed in the WUFI database. In the case of the Wall-A, the exterior short-wave radiation absorptivity was set at 0.4 while the long-wave radiation absorptivity was 0.9, since the wood frame wall structure was finished with plywood siding. In the case of the Wall-B, the exterior short-wave radiation absorptivity was set at 0.4 while the long-wave radiation absorptivity was 0.9 as well, since the concrete wall structure was finished with mineral plaster. Based on the radiation parameters, the finite element model calculated infrared heat loss under the clear sky and heat gain under the sunshine. The simulations were run for three years to evaluate long-term hygrothermal performances of the wall structures.

3. RESULTS and DISCUSSION

3.1. Effect of boundary and exposure conditions

Moisture accumulation within the wall system greatly depends on the temperature profile across the different components, as it is a major determinant of local relative humidity and hence the conditions necessary for the occurrence of condensation within the wall system. Fig. 1(a) and (b) illustrates the impact of indoor temperature on moisture accumulation in the insulation layer for both modeled walls. Day 0 corresponds to 0:00 am of December 1st and day 360 correspond to midnight of November

30th. In Fig. 1(a), it is apparent that lower indoor temperature results in higher moisture accumulation. In spite of some noticeable increase in moisture accumulation at the lower temperature, particularly during the summer months, the change in moisture accumulation due to indoor temperature was generally limited. This can be explained by the fact that for the construction type of Wall-A, conditions are not suitable to introduce condensation within the insulation layer even at an indoor temperature of 21℃. However, there has been a noticeable increase in total water content at the temperature of 18℃ approximately during 180-240 days of hot and humid outdoor climate. It can lead to condensations in the insulation layer during the summer, due to hot and humid outdoor weather and lower indoor temperature from air-conditioning. Generally, condensation risk is high in winter season, as the surface temperature is relatively low. However, adverse-condensation occurs frequently during the summer in Korea. The hot and humid summer and dry and cold winter make it more difficult to controll comfortable indoor environment. Therefore, regions with such climate should more carefully consider the indoor humidity level. On the other hand, Fig. 1 (b) shows that water content in Wall-B structure has been decreased in spite of lower indoor temperature, except for about 190-230 days in the summer. It also has condensation risk in summer, which is similar to the wood frame wall. Wall-B exhibits major change in moisture behavior during the year. The increase in moisture accumulation is indicative of the higher potential and frequency for the occurrences of condensation.

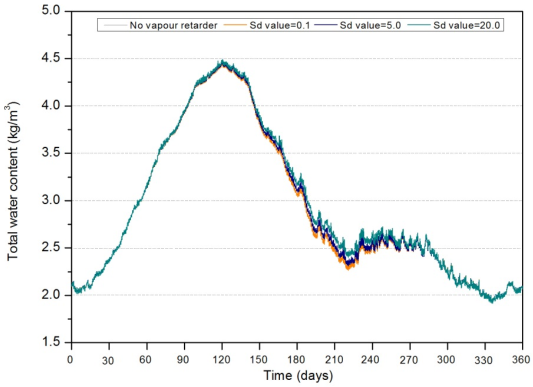


Fig. 2. Total water content in Wall-A, by comparing different sd-values of the wall without vapour retarder and the wall with vapour retarder.

3.2. Moisture content

Sd-value is a major factor for ensuring hygrothermal performance of the wall structures. Generally, air and vapour barrier is installed in the interior side of the insulation in cold and dry regions where heating is required. In contrary, air and vapour barrier is installed on the outside of the insulation in hot and humid regions where air conditioning is required, so that it can protect the insulation from condensation. In Korea, careful designing is required because the adverse-condensation can occur as the indoors are heating in the winter and cooling in the summer.

Fig. 2 illustrates moisture accumulation variations of Wall-A over the period of one year. Day 0 corresponds to 0:00 am of December 1st

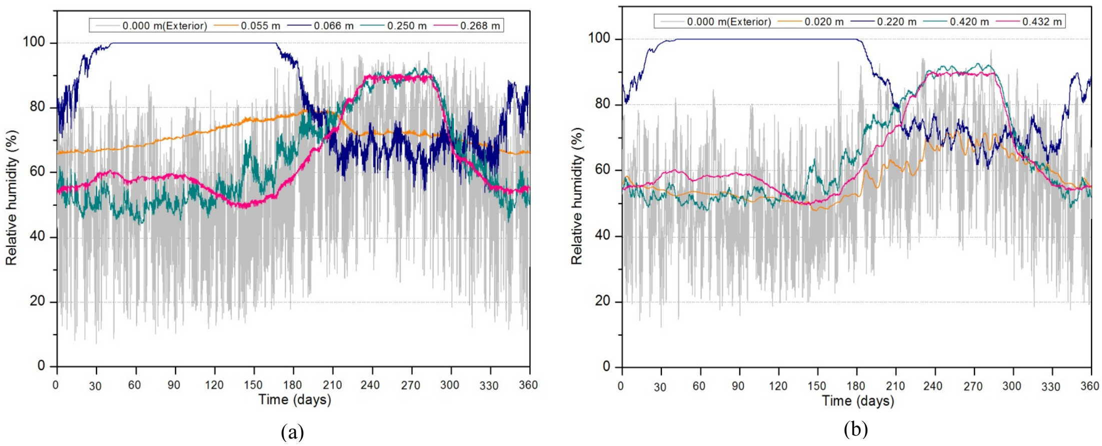


Fig. 3. Relative humidity of different building layers (a) in Wall-A and (b) in Wall-B.

and day 360 correspond to midnight of November 30th. It shows the total water contents as a comparison between the wall without vapour retarder and with vapour retarder, which have different Sd-values. It shows that there has been a noticeable difference only in the summer (180-240 days), and the highest moisture accumulation occurs in the wall with high sd-value of 20 m. The sd-value of more than 10 m is not permeable, so high water content was accumulated. Generally, vapour permeable membrane with sd-values of 0.01-0.1 m are mainly used in the wood frame structures. By adding a vapour retarder with a lower sd-value, the yearly moisture accumulation profile exhibited a downward shift throughout the year, with a maximum decrease of more than about 7% occurring during the summer. The presence of a low sd-value in the wall layer added relatively higher moisture permeability compared to the other wall components. This resulted in increased moisture transfer to the interior environment and consequently caused less moisture to be trapped within the various wall components including the insulation layer. It can be concluded that a different moisture behavior is attained depending on the moisture characteristics of other wall components and vapour retarder.

3.3. Relative humidity

The relative humidities at all monitored locations are shown in Fig. 3 (a) and (b). Day 0 corresponds to 0:00 am of December 1st and Day 360 corresponds to midnight of November 30th. Fig. 3 (a) shows the relative humidity of wall-A, and the monitoring positions represent distance from the outdoor: 0.000 m on exterior side of plywood board, 0.055 m between air layer and weather resistive barrier, 0.066 m between OSB and fiber glass, 0.250 m between fiber glass and gypsum board, and 0.268 m on interior side of the gypsum board. Monitoring

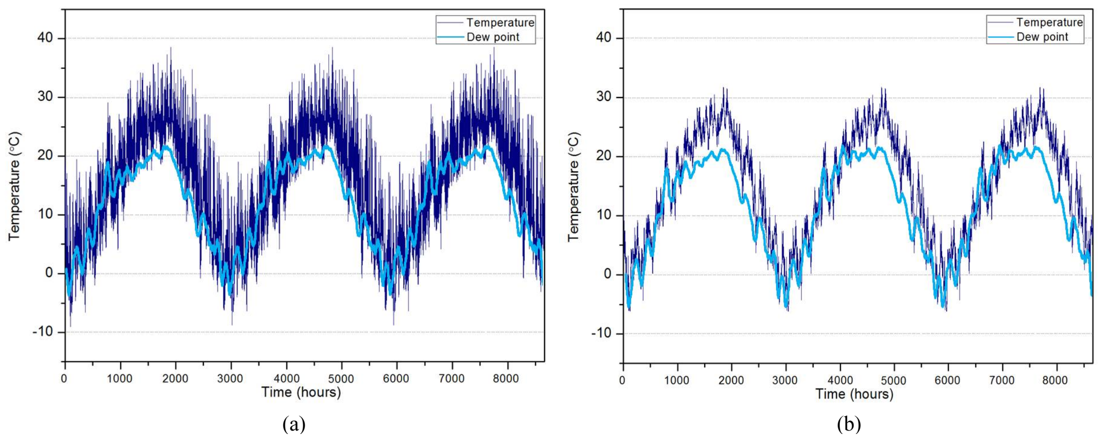
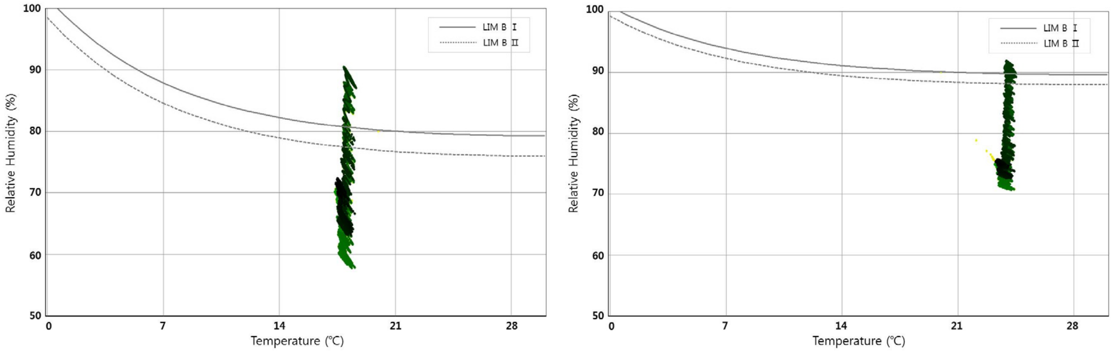


Fig. 4. Interior surface temperature and dew point (a) in Wall-A and (b) in Wall-B.

position 2, which is 0.055 m between air layer and weather resistive barrier, is a buffer zone between outside and inside of the structure for their high vapour flow resistance performance. Monitoring position 3, which is 0.066 m between OSB and fiber glass, showed relative humidity level to be high in winter and relatively low in summer due to high water storage capacity of OSB. Generally, if the humidity of the biodegradable material is more than 80%, there is a risk of condensation. In the summer, there are some condensation risk underneath the gypsum board which is commonly found in wood frame houses, due to moisture accumulation in the insulation layer. Fig. 3 (b) shows the relative humidity of wall-B, and monitoring positions represent distances from the outdoor: 0.000 m on exterior side of mineral plaster, 0.020 m between mineral plaster and concrete, 0.220 m between concrete and fiber glass, 0.420 m between fiber glass and gypsum board, and 0.432 m on interior side of the gypsum board. It also has the condensation risk in the summer, due to moisture accumulation caused by high relative humidity level.

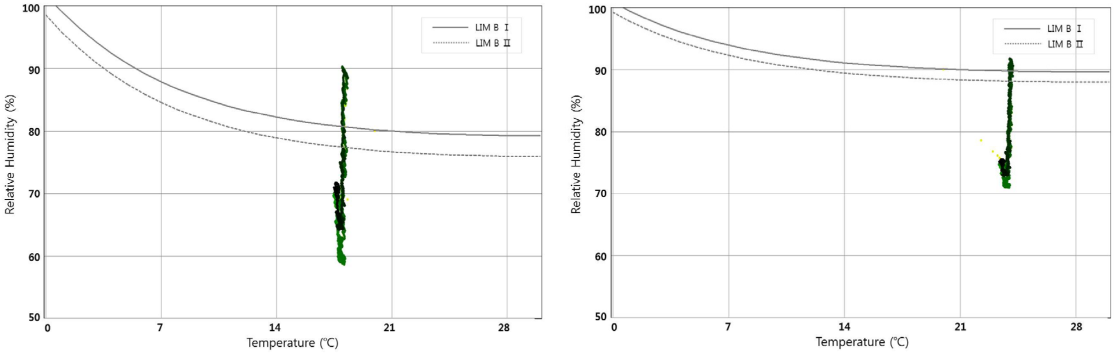
3.4. Condensation risk

The surface condensation occurs on the surface of the building material, which is easily noticeable. However, internal condensation occurring in the inner wall structure is a major problem for degradation of the durability. The indoor temperature is usually higher than the outside temperature of the building. Also, many moisture sources of indoors and the lack of ventilation lead to moisture accumulation. Fig. 4 (a) and (b) show interior surface temperature and dew point in the insulation layer of wall-A and wall-B. Both of the two walls have condensation risk in winter due to low temperature level. The wood frame structure has a bigger fluctuation and higher condensation risk than the concrete structure. Basically, higher ambient



(a) (b)

Fig. 5. Mould growth risk in Wall-A at indoor temperatures of (a) 18℃ and (b) 24℃.



(a) (b)

Fig. 6. Mould growth risk in Wall-B at indoor temperatures of (a) 18℃ and (b) 24℃.

air temperature is needed to avoid surface condensation. However, control of the internal condensation is more complicated. The most effective way is to design external insulation system to increase the internal temperature above the dew point temperature.

3.5. Mould growth potential

Fig. 5 (a) and (b) show mould growth risk in Wall-A with different indoor temperatures of 18℃ and 24℃. Also, mould growth risk in Wall-B is shown in Fig. 6 (a) and (b). The Lowest Isopleth for Mold growth (LIM) system is used for evaluation of the mold growth risk using (Sedlbauer and Breuer, 2003). None of the considered species can germinate below this LIM, and germination is possible for one or several of these species above the LIM. LIM B I represents bio-utilizable substrates such as wallpaper and plasterboard, and LIM B II represents less bio-utilizable substrates with porous structures such as plasters, mineral building materials, certain woods, and insulating materials

(Ryu, 2010). In the Fig. 5 (a) and (b), it can be concluded that there is a mould growth risk when the relative humidity is about 78% or more in the wood frame wall structure. In the case of concrete wall structure, mould growh risk is appeared to be higher in relative humidity greater than 89%, as shown in Fig. 6 (a) and (b). This is because wood frame structure has many bio-utilizable materials, and it leads mould growth environment.

4. CONCLUSION

The effect of moisture transport on hygrothermal performance of two selected wall structures was investigated based on thermal and hygric simulation. The effect of boundary and exposure conditions, the effect of vapour retarder on the moisture performance of the walls, humidity level in wood and concrete wall structures, condensation risk and mould growth potential were investigated.

The impact of indoor temperature on moisture accumulation in the insulation layer for both modeled walls was evaluated. It is apparent that lower indoor temperature results in higher moisture accumulation, especially in the wood frame structure. There has been a noticeable increase in total water content at the temperature of 18℃, during about 180 - 240 days of hot and humid outdoor climate. By adding a vapour retarder with a lower sd-value, the yearly moisture accumulation profile exhibited a downward shift throughout the year, with a maximum decrease of more than about 7% during the summer. In the summer, there are some condensation risk underneath the gypsum board, caused by high relative humidity level. Both of the two walls have condensation risk in winter, due to low temperature level. The wood frame structure has a bigger fluctuation and higher condensation risk than the concrete structure. There are mould growth risks for wood frame and concrete structure when the relative humidity is about 78% and 89%, respectively.

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