Drying Rate of Timber-Framed External Wall Assemblies in Nordic Climate

Juha Vinha
Member ASHRAE

Pasi Käkelä

ABSTRACT

This research looks into the moisture behavior of timber-framed external wall assemblies under Nordic climate conditions. The focus of this study was to measure drying rates of wall assemblies and to study the effects of different material layers on drying times from the viewpoint of water vapor diffusion of moisture-permeable walls (walls with an air barrier and no vapor barrier) and moisture-impermeable walls (walls with air and vapor barrier). Drying times have been estimated from laboratory test results. Laboratory tests were done with test equipment that allowed full-scale laboratory tests in real climate conditions. The main focus has been on relative humidity and temperature changes in the outer surface of the insulation layer (behind the sheathing) in different climatic conditions. Analysis was based on three criteria: limit value of mold growth during the autumn period, condensation during the winter period, and drying times during the spring period. It was noticed that water vapor resistance of the inner lining of the wall assembly has no significant effect on drying times during the spring period. In other words, moisture-permeable and impermeable walls have the same drying times if their other properties are identical. It can be generally noted that the water vapor resistance ratio between the inner and outer lining should be at least 5:1 in a Finnish climate. However, there are a lot of different variables that have an effect on this ratio (conditions of outdoor air, humidity excess of indoor air, physical properties of materials, etc.) and, therefore, in some cases, this ratio should be bigger.

INTRODUCTION

It is important to know the moisture behavior of building envelopes because earlier massive structures have been replaced by insulated layered structures and, at the same time, the use of water inside buildings has increased considerably. Materials may also get moist before they are even installed due to improper protection on site. In addition, new ecological and synthetic building materials, whose behavior has not been examined, have come onto the market. Also, there has been a lot of discussion in Finland on how vapor permeable inner parts of wall assemblies could be. Among other things, these reasons were the basis for our research. The research began in 1999 and ended in 2004. This paper is focused on the relative humidity levels and drying properties of external walls during different season conditions in Finland.

The research consists of laboratory tests, computer calculations, and material tests (42 different materials have been tested). The material tests are needed to get the right basic values for calculational programs (such as a water vapor resistance, thermal conductivity, etc.). Full-scale building physical laboratory tests are needed to make sure that calculation analyses and basic values for materials are correct. Material test results are presented in another paper at this conference. This research continues earlier research on moisture transport due to diffusion and convection in eight different timber-framed wall assemblies under winter conditions (Vinha and Käkelä 1999). Some laboratory tests have been done and articles written for the drying of timber-framed external walls in Finnish climate at the Technical Research Center in Finland (e.g., Ojanen [1998], Ojanen et al. [1993], Nieminen [1987]), but this research has been quite limited. Basically, comparison to other research done elsewhere is difficult because our test equipment is unique and most of the tested materials are commonly used mostly in Finland. Furthermore, the climatic conditions in Nordic countries are quite unique.

In the Finnish climate, the relative humidity of the outdoor air is usually over 60% RH in summer, while in

Juha Vinha is a senior research scientist and **Pasi Käkelä** is a research scientist in the Department of Civil Engineering, Tampere University of Technology, Tampere, Finland.

winter, the average relative humidity is about 90% RH. Another typical characteristic is that the fluctuation of outdoor temperature is also rather high, not only between different seasons (summer-winter) but also between day and night (especially in the early spring). However, the humidity by volume is quite low in winter because the average temperature in winter is about –10°C (14°F). Humidity excess of the indoor air over outdoor air may be rather high (EN ISO 13788). These facts were the basis to boundary conditions that were used in the laboratory tests.

Moisture loads on wall assemblies might cause problems such as mold growth or condensation behind the sheathing (in the insulation layer). For example, condensation may occur during the first year after construction because of the initial moisture level of the materials. In these cases, the most important thing is that moisture does not accumulate in the assemblies (due to diffusion) and that the moisture level decreases through time. This means that the wall assembly must have adequate drying capability and, on the other hand, that the internal wall lining should have sufficient water vapor resistance.

Laboratory tests have been done with the building physical test equipment. The equipment was built at Tampere University of Technology. As many as 56 wall assemblies were tested during 2000-2004 under Finnish autumn, winter, and spring conditions. The criteria that have been used in estimating the performance of the wall assemblies were the limit value for mold growth (Viitanen 1996) in autumn conditions, condensation behind the sheathing (in the insulation layer) in winter conditions, and the drying capability under spring conditions. In this connection, the main focus is on the laboratory tests, from the view of drying capabilities and diffusion.

TEST METHOD

Test Equipment

The equipment for the building physical tests was built at the Laboratory of Structural Engineering at the Tampere University of Technology (TUT). The apparatus was built for studying the moisture behavior of building envelope structures under different conditions free from external disturbances. The test equipment was developed on the basis of earlier calibrated hot box (CHB) equipment that was used to determine the thermal transmittance of structures (U-factor) (Vinha 1998).

The equipment consists of a warm chamber and a protective chamber. The wall assembly under examination is placed between them. The warm chamber is used to model indoor air conditions, while the protective chamber models outdoor air conditions. These chambers are all set in a large freezer room where the outdoor temperature is controlled by a refrigeration unit (Figure 1).

The equipment incorporates numerous measurement and control instruments that are computer-controlled. Accurate and fast regulation of conditions requires an effective control program that continually maintains equilibrium between the various factors. Tests can be conducted either under constant or varying conditions, and condition values can be chosen freely. In tests, the controllable variables, control ranges, and accuracies are as follows:

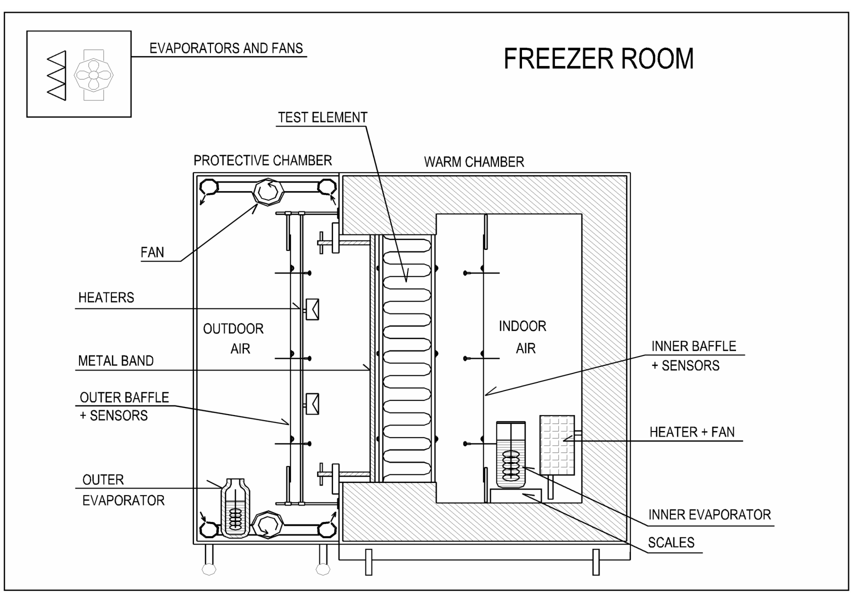

Figure 1 *Test arrangement for the tests of wall structures in the building physical test equipment. The test area is 1200 × 1200 mm² (47.2 × 47.2 in.²), depth is 400 mm (15.7 in.).*

Table 1. Material Layers of Some Examined Wall Assemblies

Test Wall	Air/Vapor Barrier	Thermal Insulation	Sheathing
1	Plastic 0.2 mm (0.008 in.)	Glass wool 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
2	Plastic 0.2 mm (0.008 in.)	Rock wool 173 mm (6.81 in.)	Rock wool board (IRL) 30 mm (1.2 in.)
3	Bitumen paper	Cellulose insulation 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
4	Bitumen paper	Cellulose batt insulation 173 mm (6.81 in.)	Cellulose insulation board 25 mm (0.98 in.)
5	Bitumen paper	Mixed sawdust and chipping 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
6	Bitumen paper	Flax insulation 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
7	Plastic 0.2 mm (0.008 in.)	Mixed sawdust and chipping 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
8	Plastic 0.2 mm (0.008 in.)	Cellulose insulation 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
9	Bitumen paper	Cellulose insulation 197 mm (7.76 in.)	Gypsum board 9 mm (0.35 in.)
10	Bitumen paper	Cellulose insulation 197 mm (7.76 in.)	Wood hardboard 4.8 mm (0.19 in.)
11	Bitumen paper	Glass wool 197 mm (7.76 in.)	Gypsum board 9 mm (0.35 in.)
12	Bitumen paper	Glass wool 197 mm (7.76 in.)	Wood hardboard 4.8 mm (0.19 in.)
13	Plastic-coated paper	Cellulose insulation 197 mm (7.76 in.)	Gypsum board 9 mm (0.35 in.)
14	Plastic-coated paper	Cellulose insulation 197 mm (7.76 in.)	Wood hardboard 4.8 mm (0.19 in.)
15	Plastic-coated paper	Glass wool 197 mm (7.76 in.)	Gypsum board 9 mm (0.35 in.)
16	Plastic-coated paper	Glass wool 197 mm (7.76 in.)	Wood hardboard 4.8 mm (0.19 in.)
17	Bitumen paper	Flax insulation 197 mm (7.76 in.)	Weatherization membrane (type 1)
18	Bitumen paper	Rock wool 197 mm (7.76 in.)	Weatherization membrane (type 1)
19	Bitumen paper	Flax insulation 197 mm (7.76 in.)	Weatherization membrane (type 2)
20	Bitumen paper	Rock wool 197 mm (7.76 in.)	Weatherization membrane (type 2)
25	Bitumen paper	Cellulose insulation 197 mm (7.76 in.)	Gypsum board 9 mm (0.35 in.)
26	Bitumen paper	Cellulose insulation 197 mm (7.76 in.)	Wood fiberboard 25 mm (0.98 in.)
27	Bitumen paper	Glass wool 173 mm (6.81 in.)	Gypsum board 9 mm (0.35 in.)
28	Bitumen paper	Glass wool 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
29	Plastic 0.2 mm (0.008 in.) Fir plywood 9 mm (0.29 ft)	Cellulose insulation 173 mm (6.81 in.)	Fir plywood 9 mm (0.35 in.) + Glass wool 25 mm (0.98 in.)
30	Plastic 0.2 mm (0.008 in.) Fir plywood 9 mm (0.35 in.)	Cellulose insulation 197 mm (7.76 in.)	Fir plywood 9 mm (0.35 in.)
31	Plastic 0.2 mm (0.008 in.) Fir plywood 9 mm (0.35 in.)	Rock wool 173 mm (6.81 in.)	Fir plywood 9 mm (0.35 in.) + Glass wool 25 mm (0.98 in.)
32	Plastic 0.2 mm (0.008 in.) Fir plywood 9 mm (0.35 in.)	Rock wool 197 mm (7.76 in.)	Fir plywood 9 mm (0.35 in.)
33	Bitumen paper	Flax insulation 197 mm (7.76 in.	Weatherization membrane (type 3)
34	Bitumen paper	Flax insulation 197 mm (7.76 in.)	Plastic 0.2 mm (0.008 in.)
35	Bitumen paper	Rock wool 197 mm (7.76 in.)	Weatherization membrane (type 3)
36	Bitumen paper	Rock wool 197 mm (7.76 in.)	Plastic 0.2 mm (0.008 in.)

- Indoor air temperature (T) 0…+60°C ± 0.1°C
- Outdoor air temperature (T) –40…+20°C ± 0.2°C
- Indoor relative humidity (φ, RH) 20…80% RH ±2% RH
- Outdoor relative humidity (φ, RH) 50…95% RH ±2-3% RH
- Pressure difference (Δp) –50…+50 Pa ±1 Pa

The control range of an individual condition varies somewhat depending upon what other condition variables are selected and what their properties are. In particular, the control range of differential pressure varies considerably with the impermeability of the materials that the test wall assembly is made of.

Examples of variables to be measured during the test are:

- indoor and outdoor temperatures, temperatures in the assembly and on the surfaces T (°C, °F)
- relative humidity of the indoor air, the outdoor air, and the air in the porous space of the assembly φ (% RH)
- differential pressure across the assembly at the upper and lower section of the test element Δp (Pa)
- humidity by volume indoors, outdoors, and in the porous space of the assembly ν (g/m^3, lb/ft^3)
- velocity of airflow indoors, outdoors, and in the ventilation gap r (m/s, ft/s)
- total airflow rate to and from the warm chamber R_{tot} (L/min, ft^3/min)
- total moisture flow rate from the warm chamber G_{tot} (g/day, lb/day)
- total heat flow rate out of the warm chamber Φ_{tot} (W, cal/h)

In addition, samples taken from the structure yield the following data:

- moisture content of the building materials u (%), w (kg/m^3, lb/ft^3)
- amount of moisture in the building materials m (g, lb)
- condensation rate behind the sheathing

The measured variables can be used for calculating various other values for the test wall assembly (e.g., the risk of mold growth). The mold growth risk analysis that was used in this research is based on research work of Viitanen (1996). The limit values for mold growth (RHcrit) may be expressed as (Hukka and Viitanen 1999)

$$Rh_{crit} = -0.00267T^3 + 0.160T^2 - 3.13T + 100.0,$$

when 0°C < T < 20°C (32°F < T < 68°F);

$$Rh_{crit} = 80,$$

when T > 20°C (68°F),

T = temperature reading from the point that is analyzed.

The building physical test equipment also has many other features that together make it a novel and versatile apparatus. The performance of the test equipment is described in more detail in Vinha and Käkelä (1999).

Test Wall Assemblies

The test walls were assembled in frames made of 9 mm (0.35 in.) film-coated plywood to eliminate air and moisture losses. The size of the frames was 1185 × 1185 mm^2 (46.7 × 46.7 in.^{2}). The thickness of the frames varied between 195

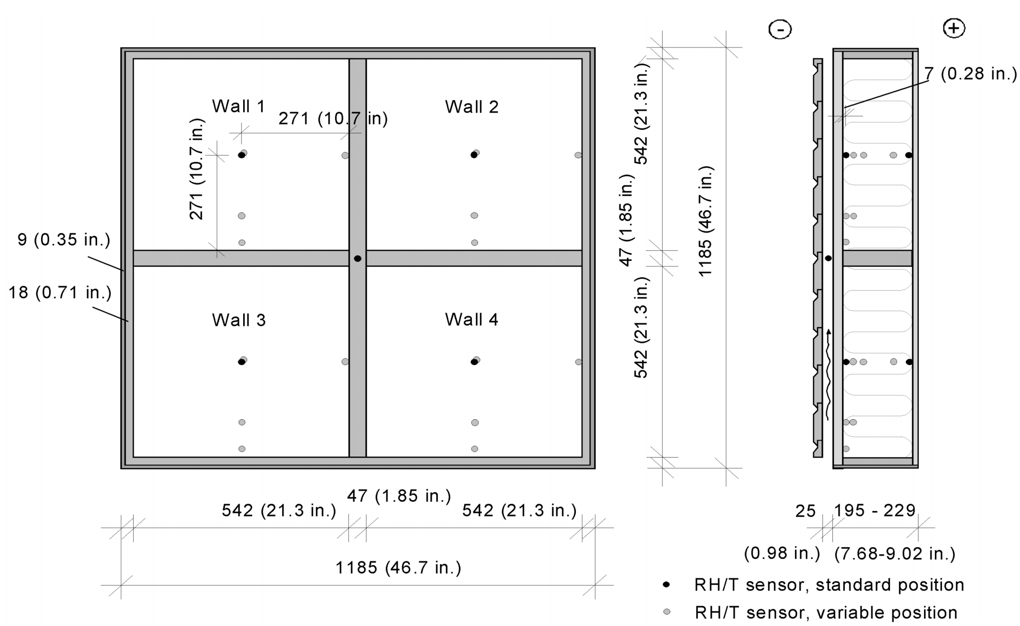

Figure 2 *Structure of the test wall assemblies and measuring points in wall assemblies under test.*

Table 2. Boundary Conditions During the Laboratory Tests. Indoor Humidity Excess Was in Most Cases 4.0 g/m³ (2.5*10⁻⁴ lb/ft³) (Humidity by Volume). Under Spring Period Conditions the Indoor Humidity Excess was Typically a Little Bit Higher: About 5.0 g/m³ (3.1*10⁻⁴ lb/ft³).

Variable	Autumn	Winter	Spring
T indoor	+20°C (68°F)	+20°C (68°F)	+20°C (68°F)
I outdoor	+7°C (44.6°F)	−10°C (14°F)	−6…+10°C (21.2…50°F), 1 cycle/ day
φ indoor	62% RH	35% RH	46% RH
φ outdoor	85% RH	90% RH	50…90%, 1 cycle/ day
Δp	0 Pa	0 Pa	0 Pa
Test period	6 to 11 weeks altogether		

(7.68 in.) and 229 mm (9.02 in.), depending on the test wall type. The test element was divided into four sectors (test walls) by a 47 mm (1.85 in.) wide bracing, and the edges were lined with 18 mm (0.71 in.) wide mixed plywood sheets. In each test wall, the insulation space was 542×542 mm^2 (21.3×21.3 in.^{2}) (Figure 2). Some test elements were divided vertically into only two sectors (capillary range tests that are not handled in this presentation).

The elements were usually assembled with the first interior board with the air/vapor barrier installed on the inner edge of the frame. After this, the thermal insulation material and the sheathing were installed. The thicknesses of thermal insulation were chosen so that the new thermal insulation requirements of external walls (Finnish building code, Section C3, 2003) were fulfilled excluding assemblies insulated by mixed sawdust and shipping. Sheathings in different walls were separated from each other by a plastic sheet to prevent capillary moisture flow from one sheathing to another. The interior board, the air/vapor barrier, and the sheathing were sealed to the rabbets of the frame with silicone. The inner board was always uncoated. The loose thermal insulation materials were also weighed before the test to determine their density.

Humidity and temperature sensors were placed inside the wall to measure both temperature and relative humidity. In all of the tests, the sensors were placed beside the air/vapor barrier and the sheathing in the insulation space of the wall assembly (see Figure 2). In addition, there were four sensors in some positions, which varied between tests. These sensor positions are shown in Figure 2. The measuring point of humidity sensors is approximately 7 mm (0.28 in.) distance from surface of the sheathing and the inner membrane because the diameter of sensors was 13.5 mm (0.53 in.). Airflow and humidity sensors were placed in the ventilation gap in the middle of the element under test. The indoor and outdoor airflow and humidity sensors were located between the baffle and the element surfaces at a distance of 150 mm (5.91 in.) from either surface. Viewed from the front, these sensors were also located in the center of the test element.

The material layers of the wall assemblies tested, which are handled in this connection, are shown in Table 1. The same external cladding was used in all wall assemblies: horizontal paneling (22 mm [0.87 in.]) with a ventilation gap (25 mm [0.98 in.]) behind it. The inner board was also always the same: uncoated gypsum board (13 mm [0.51 in.]). The water vapor

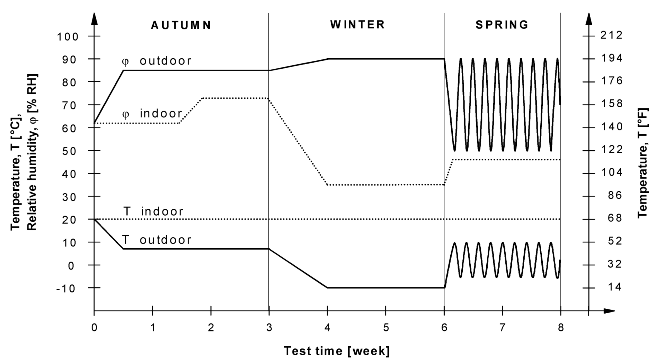

Figure 3 *The boundary conditions during the tests.*

permeability and thermal conductivity of each material is given in another paper presented at this conference. These values were also determined in the same research project.

The initial humidity level in the pores of the insulation materials and sheathings of the test walls was 86% RH at the beginning of the autumn period. The inner boards and sheets, frames, and bracings always had the same initial humidity level (the storage conditions were about 65% RH).

Test Conditions

The test conditions are based on the average outdoor air conditions in Finland. The temperature of the indoor air was held constant at +20°C (68°F). The relative humidity of the indoor air was adjusted so that the humidity excess of the indoor air was 4 g/m^3 (2.5×10^{-4} lb/ft^3), but, in some cases, during the end part of the autumn period, a humidity excess of 6 g/m^3 (3.7×10^{-4} lb/ft^3) was also used. The air pressure difference was set at zero pascals. The overall test duration was mostly about 1½…2½ months. The test conditions used are shown in Table 2 and in Figure 3.

During the spring period, the outdoor temperature was adjusted cyclically by heaters, so that the duration of one cycle was one day. Because the outdoor temperature was cyclical, the outdoor air relative humidity was cyclical too. Adjusting the relative humidity was quite difficult because of the cyclical temperature. That is why the average value of the indoor air was about 5.0 g/m^3 (3.1*10^{-4} lb/ft^3).

When going from the autumn period to the winter period, the temperature was adjusted smoothly over one week (Figure 3).

TEST RESULTS

The focus of the results has been the relative humidity values behind the sheathings in the insulation layer. Results from some of the test walls after the autumn and winter periods are given below in the first part of the results. These results have been analyzed also earlier in other conference papers (Vinha et al. 2001a, 2001b; Vinha and Käkelä 2002). In the second part, the results after the spring period are given.

Impact of Diffusion and Structural Moisture under Autumn and Winter Conditions

Figures 4 to 7 show the relative humidity values in the pore air of the insulation layer after an autumn or winter period when the values are near equilibrium. In the same figures, the water vapor resistance ratio between the inside and outside of walls is also presented next to each test wall number (between inner board +air/vapor barrier and sheathing).

The humidity values of moisture-permeable structures 3, 4, and 6 are higher behind the sheathing than those of moisture-impermeable structures 1 and 2 after the autumn period (Figure 4). The mold growth limit value is also shown in Figure 4; when the RH exceeds it, mold growth may occur. Test walls 3 and 6 exceed the limit slightly. Thus, there is no difference between cellulose insulation and flax insulation, either. When the sheathing is more vapor permeable (test wall 4), the relative humidity is lower. The same phenomenon can be noticed in the case of test walls 1 and 2; rock wool sheathing (wall 2) is more permeable than wood fiberboard (wall 1). In the case of moisture-impermeable walls, the results of test wall 8 also indicate that no significant difference in RH occurs whether mineral wool or hygroscopic natural fiber insulation is used as thermal insulation.

The same phenomenon can be seen if we look at the same type of walls under winter conditions (Figure 5). The differences between moisture-permeable and impermeable walls are now clearly greater. However, there was no condensation behind the sheathing of any wall. Therefore, the mold risk during the autumn period might often be more critical than the condensation risk in winter conditions for the Finnish climate. After all, actual mold growth requires that these temperature and humidity conditions exist for quite a long time.

Figures 6 and 7 show the same type of test results when the sheathings of the test walls are thinner or less vapor permeable than in the previous test walls. In these test walls, the thermal insulation was also 25 mm thicker. Because the water

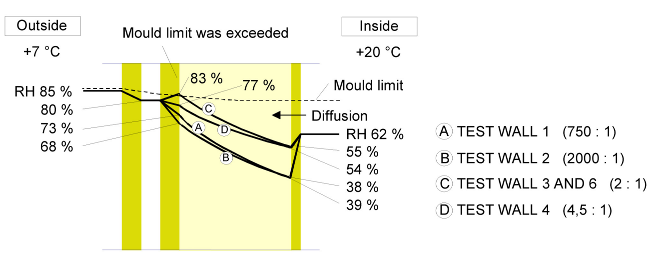

Figure 4 *Relative humidity values of test walls 1, 2, 3, 4, and 6 after the autumn period. The water vapor resistance ratio between the inside and outside of structures is presented next to each test wall number.*

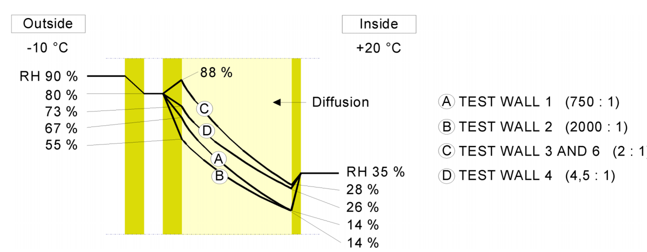

Figure 5 *Relative humidity values of test walls 1, 2, 3, 4, and 6 after the winter period.*

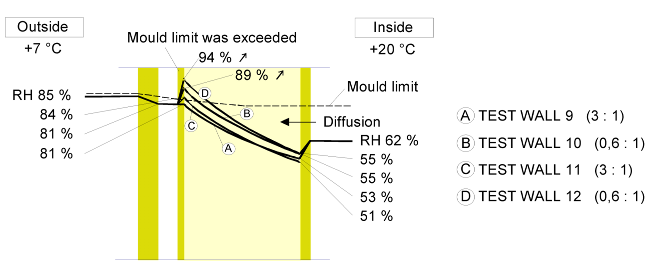

Figure 6 *Relative humidity values of test walls 9, 10, 11, and 12 after the autumn period.*

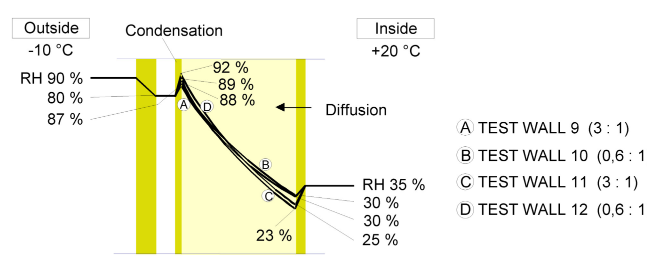

Figure 7 *Relative humidity values of test walls 9, 10, 11, and 12 after the winter period.*

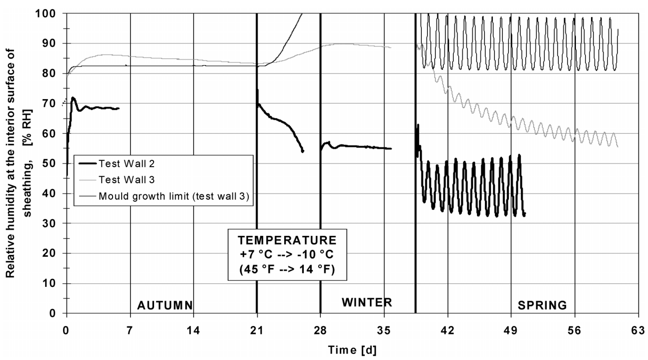

Figure 8   *Relative humidity curves at the interior surface of the sheathing during two test runs. The mold limit curve is almost the same for all wall assemblies at this point because it depends on temperature (which was almost the same for all wall assemblies).*

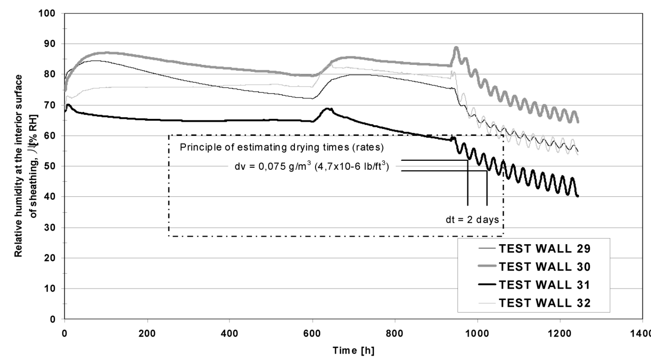

Figure 9   *Relative humidity curves at the interior surface of the sheathing during the test on test walls 29-32, showing the method of estimating drying times.*

vapor resistance and the thermal conductance of wood hardboard are higher than in mineral wool and in wood fiberboard, the RH values rose with test walls 10 and 12 (Figure 4). These values were clearly over the mold limit. When gypsum board was used, the values were of almost the same level as with test walls 3 and 6.

These same walls were tested under autumn conditions also where the humidity excess of indoor air was 6.0 g/m^3. In this test, the RH values kept rising, and in the end they were about 5% higher. Water also condensed behind the wood hardboard. Thus, the effect of the indoor humidity excess is significant.

After running these autumn conditions, the same structures were subjected to winter conditions where the humidity excess was 4.0 g/m^3. During this test period, condensation occurred in all these assemblies, including walls with a gypsum board sheathing (Figure 7).

In addition, this test showed that condensation is possible in a moisture-permeable wall structure despite containing insulation material. The only difference is that condensation begins later when cellulose insulation is used in the assembly. In other words, the moisture capacity of hygroscopic insulation is limited.

In the next test (walls 13…16), the air barriers of the structures were changed from bitumen paper to a more vapor-tight plastic-coated paper. The other materials of structures were unchanged (the water vapor resistance ratio between the indoor and outdoor wall linings was 10:1…55:1). Now, the relative humidity values were about 10% lower after the autumn period, and there was no significant difference between gypsum board and wood hardboard. The results were the same even when these assemblies were subjected to a higher humidity excess (6.0 g/m^3, 3.7 *10^{-4} lb/ft^3) for a week at the end of the autumn period. There were no problems during the winter period either. Thus, these walls behaved extremely well in the test.

Wall tests also indicated that the good thermal resistance of sheathing lowered relative humidities at the interior surface of sheathing and thus improved the moisture behavior of assemblies remarkably.

Drying Properties of Test Wall Assemblies

The drying time describes the time that elapses from the moment the indoor or outdoor air conditions change (winter period to spring period), allowing the wall to start drying from a higher moisture content to a lower one until the moment the moisture contents of a wall assembly reach equilibrium or the chosen drying level. Because every wall assembly behaved differently in the autumn and winter periods, so the initial humidity level was different for each wall assembly at the beginning of the spring period. But, on the other hand, this described drying properties for different wall assemblies after real winter conditions. What this means practically differs from case to case. Figure 8 shows some example curves that have been measured.

If we look at the curves in Figure 8, we will notice that there is a significant difference between the drying rates for test walls 2 and 3. Test wall 3 is made of hygroscopic materials and test wall 2 is made of nonhygroscopic materials. In this research, drying times have been determined in the way shown in Figure 9. Here the drying time is the time from the beginning of the spring period to the point when the drying rate (humidity by volume at the interior surface of the sheathing) reaches (slows down) the level of 0.075 g/m^3 (4.7*10^{-6} lb/ft^2) for two days.

If we were to take the endpoint measurement of the drying rate closer to equilibrium, the differences between wall assemblies would increase. The drying times that are shown in Figure 10, are taken straight from the measured data. Because we did not continue the test until equilibrium, it is hard to find

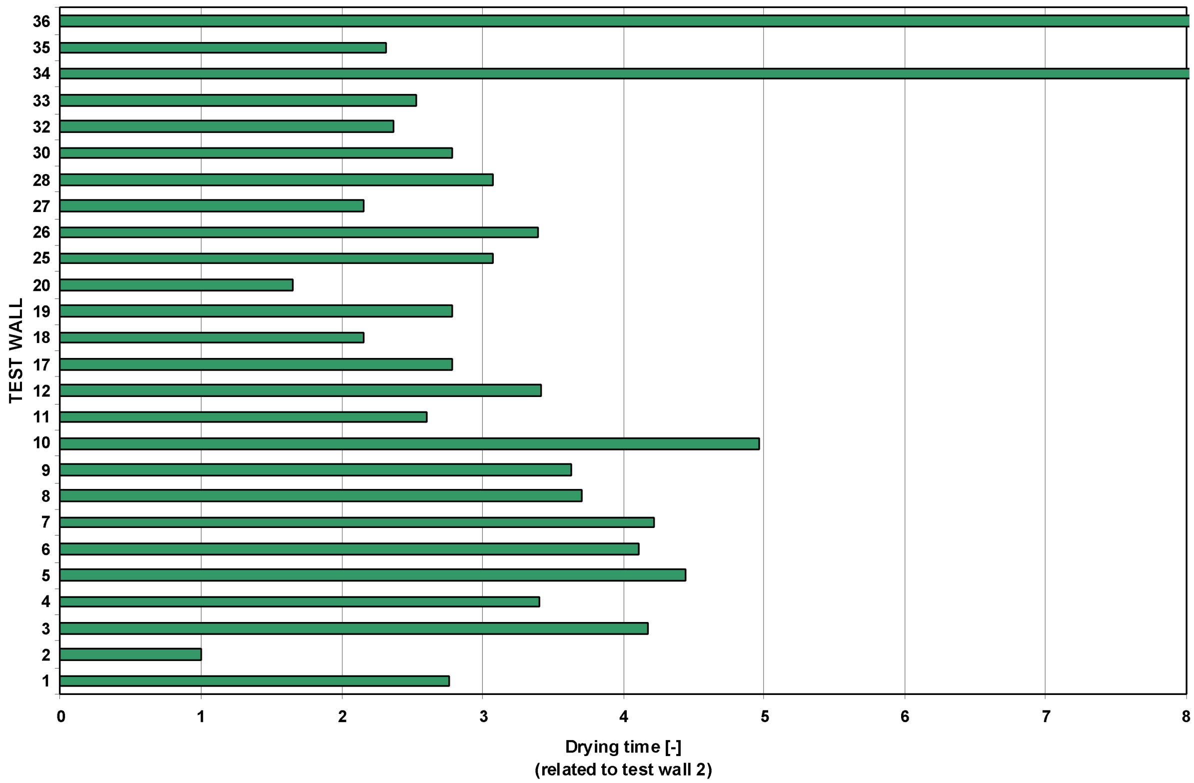

Figure 10 *Drying times of some wall assemblies during the spring period compared to test wall 2. Drying times have been taken straight from measured data. In this figure, the endpoint of drying time is the point when the drying rate is 0.075 g/m^3 for two days (see also Figure 9). The results have been scaled so that the drying time of test wall 2 is 1.*

the exact (absolute) values of drying times. Many of the test assemblies, for example, 29…32, dried rapidly at the beginning of the spring period, but then the drying rate decelerated and the absolute drying time was very long.

If we use nonhygroscopic mineral wool insulation and sheathing with a high vapor permeability (mineral wool), the drying time is very short, as with test wall 2 (absolute value is under 100 hours). When the vapor resistance of the sheathing increases (wood fiberboard), but the other materials are the same, the drying time is also longer, as with test wall 1 (the same phenomenon is seen in test walls 25-26 and 27-28). However, one has to keep in mind that the moisture capacity of sheathing can, to some extent, increase the drying time too. The drying time is longer when the insulation is hygroscopic, as with test wall 8, with the other materials the same, as in wall 1.

Using mixed sawdust and chipping insulation (wall 7) extends the drying time so much that the test periods used do not allow accurate estimation. Actually, this insulation material reaches equilibrium very seldom in real-life conditions. The same phenomenon occurs also with test wall 5, which was similar to test wall 7 except that the inner barrier was bitumen paper instead of plastic.

Test wall 3 was also similar to test wall 8 except that the inner barrier was plastic in test wall 8 and bitumen paper in test wall 3. The drying time was almost the same, and it remained the same when cellulose insulation was changed to flax insulation (wall 6). These test results indicate that using a plastic vapor barrier inside does not slow down the drying time when other material layers are the same.

A comparison of wall 10 with walls 3 and 6 and of wall 12 with walls 1 and 2 indicates that a less permeable sheathing (wood hardboard) increases the drying time remarkably. Thus, the results show that a hygroscopic insulation material and a more vapor-tight sheathing material increase the drying time of structures in spring conditions. Because the water vapor resistance of wood hardboard was about 2.0×10^9 m^2 s Pa/kg (1.15 ft^2·h in. Hg/gr), the vapor resistance of a suitable sheathing is even lower, maybe under 1.0×10^9 m^2 s Pa/kg (0.58 ft^2· h in. Hg/gr).

Decrease of measured relative humidity values behind the sheathing does not necessarily mean that moisture is leaving the structure. Part of the moisture is just dividing equally to insulation layer due to temperature changes, and part of the moisture goes to the outdoor air (depending upon the water vapor resistances of the sheathing). However, it is important that the relative humidity level decreases behind the sheathing to avoid mold growth.

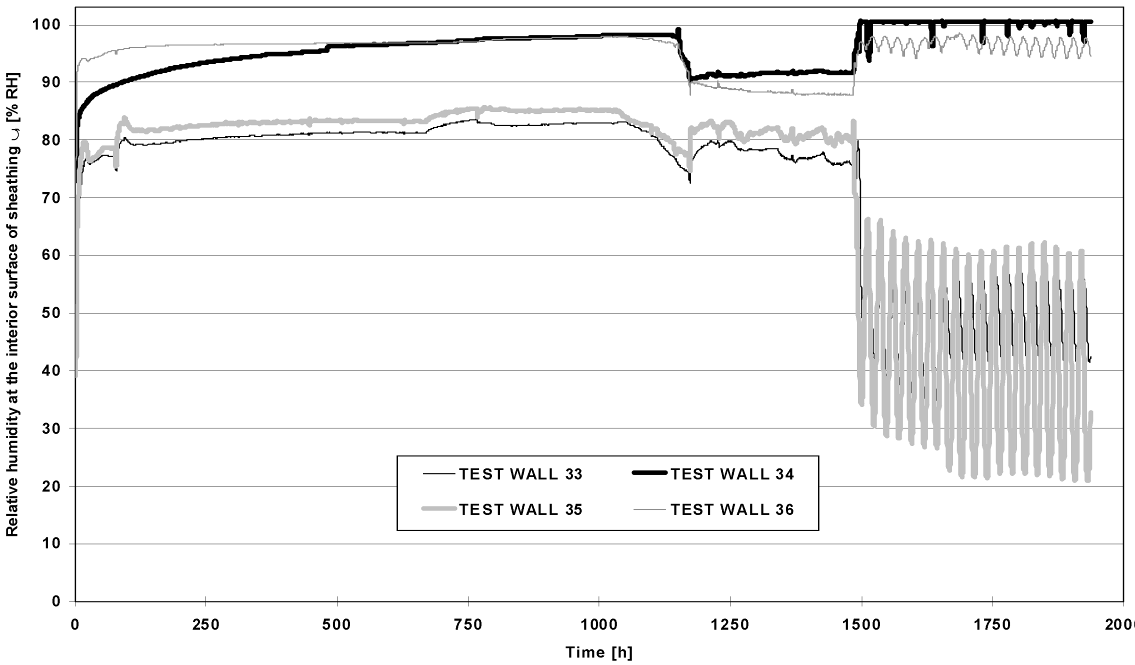

Figure 11 *The effect of water vapor impermeable sheathing material to drying rate (test walls 34 and 36) and drying capabilities toward indoors (comparing test wall 33 to 34 and test wall 35 to 36).*

In test walls 34 and 36, a plastic vapor barrier was used as a sheathing and the air barrier was bitumen paper. The only difference between test walls 33 and 34 as well as walls 35 and 36 was the sheathing material. The drying time is almost infinite when using very tight sheathing materials. So drying capability toward indoors is quite weak, at least for these outdoor and indoor conditions (Figure 11). Condensation takes place almost continuously behind the sheathing in test walls 34 and 36.

The relative humidity level was quite high (> 93% RH) in the autumn and winter periods when using thin sheathing materials (e.g., test walls 17…20) because of the low thermal resistance of the sheathings. In the spring period, test walls with thin sheathing behaved quite similarly, depending upon the water vapor resistances of the sheathings. So the thermal resistance of the sheathing layer had a large effect on the moisture levels.

The amplitude of the relative humidity was larger when the insulation was mineral wool because mineral wool insulation has a smaller water vapor resistance than natural fiber insulation. Similarly, temperature amplitudes are also larger when using thin sheathing materials instead of thicker sheathing materials with higher thermal resistance.

Those test walls where condensation occurred (e.g., 10 and 12, also 17…20) behaved differently from the others. In the beginning of the spring period, the relative humidity rose, and then after two or three days, drying of the walls began (because at the beginning, ice behind the sheathing thawed).

The humidity by volume level of pore air at the interior surface of the sheathing in the spring period is also an important factor. Figure 12 shows the absolute values of humidity by volume behind the sheathings in the insulation layer. It can be seen that the shapes of the curves are the same for test walls 2 and 10. However, test wall 10 stayed above the critical mold level, and drying was very slow due to the water vapor resistance of wood hardboard. In test wall 17, the humidity by volume was quite high after the winter period, but it had quite good drying capabilities as we see in Figure 12. Test wall 2 was far below the level for mold growth because it contained a vapor-permeable sheathing material and a nonhygroscopic insulation material and also because it had a vapor barrier (the absolute humidity was at safe levels throughout the test).

SUMMARY AND DISCUSSION

This research was done from the viewpoint of water vapor diffusion. The effect of air convection was not studied. Pressure difference was set to zero and air leakages were not allowed to test walls. An assembly permeable to moisture is clearly more at risk for condensation and mold growth than one with a vapor barrier. To avoid this, the internal wall lining must have a sufficient water vapor resistance. Of course, the water vapor resistance ratio should also be favorable. In Nordic countries, autumn is even more critical than winter because mold risk is higher than condensation risk. In the Finnish climate, the vapor resistance of the inner surface should be at least five times greater than the resistance of the

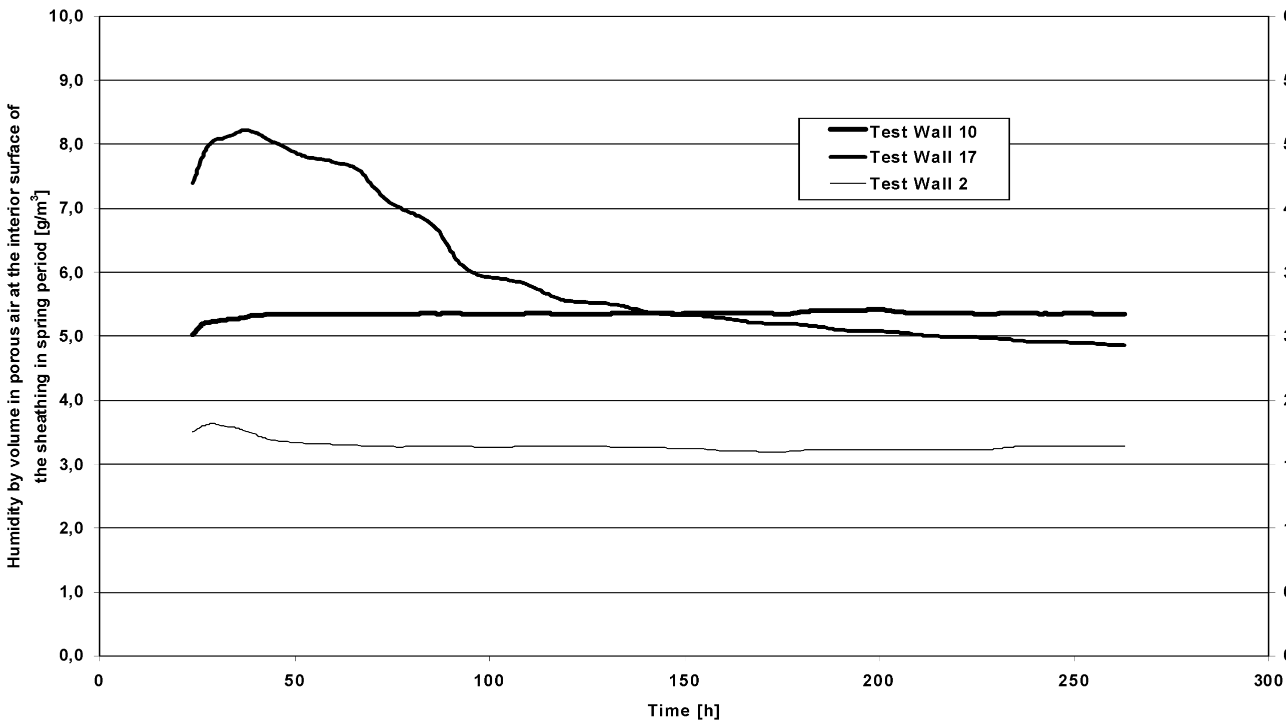

Figure 12 *Showing the effect of ice melt during the spring period (test wall 17) and the effect of sheathing permeability on humidity by volume of the pore air behind the sheathing during the spring period (test walls 2 and 10).*

outer surface in most cases. This ratio has been introduced also in Finnish building code, Section C2 (1998). However, this rule is not enough if, e.g., the humidity excess of the indoor air is high or thermal resistance of sheathing is low. Naturally, the other physical properties of the materials also have an effect on this rule.

If the internal wall lining has proper air and vapor barriers, both natural fiber insulation and mineral wool insulation can be used. The biggest difference between them is that natural fiber insulation moistens and dries more slowly than mineral wool insulation, but the final RH values are at the same level with both structure types. Surplus moisture retained by materials increases the risk of condensation and mold growth. In the case of wood-based materials, the risk is high since they can retain a lot of moisture. When using hygroscopic sheathing materials, drying times are longer than when using nonhygroscopic materials.

Even if the internal surface has sufficient water vapor resistance, it should be kept in mind that the sheathing must not be vapor impermeable. Furthermore, there must be a functioning ventilation gap outside of the sheathing. The test results reported here have also shown that the drying time in spring is not longer for a wall assembly having a water vapor barrier inside than for a wall assembly having only an air barrier inside.

REFERENCES

ISO. 2001. EN ISO 13788, Hygrothermal performance of building components and building elements—Internal surface temperature to avoid critical surface humidity and interstitial condensation—Calculation methods. European Committee for Standardization.

Finnish building code. 1998. Section C2, Kosteus. Määräykset ja ohjeet [Moisture, requirements and instructions]. *Ministry of Environment* (in Finnish).

Finnish building code. 2003. Section C3, Rakennuksen lämmöneristys, määräykset [Thermal insulation of building requirements]. *Ministry of Environment* (in Finnish).

Hukka, A., and H. Viitanen. 1999. A mathematical model to mould growth on wooden material. *Wood Science and Technology*, Vol. 33, pp. 475-485.

Nieminen, J. 1987. Höyrynsuluton puuseinärakenne. [Timber-framed wall assembly without vapour barrier]. State Technical Research Centre (VTT), Research Notes 735. Espoo, Finland (in Finnish).

Ojanen, T. 1998. Improving the drying efficiency of timber frame walls in cold climates by using exterior insulation. *Proceedings of DOE/ASHRAE/ORNL/BETEC/NRCC/CIBCE Conference, Thermal Performance of the Exterior Envelopes of Buildings VII. Clearwater Beach, Florida*, pp. 155-164.

Ojanen, T., E. Kokko, and M.-L. Pallari. 1993. Tuulensuojan toimintaperusteet. (Functioning principle of sheathings.) State Technical Research Centre (VTT), Research Notes 1870. Espoo, Finland (in Finnish).

Viitanen, H. 1996. Factors affecting the development of mould and brown decay in wooden material and wooden structures. Effect of humidity, temperature and exposure time. Dissertation. The Swedish University of Agricultural Sciences, Dept. of Forest Products, Uppsala.

Vinha, J. 1998. Measuring thermal insulation properties of structures with calibrated hot box apparatus. Licentiate's Thesis. Tampere University of Technology, Lab. of Structural Engineering, Tampere (in Finnish).

Vinha, J., and P. Käkelä. 1999. Water vapour transmission in wall structures due to diffusion and convection. Publication 103. Department of Civil Engineering, Tampere University of Technology, Tampere, Finland.

Vinha, J., P. Käkelä, and R. Lindberg. 2001a. Moisture performance of timber-framed external wall structures. *Proceedings of ICBEST—2001 International Conference on Building Envelope Systems and Technology, Ottawa, Ontario, Canada*, Volume 1, pp. 137-142.

Vinha, J., P. Käkelä, and R. Lindberg. 2001b. Moisture performance of timber-framed external wall structures in Nordic climate. *Proceedings of International Conference on Indoor Air Quality 2001: Moisture, Microbes and Health effects: Indoor Air Quality and Moisture in Buildings, San Francisco,* Session 4, 8 p.

Vinha, J., P. Käkelä, and R. Lindberg. 2002. Moisture transport in timber-framed external wall structures in Nordic climate—Laboratory tests. *Proceedings of the 6th Symposium on Building Physics in the Nordic Countries, Trondheim, Norway*, Vol. 2, pp. 595-602.