Numerical study on drying tendencies of common concrete wall structures insulated with different thermal insulation materials

Susanne Fagerlund (PhD in Inorganic Chemistry), Product properties and Certification manager, Paroc Oy AB

Hannu-Petteri Mattila (PhD in Thermal and Flow Engineering), Development Engineer, Paroc Group Oy

Abstract

The drying time of common concrete structures is among other factors influenced also by the selection of the thermal insulation material. In this paper we summarize the findings from an extensive simulation and numerical analysis work conducted by VTT Technical Research Centre of Finland Ltd by Paroc's assignment during 2017. The main goal of VTT was to investigate the effect of the insulation material to the drying patterns of concrete wall structures. In the numerical analysis three typical concrete wall structures (sandwich, rendered façade, and ventilated façade) were utilized to estimate the impact of using stone wool, expanded polystyrene, polyurethane, or phenolic foam as the thermal insulation material to the drying times of concrete layers and of the complete structure. In addition, the moisture flow rates between the material layers and interfaces were studied. The drying efficiency of the structures was simulated using northern climate and typical indoor conditions for apartment houses. The main moisture load in the study originated from the initial moisture in the fresh concrete layers. This work is a direct continuation of our previous work and aims to deepen further our understanding of the moisture behavior and performance of various building insulation materials. The numerical results demonstrate that open-cell fibrous insulation materials, like stone wool, can significantly improve the drying behavior of the inner concrete layer of the structure, essentially enabling possibilities for shorter construction times as well. The insulation materials as such have only minor effects on the overall drying behavior of the concrete structures.

Keywords: concrete; numerical analysis; moisture performance; thermal insulation; drying efficiency; moisture flow rates

1. Introduction

The awareness of the importance of a proper moisture management on building sites during the construction period and the long-term practical moisture properties of structures when building a safe, healthy and durable building has risen during the past years. For example, in Finland there exists a new operational model, Kuivaketju10 [1]. This model has been created to ensure that the dry chain on the building sites are properly designed and executed at all stages. It is important to secure a continuous dry chain with appropriate protection of building materials during the warehousing. In addition, it is vital that moisture accumulated in building materials during construction is dried out as efficiently and quickly as possible. The overall structures must be designed so that the structural moisture is dried towards the exterior and the possibly formed free liquid water is guided safely out from the structure. [2]

As described in our previous paper, insulations may be exposed to liquid water for instance during rain or concrete casting in the construction phase, or at a later stage due to construction damage or faults. Also snow can penetrate into insulated spaces driven by the wind. [2] The study summarized the extensive experimental work on the moisture behavior of insulation materials assigned by Paroc to VTT Expert Services Oy [3]. The laboratory work defined the moisture binding properties of building insulation materials with different mechanisms as well as the recovery of initial material properties after drying. In this study stone and glass wool, EPS, PIR, phenolic foam and cellulose insulations were compared. All the examined insulation materials absorbed water when exposed to moisture, although with significant differences in wetting and drying capacities. Moisture absorbed in insulation materials always causes an adverse effect on both thermal insulation capacity and surrounding structures. [2] The present paper is a direct continuation of our previous work and aims to deepen our understanding of the moisture behavior and performance of various building insulation materials.

In fresh concrete structures the initial moisture load is substantial; humidity of fresh concrete is initially 100 % RH, corresponding to about 150 kg/m^3 moisture content. When this is combined with a slow moisture transport through the concrete layers, the needed drying times are long compared to many other building materials. The time needed for drying of concrete structures is directly connected to the cost efficiency of the building process. Before for example a wall can be finished with surface coating, the moisture content of the core structure has to be on sufficient level. Ojanen, in his studies, suggests values around 80-85 % RH as a typical maximum limit for the required RH level. [4] [5] [6] In his article, he gives an additional example of the importance of the drying process related to vapor tight coating. If the coating layers are applied too early in the drying process there exists a risk that chemical reactions of materials, like glues and softeners of plastic carpets, occur due to the high humidity conditions leading possibly to formation of undesired emissions (such as VOCs) that may affect the indoor air quality.

This work concentrates on the evaluation of drying efficiency of concrete structures by numerical simulation analysis. This paper summarizes the findings by Ojanen [4] [5] [6]. The simulations were assigned to VTT Technical Research Centre of Finland Ltd and they were performed and reported during 2017. The studies used three different concrete structures having different types of thermal insulation products, with the objective to compare the drying behavior of concrete structures having open-cell fibrous insulation (like stone wool) with similar structures using more vapor tight thermal insulations (like expanded polystyrene, polyurethane or phenolic foam). Also the effect of vapor tight surface coating of the insulation layer was studied. The key variable in the simulations was the insulation material. The reader is kindly reminded that the simulation results are as such only valid for the given conditions and material properties. Within the material groups there may be variances in the product properties. In practice there can be several materials with same general name that have a large range of properties. The selected properties represent well those of some typical products.

2. Simulation model and the input parameters

Three concrete structures were studied in the simulations: a concrete sandwich panel, a rendered façade, and a ventilated façade. The structures were described numerically in WUFI 6.0 model. Figure 1 gives a principal illustration of these structures, with stone wool as an example of the insulation material layer.

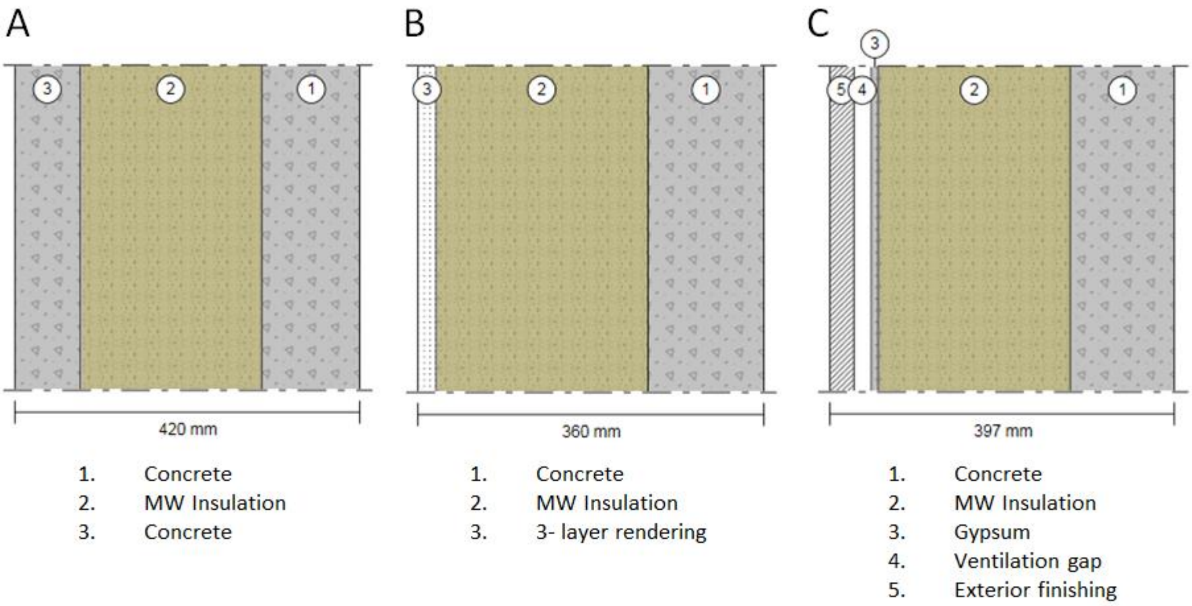

Figure 1. The intersections of the wall structures used in simulations: A) a concrete sandwich panel, B) a rendered façade, and C) a ventilated façade. Constructions based on data given by Ojanen [5] [6].

Figure 2 shows the second setup used in the VTT studies with stone wool thermal insulation in a sandwich concrete structure as discussed above. The stone wool was ventilated via grooves in the insulation: vertical grooves (30 x 20 mm at 200 mm division) were connected to 20 x 50 mm horizontal grooves at each horizontal boundary of the wall elements. These horizontal grooves were connected to outdoor air through pipes having minimum 12 mm inner diameter. These pipes are installed horizontally 2 m apart and vertically 3 m apart (the height of the wall element). The connection pipes and horizontal and vertical grooves form a ventilation system for the wall. The ventilation air flow rate has an effect on the drying of the structure. In this case the stone wool thermal insulation was assumed to have rather limited ventilation (corresponding to 6 h^{-1} in a 10 mm continuous air cavity) between the thermal insulation and the exterior concrete layer. No other simulated case had such ventilation and their drying was based simply on vapor diffusion through the concrete layers. [5] [6]

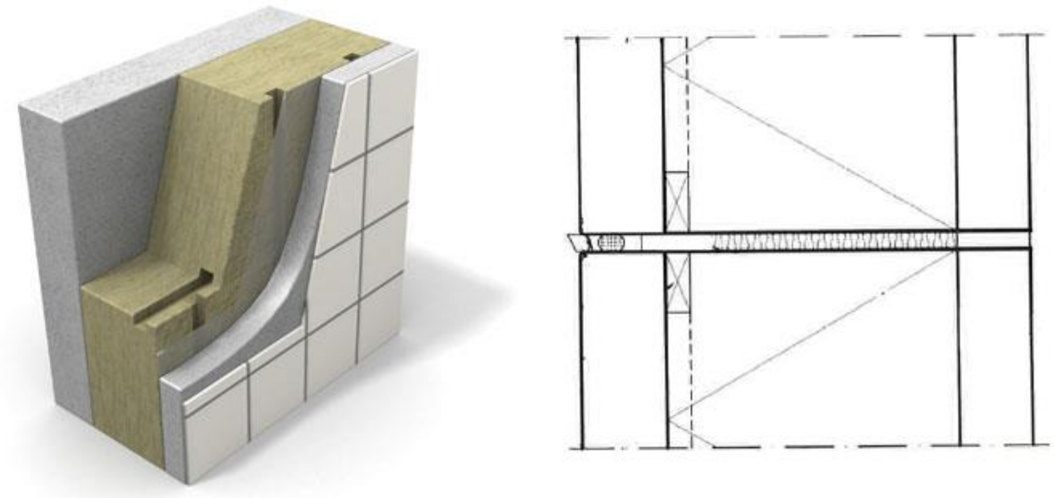

Figure 2. Ventilated stone wool insulation system used in concrete sandwich panel: a 3D illustration of the grooved insulation on the left and on the right a detail (side view section) from the air inlet/outlet pipes between the elements.

VTT utilized the WUFI 6.0 simulation tool with the WUFI material library to study the drying of concrete as a function of time in the selected structures. The following assumptions and parameters were used [5] [6]:

- Simulation period was four years, with identical yearly climate variations.
- The exterior climate conditions in the simulations were given by the hourly values of Vantaa, Finland moisture design climate data corresponding to northern climate conditions.
- For indoor air, ISO 13788 class 2 conditions were utilized. The indoor air had +20°C temperature and a moisture load +4 g/m^3 below 0°C outdoor temperature and the load decreased linearly to +1 g/m^3 when outdoor temperature increased from 0°C to +20°C.
- The yearly indoor air relative humidity varied between 33 % RH and 75 % RH. This translates to typical indoor moisture load conditions for apartment houses.
- The drying effect of solar radiation was omitted in simulations, but driving rain was assumed to hit the south facing wall surface (a low < 10m high building).

Material properties and insulation layer thicknesses for the numerical simulations are listed in

Table 1. [5] [6] The simulated thermal insulations were stone wool (MW), expanded polystyrene (EPS), polyurethane (PU), and phenolic foam (PF) [5] [6]. The thermal insulation thicknesses were set according to their thermal conductivity performances to 220 mm for SW and EPS, to 170 mm for PU, and to 130 mm for PF insulation. The thicknesses do not yield exactly the same thermal performances for the insulation layers (U-values 0.14-0.17 W/(m^{2}K)); however from moisture performance point of view the accuracy is considered sufficient. The PU+Al (PU insulation with the aluminum foil coating) simulation describes a reference case in which there is no moisture transfer into the insulation layer from the inner concrete layer. This simulation was only performed to one of the structures for comparison.

Table 1. Material properties based on WUFI material library and the thickness of the used layer. [5] [6]

Material	Abbreviation	Thickness of the layer [mm]	Thermal conductivity, [W/(m*K)]	Diffusion resistance coefficient [μ]
Concrete, w/c = 0,5		**120/80**	**1.6**	**180**
Stone wool	**MW**	**220**	**0.035**	**1.3**
Expanded polystyrene	**EPS**	**220**	**0.035**	**50**
Polyurethane insulation	**PU**	**170**	**0.025**	**50**
Phenolic foam insulation*	**PF**	**130**	**0.020**	**35**
Aluminum foil	**Al**	**0.1**	**-**	**High**
Rendering, 3 layers		**20**	**0.4**	**9**
Gypsum board		**13**	**0.2**	**8.3**

**** VTT has extracted the information from product manufacturer's internet pages***

The following initial moisture contents and performance criteria were used [4] [5] [6]:

- The main moisture load for the structures is the initial moisture content in the fresh concrete slabs; 150 kg/m^3 corresponding to 100 % RH conditions.
- For all other material layers 80 % RH initial moisture conditions were used.
- The moisture levels are measured at 40 % of the slab thickness from the inside surface.
- Before the internal concrete slab can be coated, the humidity of the concrete should dry out to 80 – 90 % RH depending on the coating material, a typical limit being 85 % RH (about 93 kg/m^3).
- These maximum allowed RH levels for floor slabs give comparable critical levels and needed drying times also for the concrete wall slabs with different thermal insulation materials.

3. Simulation results and discussion

The numerical simulations by VTT were carried out to study the effect of thermal insulation materials on the drying of three concrete structures. The reader is kindly reminder that the difference between real conditions and those used in a numerical study can be rather high especially at the exterior boundary of the thermal insulation due to the omitted drying impact of the solar radiation or wind load. The results can thus be seen as a "worst case" approach to the subject.

Figure 3 gives an example of the simulation results by Ojanen for the concrete sandwich wall structure during the studied four year simulation period. The numerical analysis results are summarized as the drying behavior of the inner concrete slab and of the whole structure and the moisture flow rates through the structural layers as indicators of the moisture transport. The simulation results are expressed as total mass of moisture dried out from the structure and the average moisture content in the inner concrete slabs of the structure with different insulation materials. The two horizontal lines given in the figure represent 80 % RH and 85 % RH humidity levels corresponding to an indication of a sufficient level of drying of the structure. [5] [6] The findings for the sandwich panels are in principle valid also for the rendered and ventilated façades. Thus, the detailed discussion around these structures is very limited in this paper.

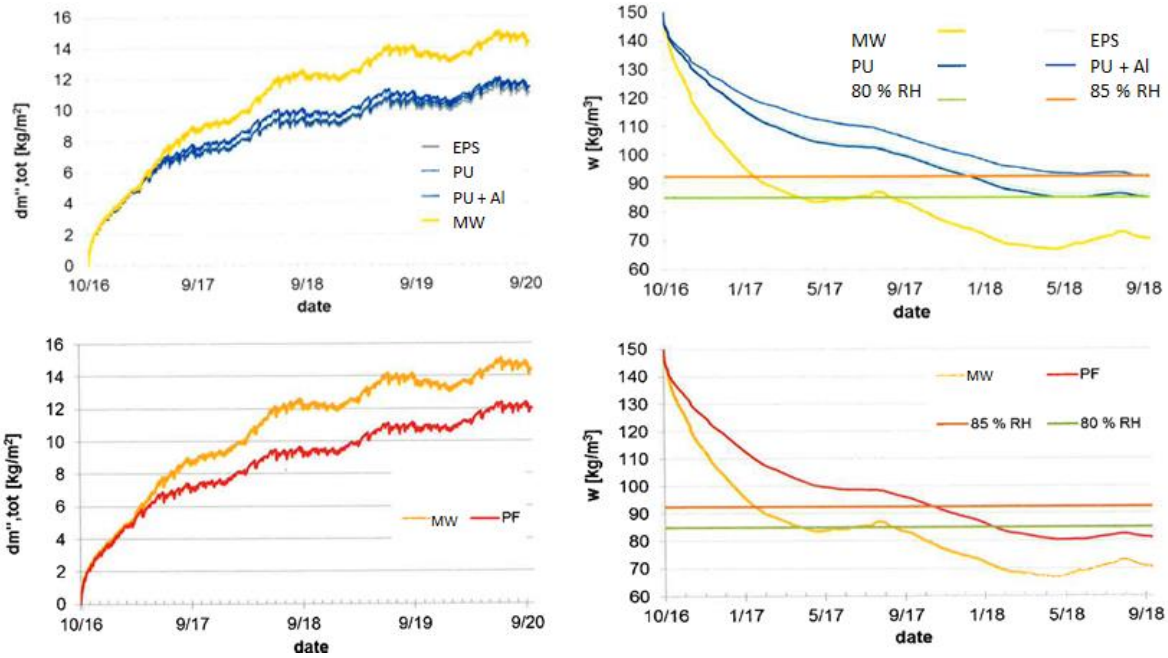

Figure 3. Total mass of moisture dried out from the structure (left) and the average moisture content levels of the inner concrete slabs (right) for a concrete sandwich wall with different insulation materials. The horizontal lines represent 80 % RH and 85 % RH humidity levels. Observe that the stone wool curves in the top and bottom graphs are the same to guide the eye of the reader. The figures are sourced from the VTT studies [5] [6].

Ojanen showed that the difference between the total mass of moisture dried out from the structures having different thermal insulations was small during the first six months of the simulations. After that the structures having internal ventilation and a vapor open thermal insulation tended to dry out somewhat faster than those having more vapor tight insulations. [4] [5] [6]. The differences in the total amount of moisture dried out from the structures were quite moderate compared to the effect of thermal insulation on the drying of the inner concrete layer due to moisture redistribution in all the wall structures.

If we take as a numerical example the difference of the total mass of moisture dried out from the sandwich structures having stone wool and phenolic foam insulation after one to two years of the simulation period start, the maximum difference was on a level of 30-35 %. At the end of the four year simulation period the total dried out moisture from concrete sandwich structure with stone wool insulation (including limited ventilation) was about 20 % higher than in case of non-ventilated phenolic foam insulation. In the rendered and ventilated façade cases this difference was around 8-9 %. [5] [6].

It is clearly visible that the vapor open thermal insulation, such as stone wool, allows a significantly faster drying of the inner concrete layer than all the other cases with more vapor tight insulations. Because the water vapor diffusion is not hindered in the vapor open insulation, strong moisture redistribution inside the structure occurs almost immediately. This enables drying of the structure both towards the interior and towards the adjacent insulation air space. [5] [6]

If we take another numerical example from the data set, in the sandwich panel case the inner concrete core could dry out to 85 % RH moisture level in 135 days, while with unventilated phenolic foam the drying took roughly 400 days and with EPS and PU insulations roughly 460-470 days, and with PU+Al roughly 700 days. This is illustrated in Figure 4 together with the drying times to 80 % RH. It was also shown by the simulations that the difference between the grooved, i.e. limited ventilation, stone wool structure versus the non-ventilated stone wool is rather small (7 days). In the same figure, the corresponding values are given also for the two other studied wall structures.

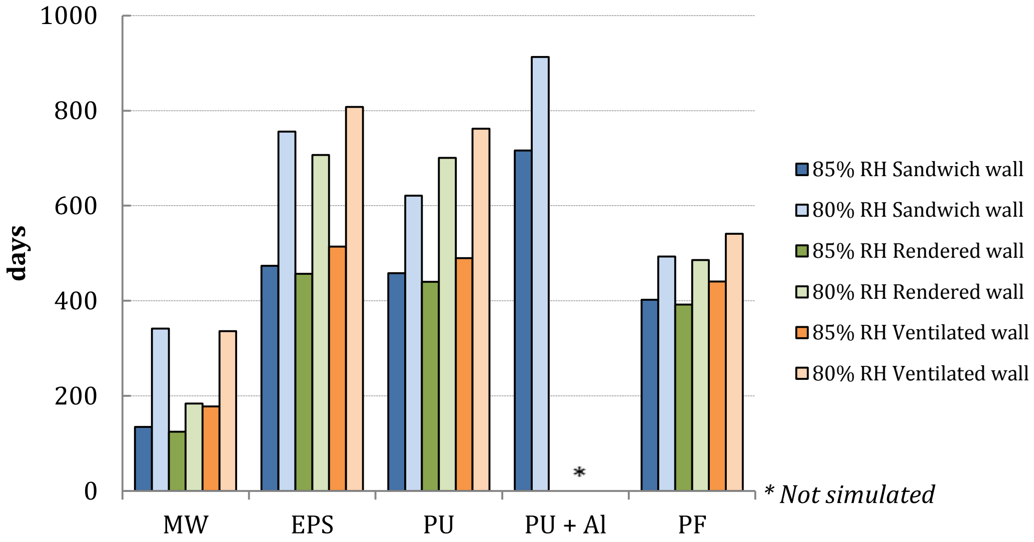

Figure 4. Time needed for the interior concrete layer (thickness = 120 mm) to reach the average moisture contents corresponding to 85 % RH or 80 % RH for the three studied wall structures given in Figure 1. The data is collected from [5] [6].

The accumulated moisture flows during the four year simulation period gained with WUFI 6.0 are shown in Figure 5 for the concrete sandwich wall structures. The different pathways for the moisture are separated in the graphs as the moisture transported from inner surface to indoor air; from inside concrete core to thermal insulation; from thermal insulation to exterior core and possible ventilation system in stone wool case; and from the exterior core to outdoor air. The positive values correspond to moisture flow towards indoor air, negative towards outdoor air.

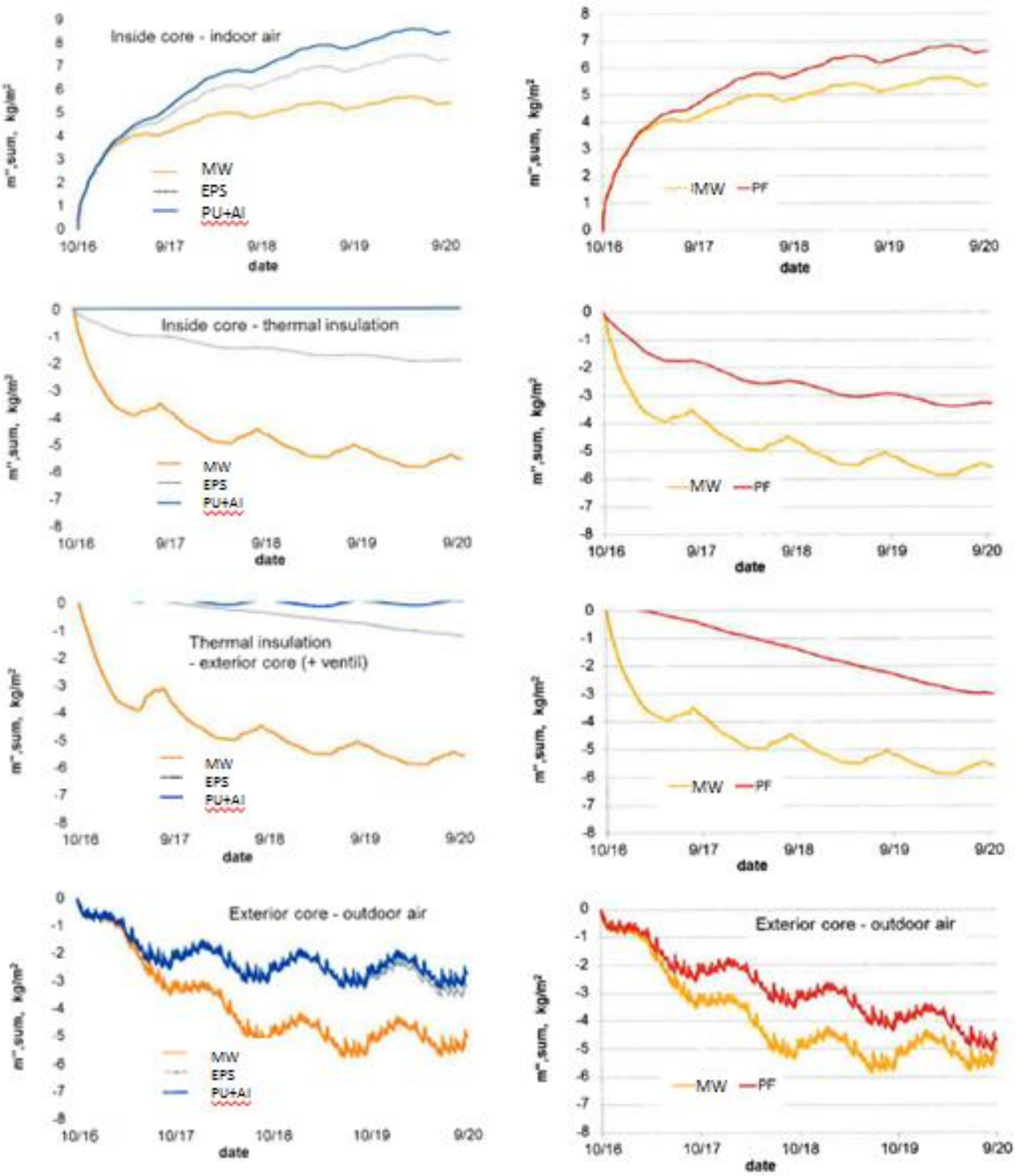

Figure 5. The accumulated moisture flows in a concrete sandwich panel during the four year simulation period (results gained with WUFI 6.0). Top down: moisture transported from inner surface to indoor air; from inside concrete core to thermal insulation; from thermal insulation to exterior core and possible ventilation system in stone wool case; and from the exterior core to outdoor air. The positive values correspond to moisture flow towards indoor air, negative towards outdoor air. Observe that the stone wool curves in the left and right graphs are the same to guide the eye of the reader. The figures are sourced from the VTT studies [5] [6].

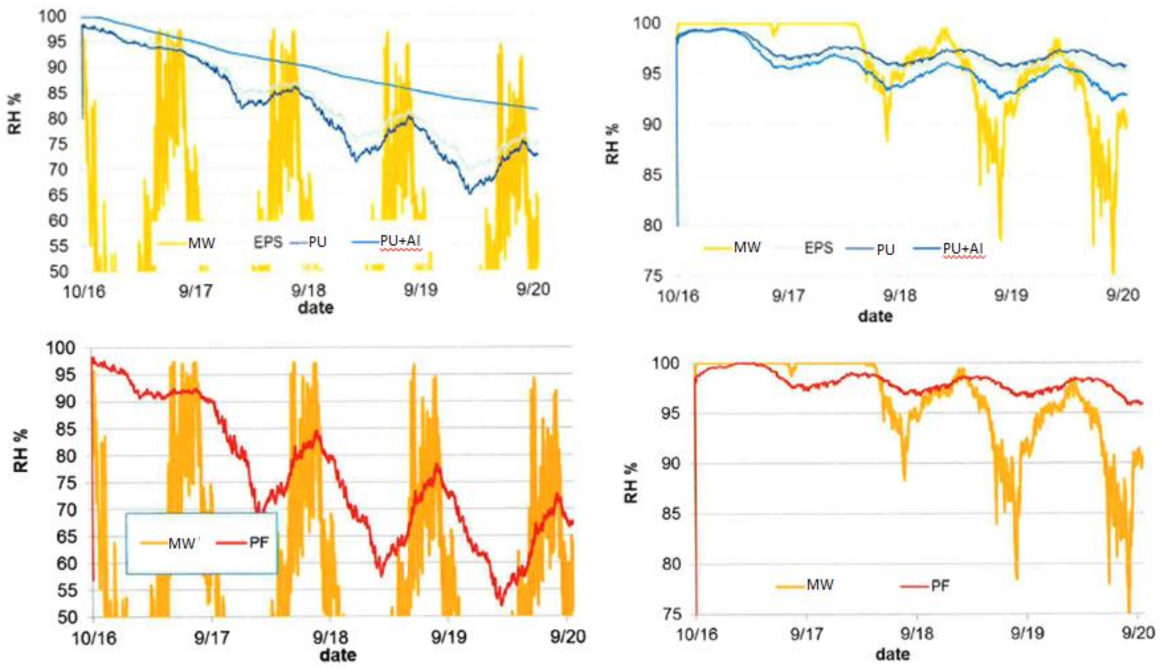

Figure 6. Simulation results on the relative humidity levels on the interior boundary (left) and on the exterior boundary (right) of the thermal insulation in a concrete sandwich wall. Observe that the stone wool curves in the top and bottom graphs are the same to guide the eye of the reader. The figures are sourced from the VTT studies [5] [6].

Figure 6 shows the simulation results on the relative humidity levels on the interior boundary and on the exterior boundary of the thermal insulation for the sandwich wall structure with the different insulation materials. [5] [6] Because stone wool, as more vapor open insulation, allowed more significant moisture movement from the inner layers towards the exterior, the relative humidity stayed higher at the surface between the outer concrete layer and the insulation when compared to the more vapor tight insulations (100 % RH vs 95 % RH). It is though good to keep in mind that both indicated moisture levels are relatively high and the observed differences are not significant in practice. Because of the alkaline, high pH environment caused by the fresh concrete the high humidity levels on the exterior boundary of the thermal insulation do not create for example a risk for biological (i.e. mold) growth. During the third simulation year the relative humidity level started to decrease below 90 % RH at the exterior layer also when using stone wool. After the third year, the stone wool structure followed a yearly moisture load cycle. Simultaneously, the more vapor tight insulations cases remained at > 90 % RH level.

All the above-mentioned findings and conclusions for concrete sandwich walls are on a principal level valid also for the other studied façade structures, even if the numerical values and results have some differences. For example, the yearly average relative humidity values on the exterior boundary of the thermal insulation layer during the first and fourth year of the simulation period for the three studied wall structures are summarized in Figure 7.

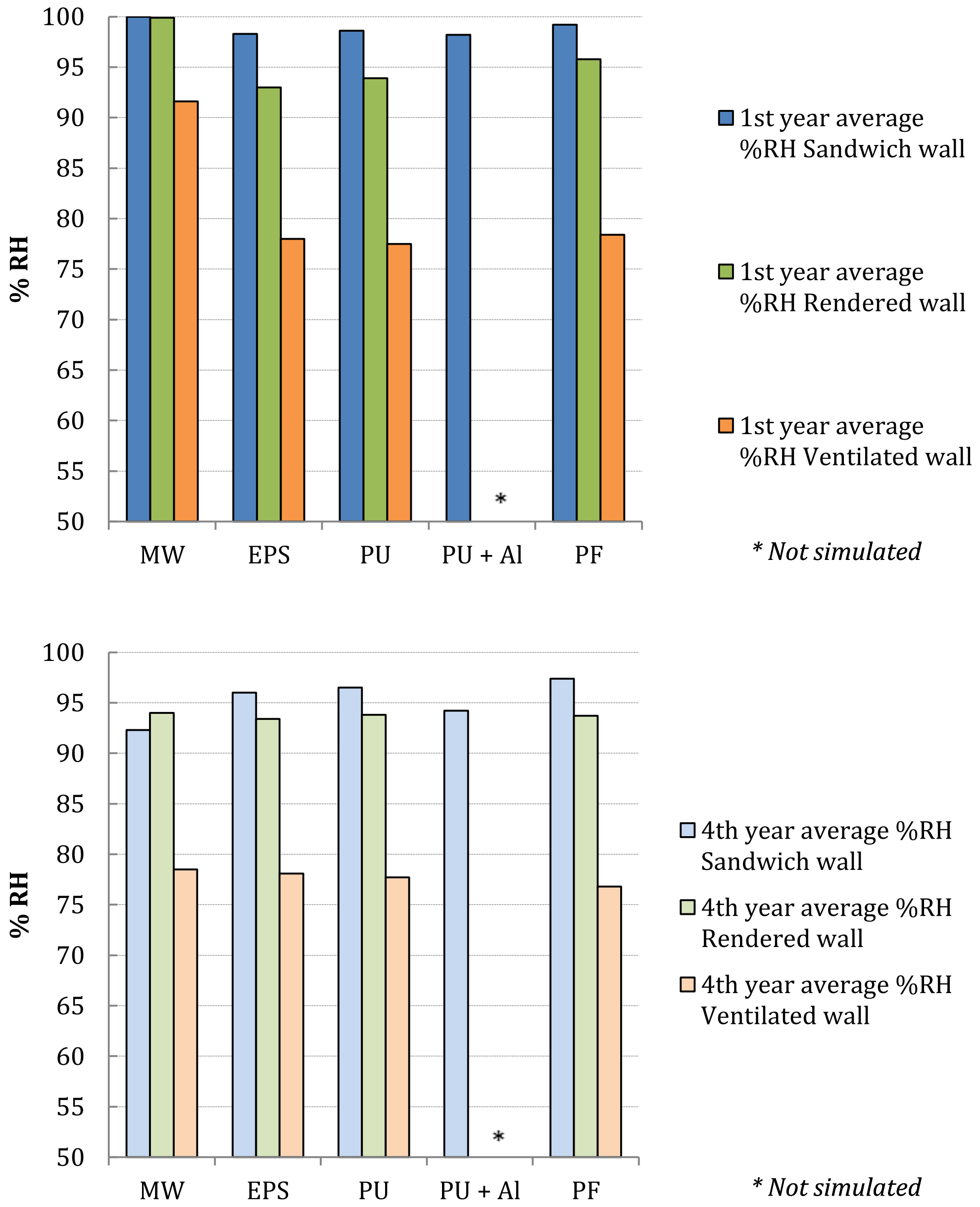

Figure 7. The yearly average relative humidity values for the exterior boundary of the thermal insulation layer during the first (top) and fourth year of the simulation period for the three studied wall structures given in Figure 1.

4. Summary

In the performed numerical simulations the observed drying behavior was rather similar for all the studied concrete wall structures. If a vapor-open thermal insulation material is used, the initial moisture content of the concrete slabs will redistribute in the wall structures rather quickly. The inner concrete slab can dry in two directions, and thus its drying time to a desired level will be shorter in comparison to structures with more vapor-tight insulation layers. At the same time, the differences in total amount of moisture dried from the structures are quite small, when the entire structures are considered. This can be explained by the moisture accumulation at the external boundary of the vapor-open thermal insulation layer, where the relative humidity remains at a high level for a longer period of time compared to vapor-tight insulations. For a well-functioning structure, it is important that the net moisture flow during a yearly cycle of climate conditions remains outwards, i.e. that all the structures are effectively drying. Local presence of liquid water in the structures may cause lower thermal and mechanical performance for the materials. Thus it is essential that the eventually condensing liquid water is drained properly out from the structures, for example via the pipes connected to the ventilation system as described above for the stone wool insulation. Biological growth in the concrete structures is prohibited by the highly alkaline environment created by the fresh concrete. It must also be remembered that the simulations did not consider the drying effect of sunlight or wind on the outer surface, and the results thus represent a "worst case" approach to the topic. Also, in case the outer surface of the wall construction is made more vapor-tight compared to the structures presented here, for example by surface tiles, a ventilated thermal insulation is recommended.

References

[1] Kuivaketju10, ”http://kuivaketju10.fi/,” [Online]. [Accessed 18.9.2018].

[2] H.-P. Mattila, ”Moisture Behavior of Building Insulation Materials and Good Building practices,” Paroc Group Oy, 2017.

[3] H. Hyttinen ja T. Seppälä, ”Moisture in building insulations. Determination of effect of moisture to the technical properties of building insulations,” VTT Expert Services Ltd, Espoo, 2017.

[4] T. Ojanen, ”Moisture performance of mineral wool insulation products in highly insulated structures,” *Energy Procedia*, 132, 2017.

[5] T. Ojanen, ”VTT-R-04783-17: Moisture performance of stone wool insulation products,” VTT Technical Research Centre of Finland Ltd, Espoo, 2017.

[6] T. Ojanen, ”VTT-R-05677-17: Moisture performance of concrete structures having stone wool or phenolic foam thermal insulation,” VTT Technical Research Centre of Finland Ltd, Espoo, 2017.