Improving the Drying Efficiency of Timber Frame Walls in Cold Climates by Using Exterior Insulation

Tuomo Ojanen

ABSTRACT

Safe moisture performance of a structure requires high drying efficiency. Even if a structure has acceptable moisture performance under normal design conditions, long exposure to moist conditions due to high initial moisture content or accidental moisture loads may start biological deterioration. Timber frame walls with rigid exterior sheathing, such as oriented strand board (OSB) or plywood, have relatively low vapor permeance. Use of exterior insulation, made of vapor permeable, open porous material and installed at the cold side of the sheathing, is an effective method to improve the drying efficiency of a wall.

The objective of this study was to present how the moisture performance of timber frame walls can be improved with vapor permeable exterior insulation. Numerical simulations and laboratory-scale experiments were used in the analysis. Both moisture content levels and a numerically solved mold growth index were used as criteria in the analyses.

Experiments with wall structures having initial moisture loads and temperature gradients were used to study the drying efficiency through sheathing boards with and without exterior insulation. The conditions corresponded to those typical for cold climates experiencing drying: condensation with below and above freezing temperatures at the exterior sheathing. In some conditions, exterior insulation could improve the drying efficiency by nearly a factor of 8. Numerical simulation results show the effect of climate, thickness of exterior insulation, and moisture loads caused by diffusion and initial moisture content on the drying efficiency and moisture performance of timber frame walls.

INTRODUCTION

When the moisture performance of a structure is analyzed numerically, normal design climate conditions are used as boundary conditions and initial moisture content levels of the materials are chosen to be typically reasonable. This approach will give an adequate prediction assuming that there will be no accidental moisture loads. In real structures, these unpredictable loads are quite possible. A vapor or an air barrier can fail, the weather proofing can leak, or the initial moisture content or inside air moisture loads may greatly exceed normal levels. The reasons may be, for example, bad workmanship, wetting of materials during construction, aging of material layers, the habits of residents, or the performance of the ventilation system. These moisture loads cannot be quantitatively predicted, but the building envelope should have some safety factor against them.

The concept of drying efficiency of walls requires higher moisture safety than what the walls have under design conditions. This is especially important with timber frame walls because they have relatively low moisture absorption capacity and the exterior sheathing boards, such as OSB and plywood, have relatively high vapor resistance. These walls can be very sensitive to water leakage or any other additional moisture load exceeding their drying capacity. Long exposure to moist conditions may start processes of biological deterioration, such as mold growth. There are many examples of how low drying efficiency may contribute to moisture problems when there is additional moisture in the structure (Dell et al. 1997) caused by water leakage or initially high moisture content. This research concentrates on structures with relatively low drying efficiency, i.e., walls with OSB and plywood sheathing.

Use of vapor permeable exterior insulation is one solution that can be used to improve the drying efficiency of a wall in cold climates. All the potentials of exterior insulation to improve the moisture performance of walls are not clearly known. The moisture performance and parameter sensitivity

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studies of walls with exterior insulation were done to find out the best practical applications of the system. The effects of exterior insulation thickness, outer surface finish (cement mortar or open to ventilated cavity), and climatic conditions were analyzed using laboratory-scale experiments and numerical simulation methods. Only highly vapor permeable exterior insulation materials, mineral or glass wool, were studied. More vapor-tight exterior insulation materials may reduce the advantage of improved drying potential by increasing the overall vapor resistance of the exterior layers.

DRYING POTENTIAL WITH EXTERIOR INSULATION

Figure 1 presents the principles of how exterior insulation can be used to improve the drying efficiency of a wall. The moisture flow rate out from the structure depends on the vapor permeability of the sheathing board and on the partial vapor pressure difference across this layer.

When a wet structure is drying in cold outdoor conditions, there are typically condensation conditions at the inner surface of the exterior sheathing. Depending on the material of the sheathing board, the vapor permeability of the board can be significantly higher in wet than in dry conditions. The wet conditions can themselves enhance the potential for drying. Figure 2 shows how the vapor permeability of plywood and OSB depend on relative humidity (Kumaran 1996; Ojanen et al. 1997).

In cold climates, when there is no exterior insulation, the temperature of the sheathing may have long periods below freezing. The apparent vapor permeability of the sheathing can be expected to decrease if a film of condensed water freezes on the board surface. The outdoor relative humidity is typically high; during winter months, it is frequently above 90% RH. Because the temperature difference over the sheathing board is small, the partial vapor pressure difference between the inside and outside surface of the sheathing board is relatively small. The overall drying potential is quite low, with wall structures having sheathing board open to a vented or ventilated air cavity with nearly outdoor air conditions.

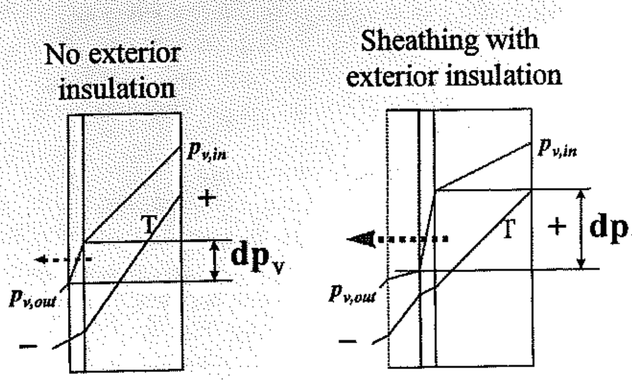

Figure 1 The effect of exterior insulation on the drying potential of a wall.

Exterior insulation raises the temperature level of the sheathing board. This has the following advantages:

1. The length and number of yearly freezing periods will be reduced.
2. The apparent vapor permeability (combined total permeability for vapor phase and liquid moisture flow) of the sheathing will be increased.
3. The partial vapor pressure of the sheathing will be increased significantly from the noninsulated case.

The increased vapor pressure level causes a high vapor pressure difference across the sheathing board and also increases the potential for moisture evaporation from the outside surface of the sheathing. Thus, with vapor permeable exterior insulation, the moisture flow rate out from the wall can be greatly increased.

The moisture transport mode through the sheathing was not studied in this research. It is obvious that part of the moisture flow takes place in the liquid phase when the material, such as plywood, is very wet. In this study, the moisture flow was considered as an apparent diffusion flow, as presented in Figure 2.

CONTENTS OF THE RESEARCH

Low drying efficiency is typical for wood frame wall structures with relatively vapor-tight sheathing, such as OSB and plywood. In cold climates, the use of exterior insulation will improve the drying efficiency of walls sheathed with these materials. The relative improvement of the drying efficiency is most likely better with OSB and plywood than with more vapor-open sheathing materials. In Northern Europe, plywood is a more common building material than OSB. The main interest in this research was of walls with plywood sheathing, but OSB and other typical sheathing materials were also studied.

Both experimental and numerical methods were used to analyze the moisture performance of wall structures with

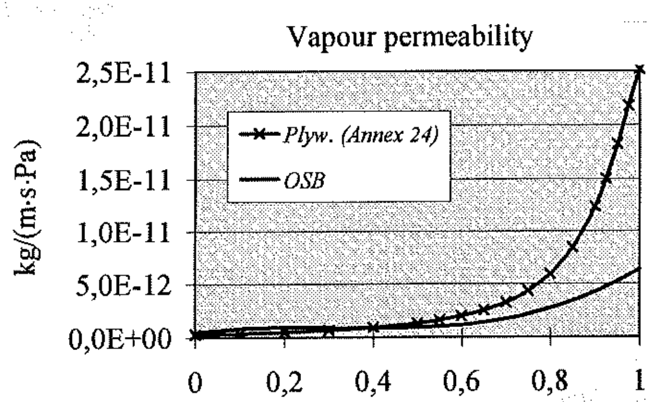

Figure 2 Vapor permeability of plywood and OSB. Plywood data from material property data set (IEA/Annex 24) confirmed by measurements. OSB from material database for simulation models, confirmed with measurement in one point.

different sheathing boards, with or without exterior insulation. The assumption was that all the analyzed walls, except those with cement mortar finish, have a vented or ventilated air cavity between the exterior cladding and the sheathing or exterior insulation. The moisture loads were presented as initial moisture content of material layers or as loading from moisture in indoor air.

WALL DRYING EXPERIMENTS

The objective of the laboratory experiments was to study the drying efficiency of walls with and without exterior insulation. Conditions used in the experiments were extreme in order to have clear differences between different cases during the relatively short measuring periods.

Test Setup, Moisture Loads, and Boundary Conditions

The intent was to measure the moisture flow rate that can dry out a wet wall structure in conditions corresponding to those in cold climates. The test setup used in the experiments is presented in Figure 3. Each of the wall sections was assembled and tested horizontally, and they consisted only of thermal insulation and exterior sheathing board with optional exterior insulation. There were no framing members in the test structures.

The wall sections were installed in plastic boxes that were open only to the cold-side air on the top. The open area of the structure surface was 0.40 m × 0.32 m. Special attention was paid to having vapor-tight caulking between the material layers and the test box surfaces in order to avoid air and vapor leakage through the joints. The conditions on the warm side were maintained in the air space below the test boxes.

The moisture load for each wall section was the same. An initial moisture load of 10 mm of free water was placed at the bottom of each box in the thermal insulation layer.

During the experiments, the temperature conditions were maintained constant at the warm- and cold-side air spaces. Horizontal installation and testing and the use of thermal insulation between each test wall section ensured one-dimensional

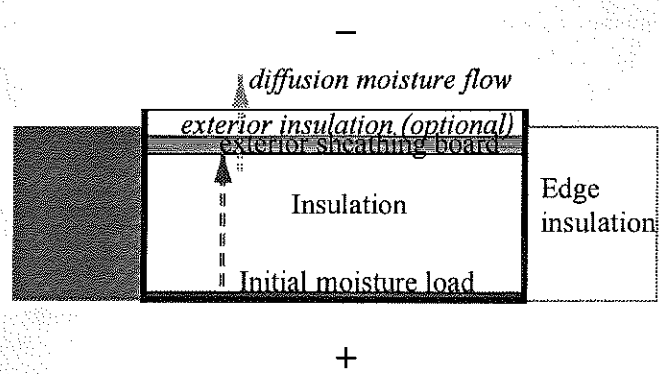

Figure 3 *Test setup used in wall drying experiments.*

temperature and moisture fields without internal convection. The temperature gradient caused moisture flow through the sheathing, and during the drying process, there were continuous water vapor condensation conditions at the cold side of the board.

The tests were done with different cold-side temperatures in order to study conditions both below and above freezing. All the walls were tested for the same time and at the same conditions. The temperature conditions of the air spaces and the inside surface of the sheathing boards were monitored throughout the tests. The moisture flow rates out from the structures were determined by repetitive weighing of the boxes containing the tested walls. The weighing was done at two- to three-day intervals to study the approach of steady-state conditions. Warm-side air temperature was kept constant in the tests. Three consecutive periods, about one month long each, were studied:

Test Period	Warm/Cold Air Temperatures
I, 32 days	+22/–10°C
II, 29 days	+22/–5°C
III, 30 days	+22/+3°C

The total thickness of each assembly was 150 mm. Thicknesses of sheathing, insulation, and exterior insulation are presented in Table 1.

TABLE 1
Sheathing Boards and Exterior Insulation in Measured Test Cases (Three of Each)*

Case	Sheathing Board	Thermal Insulation	Exterior Insulation
Open	-	150 mm GF	-
p.w.fiberbd.	12 mm porous wood fiber	138 mm GF	-
OSB	12 mm OSB	138 mm GF	-
ply9	9 mm plywood (3 ply)	141 mm GF	-
ply9(cfi)	9 mm plywood (3 ply)	141 mm CF	-
ply12	12 mm plywood (4 ply)	138 mm GF	-
Ex30ply9	9 mm plywood (3 ply)	111 mm GF	30 mm MW
Ex50ply9	9 mm plywood (3 ply)	91 mm GF	50 mm MW
Pex30ply9	9 mm plywood (3 ply)	111 mm GF	Mortar + 30 mm MW

*In one case, the insulation was cellulose fiber (CF) and all the other cases had glass fiber (GF) insulation (20 kg/m^3). Optional exterior insulation was mineral wool (MW) (45 kg/m^3).

Tested Assemblies

Table 1 presents the analyzed wall assemblies, three of each. The thermal insulation was glass fiber (20 kg/m^3), and the optional exterior insulation was high-density mineral wool (45 kg/m^3). In one case, the thermal insulation was made of cellulose fiber (about 40 kg/m^3). The sheathing used in the experiments was 9 mm and 12 mm thick (spruce) plywood (460 kg/m^3), 12 mm thick OSB (640 kg/m^3), and 12 mm thick porous wood fiberboard (280 kg/m^3). An open reference case without exterior sheathing was also analyzed. The OSB used in the experiments was specified to be suitable for construction sheathing (mark: *CSA 0325 construction sheathing, 1R32/2F16/W24*). Before the installation, the sheathing boards were stored for several weeks at constant conditions, +22±1°C and relative humidity 30±5% RH.

The cement mortar-covered mineral wool, used in case Pex30ply9, was a commercial product meant to be used, for example, in retrofitting of building facades. The vapor permeance of the mortar was unknown.

Measured Results and Conclusions

The moisture mass flow rates were determined by regular weighing of the tested wall assemblies. In all the cases except the open reference case, the moisture flow rates changed significantly during each test period. Only in the "Open" case, a clear steady state could be reached. In the other cases, the moisture mass flow rates typically approached some stable level toward the end of each period. Especially strong changes were detected during the first period because the moisture content of the sheathing boards was initially much dryer than what the test conditions caused. OSB, for example, did not reach steady moisture flow level during the first 32-day period.

The problem was how to compare the drying efficiency of different cases during these relatively short measurement periods. One possibility could have been to compare the total mass of moisture that had dried out from each assembly. Moisture absorption in the sheathing materials, especially during the first period, would have affected these results. Therefore, we decided to use moisture mass flow rates in the comparison. These were chosen so that they corresponded best to the level that the mass flow rate approached and thus also to the drying efficiency of each case. These values were typically detected at the end of each period, and they were considered to be the most characteristic values for each case. However, the rank order of drying efficiency of different assemblies, determined using the total mass of moisture dried out from each assembly and the characteristic mass flow rates, was exactly the same.

Table 2 and Figure 4 present these characteristic moisture flow rates determined at the end of each period. The only exception was in period 3 with cases Ex30ply9 and Ex50ply9, which started to dry out before the end of the tests. Their values are the maximum values determined just before the drying effect could be seen in the moisture mass flow rates.

TABLE 2
Moisture Mass Flow Rates at the End of Each Test Period*

Case	+22/−10°C kg/(s·m^2) × 10^{-7}	+22/−5°C kg/(s·m^2) × 10^{-7}	+22/+3°C kg/(s·m^2) × 10^{-7}
Open	20.2	20.8	24.1
Ex30ply 9	13.5	14.0	15.6
Ex50ply9	13.6	13.1	14.8
p.w.fiberbd.	9.6	11.3	15.8
ply9	1.8	4.0	8.4
ply9(cfi)	2.0	4.0	8.1
ply12	1.2	2.8	7.4
Pex30ply9	1.2	2.3	6.7
OSB	(0.05)	0.2	0.9

*Only case "Open" had clearly reached steady state during each test period.

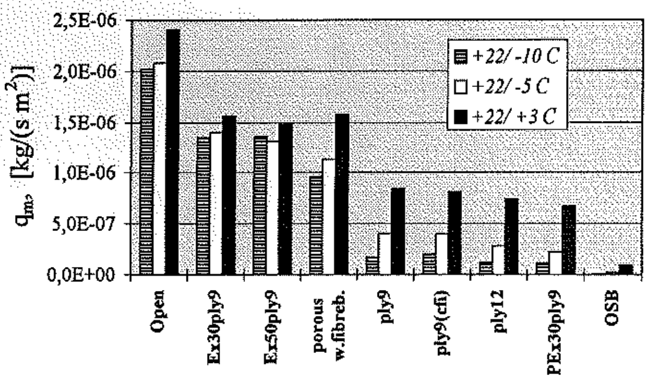

Figure 4 *Moisture mass flow rates drying out from the structures, measured at the end of each temperature period.*

The reference (open) wall had about the same moisture flow rates in both the test periods having freezing conditions at the cold-side air space. With >0°C cold-side air temperatures, the drying moisture flow increased by about 20%. Some moisture had to be added into this open wall because it nearly dried out during the first half of the third period.

The initial moisture was about to dry out just before the end of the experiments also in walls with open exterior insulation (Ex30ply9 and Ex50ply9), but no extra moisture was added into them. In these cases, the moisture flow rate started to decrease rapidly, and the selected characteristic values are the maximum values detected during the third period. The highest moisture flow rates, after the open case, were achieved in freezing cold-side conditions with walls having exterior insulation and plywood sheathing. When the cold-side air temperature was +3°C, these walls had about the same moisture flow rates as the wall with porous wood fiberboard sheathing without exterior insulation. Porous wood fiberboard is considered to be highly vapor-open material that allows effective moisture drying. Exterior insulation could improve the drying efficiency of a wall sheathing using 9 mm thick plywood to a similar level as a fiberboard-sheathed wall.

In both cases with open exterior insulation, the measured temperature of the sheathing board was above 0°C even when the cold-side temperature was −10°C. According to the dry thermal resistances, the temperature of the sheathing with thinner exterior insulation (case Ex30ply9) should have been under 0°C in these conditions. The higher temperature level was caused by the increase in the thermal conductivity of the internal insulation due to high moisture content and by the latent heat. Continuous evaporation from the warm side and condensation at the sheathing reduced the apparent thermal resistance of the warm-side insulation and warmed up the sheathing.

The effect of exterior insulation on the drying performance of an assembly was highest in cold outside temperatures. This occurred partly because freezing was avoided. The moisture flow rate through the plywood sheathing (9 mm) with exterior insulation was 7.5 times greater than through the plain plywood sheathing with −10°C cold-side air temperature. At −5°C cold-side air temperature, the drying rate was 3.5 times higher and with +3°C was nearly 2 times higher with the exterior insulation.

The thickness of the exterior insulation, whether it was 30 mm or 50 mm, hardly had any effect on the moisture flow rates when the insulation was open from the cold surface. Apparently, the increased vapor resistance of the exterior material layers nullified the effect of higher partial vapor pressure difference.

The wall section with mortar-covered exterior insulation and 9 mm plywood sheathing (Pex30ply9) only had about the same drying efficiency as the plain 12 mm plywood sheathing. The vapor resistance of the mortar finish caused different moisture distribution in test wall layers compared to cases with open exterior insulation. The open exterior insulation layers were typically almost dry, but with mortar finish, the moisture content of the exterior insulation was higher. This means that the relative humidity was high also at the cold side of the sheathing, and the partial vapor pressure difference across the sheathing board was significantly lower than in the cases with open exterior insulation. Thus, the mortar finish nullifies the increased drying potential that would be provided by the exterior insulation.

There was no difference between the moisture performance of assemblies having glass fiber or cellulose fiber insulation.

The moisture performance of the assembly with OSB sheathing was unexpectedly poor. In conditions typical to wet structures in cold climates, walls with OSB sheathing had the lowest drying efficiency during each test period. It is known that OSB has significantly lower vapor permeability in wet conditions than, for example, plywood, which is also considered to be relatively vapor-tight sheathing material. Wet cup measurements (City of Vancouver) have shown that the vapor permeability of OSB is one-fourth that of plywood. Our results confirm the weak vapor permeability of OSB, even in very wet conditions. At the end of the first period of drying experiments, there was hardly any moisture flow through OSB and the board was obviously still far from moisture equilibrium conditions. The ratio between the moisture flow rates through 12 mm plywood and OSB at the end of second and third periods was about 14 and 8, respectively.

Mold growth is very sensitive to the time that material layers are above the critical moisture content and temperature conditions (Figure 5) (Viitanen 1996). Fast drying of the structure decreases the risk of biological growth. Exterior insulation significantly enhances the drying of structures and seems to be a good solution for moisture-safe performance of walls with sheathing boards having relatively low vapor permeability.

The moisture content distributions in the test assemblies were determined after each one-month test period. Special interest was in the moisture content of the sheathing, which is the critical layer of the wall when moisture accumulation and biological growth are considered. This moisture content (Table 3) increased as long as there was a moisture source inside the test structure assembly, except in one case with plywood sheathing and cellulose fiber insulation. At the end of the experiments, the moisture content of plywood sheathing without exterior insulation was about 0.46 kg/kg (corresponding to 212 kg/m^3 partial moisture density), that of OSB was 0.3 kg/kg (190 kg/m^3), and that of porous wood fiberboard was 0.14 kg/kg (40 kg/m^3).

In cases with exterior insulation open to the outside surface, the maximum measured moisture content of plywood sheathing was as high as 0.69 kg/kg (317 kg/m^3) with 30 mm exterior insulation thickness and 0.83 kg/kg (382 kg/m^3) with 50 mm insulation thickness. At the end of the last test period, the moisture contents had decreased to 0.15 kg/kg (70 kg/m^3) and 0.19 kg/kg (90 kg/m^3), respectively. The decrease of the

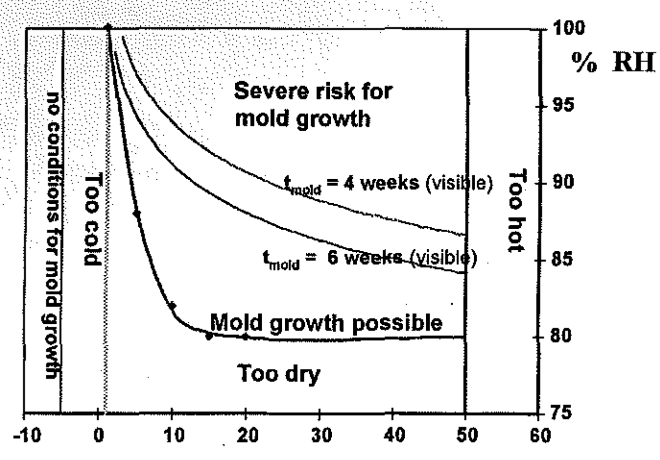

Figure 5 *Conditions for mold growth basing on measurements with wood (Viitanen 1996).*

TABLE 3
Moisture Content of the Sheathing Board at the End of Each Test Period

Case	Phase 1, u, % p	Phase 2, u, % p	Phase 3, u, % p
ply9	21.0	35.4	46.2
ply9(cfi)	-	42.1	22.8
ply12	21.8	25.7	46.0
Ex30ply 9	59.3	68.9	15.3
Ex50ply9	65.9	83.1	19.4
Pex30ply9	76.0	92.2	103.8
OSB	12.1	15.7	29.5
p.w.fiberbd.	17.0	17.1	14.4

moisture content was caused by the fact that the drying process was near its end. At the end of the last period, the moisture source had dried at the bottom of the wall assembly and the moisture that was left was distributed in the material layers.

The cement mortar-covered exterior insulation resulted in the highest moisture accumulation in the plywood sheathing; the maximum value was 1.04 kg/kg (478 kg/m^3). Unlike in the cases with exterior insulation open to ventilated air space, the mortar-covered wall contained most of the initial moisture at the end of the three-month experiments.

In cases with exterior insulation, even if they are open to outside air, there is high moisture accumulation in the sheathing during the drying process. Due to the raised temperature level caused by the exterior insulation, there is very little condensation in the actual insulation layer, and nearly all the moisture flow rate condensates at the warm surface of the sheathing. The exterior insulation causes faster drying of the structure (Table 2 and Figure 4). This clear advantage has to be considered against the fact that the wet and warm conditions in the sheathing may increase the risk for mold growth or even rot. However, if the large moisture source is dissipated, the sheathing will dry rapidly, as demonstrated in phase 3 by Ex30ply9 and Ex50ply9.

The performance criteria of a structure can be based on the possibility of mold growth. Vapor permeable external insulation can greatly increase the drying potential of walls in cold climates, although it can be expected to raise sheathing temperature and moisture content during drying. The first assumption is that shorter drying time even with higher temperatures is better than significantly longer drying time with varying temperatures. Besides, the increase of temperature level caused by the exterior insulation is significant only during the cold periods; at other times, the temperature conditions will allow mold growth in both the cases if excess water enters the wall cavities.

The relatively short moisture performance experiments were done using extreme moisture loads and constant climatic conditions. It would probably take a significantly longer time to experimentally analyze the moisture performance of walls under real climatic conditions and with more realistic (lower) moisture loads. Numerical simulation is a good tool that can be used to do sensitivity analysis for wall structures. In numerical simulation, the longtime moisture performance of different wall structures can be predicted under identical boundary conditions and the effect of a single parameter can thereby be evaluated.

MODEL USED IN SIMULATIONS

A computer program TCCC2D (Transient Coupled Convection and Conduction in 2 Dimensions) was used for the calculations (Ojanen et al. 1994). It has been verified and used in analysis for several different studies concerning heat, air, and moisture transfer in structures (Ojanen and Kumaran 1992; Ojanen and Kohonen 1995; Ojanen and Simonson 1995). This model can solve the transient heat, air, and moisture transfer in two-dimensional multilayer building structures. An ordinary finite difference method is used in the numerical solution. Heat is transferred by conduction and convection, and moisture is transferred by diffusion and convection. The material properties that are needed in simulations are dry density, thermal capacity, thermal conductivity, air and vapor permeability, and sorption isotherms. Weather files can include hourly values of ambient temperature and relative humidity, solar radiation intensities, and wind velocity and direction.

The simulation model has been improved with a mold growth simulation possibility. The mold growth model (Hukka and Viitanen 1997) is based on laboratory measurements with wood samples (Viitanen 1996). The mold growth in wood-based materials depends on temperature, relative humidity, and time (Figure 5). With these conditions, the model calculates a value for the mold growth index. The index may have values from 0 to 6, where 6 means that the surface of the material is fully covered with mold. Index value 3 is the limit value for the first visible mold growth on the material surface. The mold growth model is developed for wood, but it can be used to estimate the risks for mold growth on any material surface and it can be used as a moisture performance criterion together with moisture content levels of materials.

NUMERICAL ANALYSIS OF WALLS WITH EXTERIOR INSULATION

The objective was to study numerically the influence of exterior insulation on the drying of initial moisture from walls with OSB or plywood sheathing in different climatic conditions. The total mass of moisture and the mold growth index, solved according to Figure 5, were used as criteria in the analysis.

Only temperatures and relative humidities were used as the outdoor air boundary conditions. The analyzed walls were shaded and north facing. In cold climates, solar radiation typically enhances the drying of walls. When omitting the solar radiation, some additional safety factor was given for the moisture performance. Thus, summer condensation was not considered in the analysis.

Rain was also omitted in the study. The analyzed wall structure had a ventilated air gap, which was assumed to protect the structure from liquid water leakage. Due to the ventilated facade, the sheathing or exterior insulation was assumed to be in contact with the outdoor air conditions. Apart from the initial moisture content of the material layers, the only moisture load into the structure was the diffusive moisture flow from indoor air. The pressure difference over the wall was assumed to be zero, and there was no convective moisture flow. Indoor air exfiltration through the wall would cause significantly higher local moisture loads into the structure (Ojanen and Kumaran 1992), but it was not considered in this study.

In all the numerically solved cases, the indoor air temperature was constant, +21°C, or at least 3°C higher than the outdoor air temperature. The net moisture load of the indoor air was assumed to be constant, producing +4 g/m^3 moisture content difference between indoor and outdoor air. The indoor air relative humidity was limited to a maximum 80% RH level. For example, with −20°C outside temperature, the relative humidity of the indoor air was 27%. Significantly lower values have been measured in residential houses during winter in Finland. In the coldest analyzed climate (Jyväskylä), these assumptions resulted in 51% yearly average indoor air relative humidity. These values correspond to a relatively high average moisture load in residential houses and, thus, it even includes some safety factor.

Diffusive Moisture Loads

Diffusive moisture transport from indoor air into walls, some without a typical polyethylene vapor barrier, was studied numerically. The simulations were done using one-dimensional approximation for structures, omitting the internal air convection. All the analyzed cases had 150 mm thick glass fiber (20 kg/m^3) insulation. Table 4 presents the material layers at the interior and exterior sides of the insulation. All these cases had plywood sheathing, one with 30 mm exterior insulation. The main difference was the interior finish. Only one wall had a vapor barrier, one was made of plain plywood (12 mm) without paint, and two were made of plywood and gypsum boards with latex paint. The walls were assumed to have no building paper. The vapor permeability of the plywood was represented by the curve in Figure 2, and the diffusion resistance of the 12 mm painted gypsum board was set constant, $4 \times 10^{+9}$ (s·m^2·Pa)/kg.

TABLE 4
Numerically Analyzed Wall Structures

Case	Interior Finish	Exterior Sheathing	Exterior Insulation
Ply	Plywood 12 mm	Plywood 9 mm	-
GPly	Gypsum + paint + plywood 12 mm	Plywood 9 mm	-
Gply/R	Gypsum + paint + plywood 12 mm	Plywood 9 mm	30 mm MW
Vb	Gypsum + plywood with vapor barrier	Plywood 9 mm	-

The analysis was done using weather data from three different locations: Jyväskylä (in central Finland), Holzkirchen (in southern Germany), and Vancouver, Canada. The numerical simulation started September 1, and the simulation period was 28 months in order to include three autumns in the analysis. In cold climates, the late autumn has been found out to be the worst season for mold growth in the outer parts of wall structures, whereas the highest moisture contents are typically found during late winter and early spring.

The initial moisture content of the material layers corresponded to about the equilibrium at 75% relative humidity. Two simulations were done using different amounts of additional moisture to study both initially dry and wet cases. In the first study, there was no additional moisture except the initial equilibrium moisture in material layers. In the second study, there was 1.5 kg/m^2 additional moisture (1.5 mm layer of water) placed initially at the warm side of the thermal insulation layer.

Initially Dry Walls. Figure 6 presents the numerically solved total mass of moisture per unit wall area, and Figure 7 represents the predicted mold growth index values at the inside surface of the sheathing for each case without additional initial moisture added to the wall. Results for different climatic conditions have been marked by the initials of each location (J, H, V) before the case symbol presented in Table 4. In these cases, the moisture loads to the sheathing were caused by the diffusive moisture load from indoor air.

There was no yearly moisture accumulation in any of the analyzed wall structures. The wettest walls were those with plain plywood or plywood/gypsum board interior finish, but without exterior insulation. Walls with a vapor barrier were reference cases with presumably acceptable moisture performance. The wall with exterior insulation, but without a vapor barrier, had the lowest moisture content. With a vapor barrier and exterior insulation, the wall would most likely have dried out even faster to the final moisture level.

The first visible mold growth is possible when the index exceeds value 3. Values lower than 1 have no biological relevance; the value exceeds 0 only for numerical reasons.

The mold growth predictions supported the results from moisture performance analysis. Walls with exterior insulation did not have any signs of mold growth in the climatic conditions studied. Walls with a vapor barrier, but without exterior insulation, had no mold growth in Jyväskylä or Vancouver conditions. In the Holzkirchen climate, this structure showed yearly increase in mold growth, even though it stayed below threshold value 3 during the simulation period.

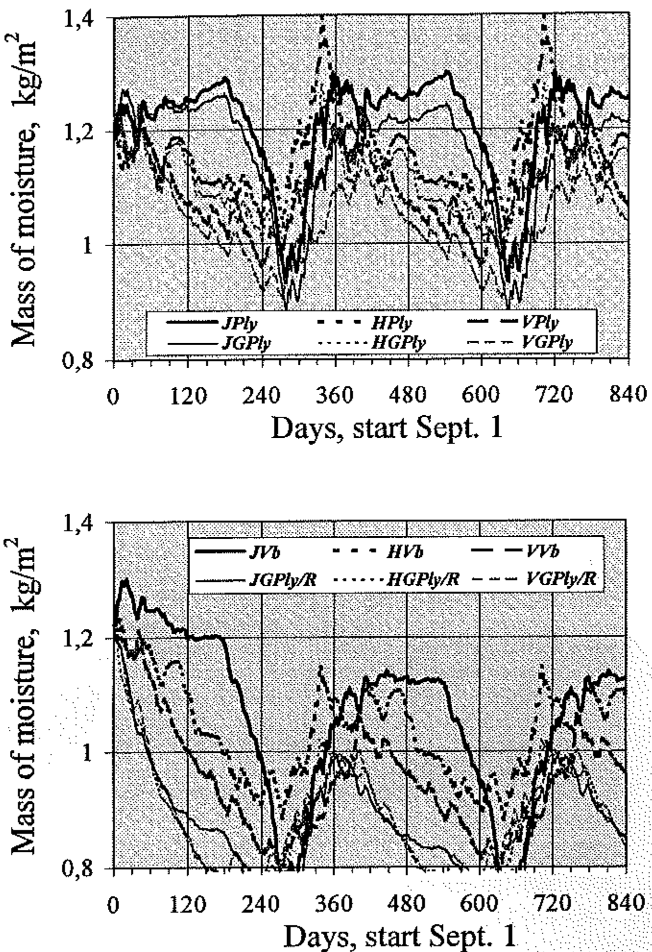

Figure 6 *Numerically predicted total mass of moisture per wall area in cases (Table 4) with only diffusive moisture load from indoor air in Jyväskylä, Finland (J), Holzkirchen, Germany (H), and Vancouver, Canada (V), climatic conditions.*

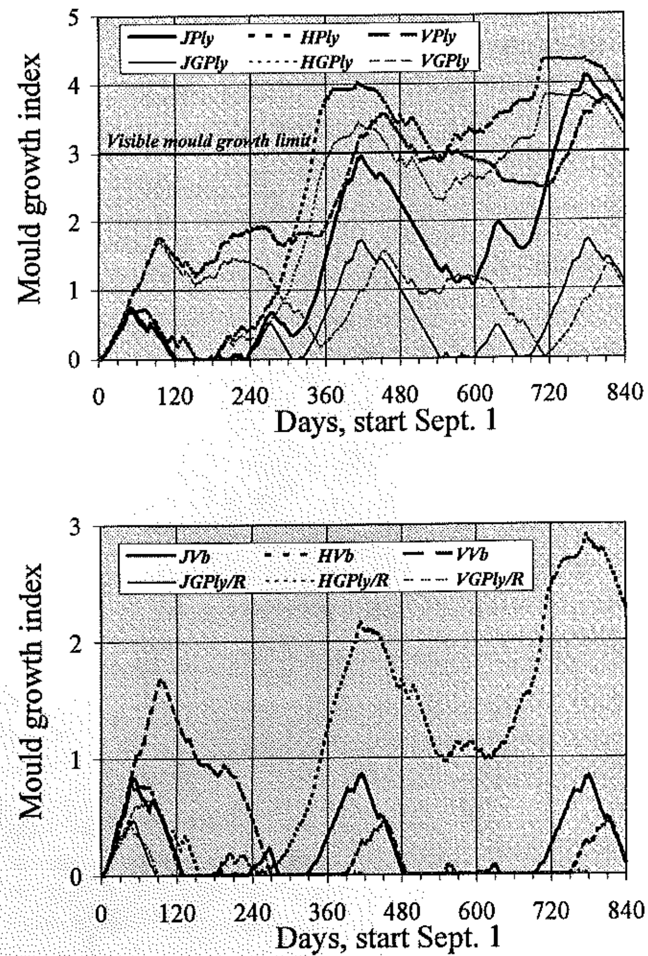

Figure 7 *Numerically predicted mold growth index at the warm surface of the sheathing board in cases (Table 4) with only diffusive moisture load from indoor air in Jyväskylä, Finland (J), Holzkirchen, Germany (H), and Vancouver, Canada (V), climatic conditions.*

In cases with plain plywood interior finish, the mold growth index exceeded the visible limit value 3 in all the studied climatic conditions. In cases with painted plywood/gypsum interior finish, this limit was exceeded in Holzkirchen climatic conditions, while the same structure in Jyväskylä and Vancouver climates did not have any mold growth problems. Holzkirchen weather conditions seemed to be more critical for the diffusion loads than the other climatic conditions used in the numerical analysis.

In cold climates where structures dry mainly outward, a vapor barrier at the inside surface, used together with exterior insulation, is an even better solution than those presented in this analysis. Vapor barriers decrease the diffusive moisture loads from indoors to negligible levels and, due to the exterior insulation, the drying efficiency against other, incidental moisture loads would be improved.

Initially Wet Walls. These cases present the effect of introducing additional moisture on the drying of the walls. The moisture load to the sheathing board was caused, in the beginning, by the redistribution of the additional moisture and by the diffusive moisture load from indoor air. Due to the relatively long drying periods, there were similar mold growth conditions in all the cases. Therefore, only the drying of the walls was compared.

Due to the low relative humidity and partial vapor pressure conditions of the indoor air during cold winter periods, it was possible that some of the moisture was transported from the wall to the indoor air. However, the moisture flow from the inside finishing boards to the inside air took place only in the coldest winter periods. The initial additional moisture was transported from the warm side of the insulation to the colder parts of the wall during the first month. The moisture flow from the structure to the indoor air was temporary, and it had only a relatively weak effect on the moisture content of the inside finishing boards, not on the additional initial moisture in the insulation layer. Therefore, in all the cases analyzed, the

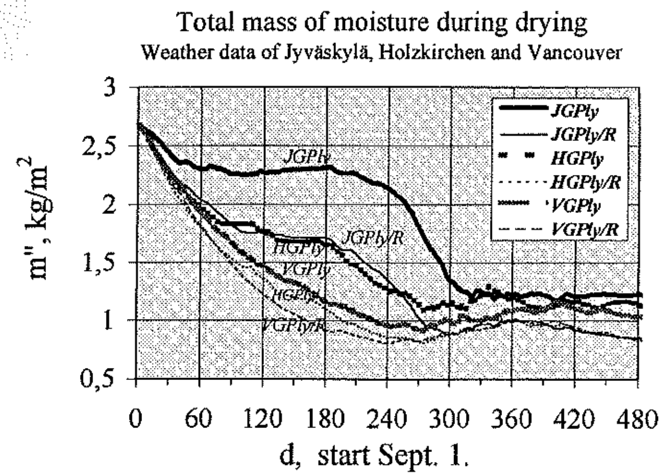

Figure 8 *Effect of exterior insulation on the drying of high initial moisture from walls having plywood sheathing. Diffusive moisture flow through drywall (painted gypsum and plywood) was possible. Simulations were done using Jyväskylä, Finland (J), Holzkirchen, Germany (H), and Vancouver, Canada (V), climatic conditions.*

dominating moisture flow was outward from the walls, and moisture transport to the indoor air had only a marginal effect on the total moisture balance of the walls, even in cases without a vapor barrier.

Figure 8 presents the numerically solved total mass of moisture per wall area in cases where the interior finish was painted gypsum and 9 mm plywood board (double board) and the exterior sheathing was 9 mm thick plywood. These structures were analyzed with and without exterior insulation in the weather conditions of the three locations. According to the simulation results, the effect of exterior insulation on the drying efficiency seemed to be strongest in cold climates and lowest in the mild climatic conditions of Vancouver. This is obvious because in cold climates the exterior insulation makes the freezing periods of the sheathing board significantly shorter and increases the drying potential more than in warmer weather conditions. If the overall temperature difference is small, exterior insulation has little effect on the temperature and vapor pressure levels of the sheathing board.

In cases without exterior insulation, the effect of winter cold could be seen in the results. During winter in Jyväskylä, the internal moisture flow into the wall exceeded the drying moisture flow, and the net drying was stopped for some time. In Holzkirchen the net drying slowed down during winter, but in Vancouver there was no significant change in the moisture mass flow rate during the cold season.

Without exterior insulation, the total mass of moisture reached the final level (about 1.2 kg/m^2) in about eleven (Jyväskylä), nine (Holzkirchen), and six months (Vancouver). With exterior insulation, it took about nine, six, and four months, respectively, to reach the same moisture level. The predicted drying periods seem to be long, but the continuous diffusive moisture load from indoor air and the lack of solar radiation changed the simulated performance compared to most of the cases in practice with a ventilated air cavity.

After the drying of additional moisture, the total mass of moisture was, depending on location, about 1 kg/m^2 to 1.2 kg/m^2 in walls without exterior insulation. With exterior insulation, the total mass of moisture was almost independent on the location, varying between 0.8 kg/m^2 and 1.0 kg/m^2 during the year.

The simulations showed clearly that the exterior insulation improves the moisture safety of walls by enhancing the drying efficiency and decreasing the final moisture content level. The effect on drying efficiency is higher in cold climates. Even if the moisture content level of the sheathing board is high during drying, the period having conditions favorable for mold growth will be significantly shorter in walls with exterior insulation than without it.

MOISTURE-SAFE WOOD FRAME STRUCTURES WITH EXTERIOR INSULATION

Moisture-safe building structures require additional drying efficiency against unpredictable moisture loads. Especially, timber frame walls that have low moisture absorption capacity and sheathing with low vapor permeability are very sensitive to these loads. High initial moisture contents caused by wetting during the building process or accidental water leakage into the wall due to failed weatherproofing are quite possible in real structures. A wall should be able to dry out from low additional moisture loads before the biological processes, such as mold growth, start. However, additional moisture safety of structures cannot be seen as a substitute for proper protection against moisture loads from indoor or outdoor air.

This study and its conclusions are based on the assumption of a wall structure with a ventilated air cavity between the siding and exterior sheathing or possibly exterior insulation. The temperature and humidity conditions of the cavity air are close to those of the outdoor air due to the ventilation.

Vapor permeable exterior insulation used at the cold side of the sheathing was found to be an effective method to enhance the drying efficiency of walls in cold climates. Improvement in drying efficiency will, however, be nullified unless the outer face of the exterior insulation is open to an air cavity vented or ventilated to the outside. Exterior insulation raises the temperature level of the sheathing. This increases the partial vapor pressure difference (drying potential) across the sheathing and also reduces the freezing periods that affect the apparent vapor permeability of the layer.

According to measurements, the drying efficiency of a wall having 9 mm plywood sheathing and 150 mm total insulation thickness could be increased 7.5 times by installing 30 mm thick insulation at the exterior side of the sheathing. In this case, the cold-side air temperature was −10°C and the exterior insulation raised the temperature of the sheathing above freezing conditions. When the cold-side air temperature was above 0°C, the drying efficiency of the same wall could still be raised by nearly 100% with exterior insulation. When the exterior insulation thickness was increased from 30 mm, the drying efficiency of the wall did not increase. A relatively small exterior insulation thickness is adequate for improving the moisture performance of a wall in climatic conditions typical to those in most locations in Finland and Canada.

Under high moisture loads, exterior insulation may raise the moisture content of the sheathing during the drying. Despite conditions favorable to mold growth during the drying, the significantly shorter drying time makes the walls with exterior insulation more effective against biological deterioration than walls without it. Besides the increased drying efficiency, exterior insulation protects the structure against thermal bridges, and, thus, it helps to avoid condensation conditions on the inside surface or internal material layers.

The requirement for an open cold-side surface of the exterior insulation is important in order to ensure safe moisture performance of the walls. With mortar-covered exterior insulation, the moisture flow rate out from the wall was slightly lower than in a case with plain sheathing board without exterior insulation. Also, the moisture content of the sheathing was found to be very high in such walls during the drying. Long drying time and high moisture content increase the risks for moisture damage. These walls may have good moisture performance in some cases, but they may be very sensitive to any additional moisture load. The increase of drying efficiency caused by the exterior insulation can be lost by outside rendering with low vapor permeability. A weather barrier with high vapor permeability can possibly be used outside the insulation without causing a significant decrease in the drying efficiency.

The OSB sheathing used in the experiments was found to have relatively low vapor permeability, even when compared to plywood, and especially in wet conditions. Drying of the walls having this OSB sheathing is very slow in cold climatic conditions. The vapor permeability of OSB may vary depending on the binder used in manufacturing of the board, and these results are only valid for the material used in the experiments.

A moisture-safe wood frame wall structure in cold climates has a sufficient air and vapor barrier at the inside surface to keep the indoor air moisture loads low and exterior insulation adjacent to a ventilated air cavity permitting higher drying efficiency against accidental moisture loads.

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