Moisture Behavior of Timber-Framed External Wall Structures in Nordic Climate

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ABSTRACT

This research looks into the moisture behavior of different timber-framed external wall structures under Nordic climatic conditions. Wall structures were studied under laboratory conditions using new test equipment built in connection with the study. The behavior of structures can be analyzed under computer-controlled conditions without disturbances. The objective of this study is to find out how different wall structures absorb moisture and also how they dry. The study examines, for instance, condensation and mold risks, the need for a vapor barrier in wall structures, and the impact of pressure difference on the behavior of structures. The study focuses especially on two wall structure types: a cellulose insulation wall with an air barrier and a mineral wool insulated wall with a vapor and air barrier. However, many other wall types have also been tested.

INTRODUCTION

Nowadays the moisture behavior of envelope structures has become more complicated because the earlier massive structures have been replaced by heat-insulated layered structures and, at the same time, the use of water inside buildings has increased considerably.

In Nordic countries, the internal wall surface must have sufficient water vapor resistance because of the cold climate. It has been unclear what is the minimum value of inside vapor resistance. The required resistance value depends on many things, e.g., 1) average outdoor air conditions, 2) average moisture increase inside the building, 3) changes of indoor and outdoor conditions due to daily and seasonal variations, and 4) materials used in the structure—especially windshield material. We have a lot of practical experience showing that many structure solutions have worked well in some cases, but in others the opposite has been true. Some environmental conditions have been different and caused moisture damage in the structures. Many efforts have been made to improve envelope structures, but experience has shown them to have been quite often defective or inadequate. In recent years, these failures have also been increasingly publicized.

It is obvious that under some conditions—with low moisture increase of indoor air and outdoor conditions favorable to drying (wind, temperature, solar radiation)—all structures perform ideally with respect to the transmission of water vapor. But the same structures may not behave ideally when the moisture load increases. Different structures do behave differently, and the differences should be determined before new structures can be introduced. More research data on moisture increase in indoor air are also needed.

Using a plastic vapor barrier is a quite clear and safe solution if the windshield is sufficiently permeable to water vapor and the ventilation of the building works well. However, many other types of foils are used as the internal surface of structures, although their water vapor resistance is unknown.

It is evidently very difficult to protect structures from moisture throughout the life cycle of the building. Therefore, fast drying is also a characteristic of a good structure, which can be achieved by proper design and selection of materials. The moisture performance of the windshield is the most important thing in this case.

Analyzing the moisture behavior of envelope structures has also been problematic because different research methods have failed to provide a reliable overall picture of the behavior of structures in different situations. Field tests can only be used to analyze the behavior of individual buildings, and the mutual significance of the factors affecting the results often remains

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ambiguous. In computational analysis, the problem often lies with selecting correct material properties and environmental factors and modeling the structures to correspond to reality. Theory may differ from reality because of the great number of factors to be considered. Laboratory experiments, on the other hand, have failed to control all environmental conditions simultaneously and independently of each other. Material tests have been made mostly at temperatures exceeding 0ºC (32°F). However, in Nordic countries, the external surface of the envelope structure is typically under 0ºC (32°F) temperature during the winter. New research methods are therefore needed for reliable analysis of structures and to determine correct material properties for computational analysis.

Therefore, one objective of this research was also to design and build new laboratory test equipment for studying envelope structures under desired conditions.

METHODS

Test Equipment

New equipment for building physical tests was built by the Laboratory of Structural Engineering at Tampere University of Technology (TUT), which allows studying the moisture behavior of envelope structures under different conditions. The new test equipment was developed on the basis of an earlier calibrated hot box (CHB), which is used to determine the thermal transmittance of structures (U-factor) (Vinha 1998).

The new equipment consists of a warm and a protective chamber—the examined structure is placed between them.

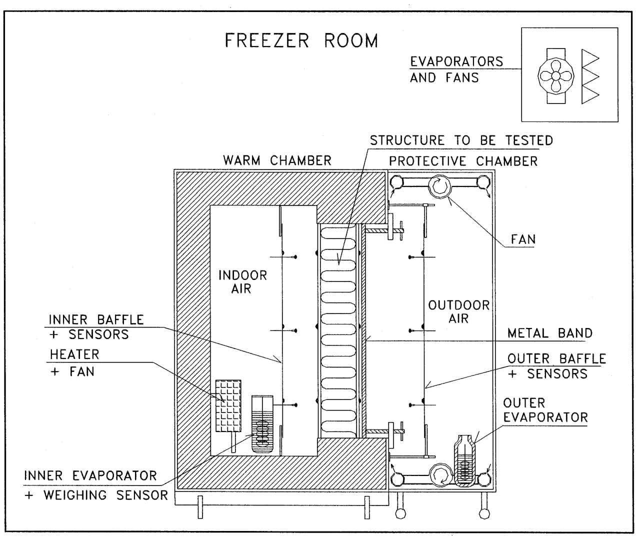

Figure 1 *Test arrangement for the tests on wall structures in the building physical test equipment. The test area is 1200 × 1200 mm² (47.2 × 47.2 in.²); depth: 400 mm (15.7 in.).*

The warm chamber is used to model indoor air conditions while the protective chamber models outdoor air conditions. These chambers are set in a big freezer room in which the outdoor temperature is controlled by a refrigeration unit (Figure 1).

The test arrangement for the tests on wall structures was as follows: the test area is 1200×1200 mm^2 (47.2×47.2 in.^{2}); the depth is 400 mm (15.7 in.).

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 an equilibrium between various factors. In tests, the controllable variables are indoor and outdoor air temperature (T) and relative humidity (ϕ, RH), as well as the pressure difference (Δp) across the examined structure. Tests can be conducted either under constant or varying conditions and condition values can be chosen freely. Structures can be tested in indoor and outdoor air conditions that correspond to real-life situations. A moisture flow through the structure due to diffusion and convection can be measured separately. The building's physical test equipment also has many other features that together make it a novel and versatile apparatus. Function of test equipment has been described more exactly in the Vinha and Käkelä (1999).

Test Walls and Conditions

The first test series began in 1997; eight wall structures were tested in this series under Nordic winter conditions. In 2000, a new test series began where about 20 to 30 different wall types will be tested. These tests will be done under Nordic autumn, winter, and spring conditions (Tables 1 and 2). During winter, tests have been analyzed (e.g., amount of condensation behind the windshield). During autumn, conditions have been researched (e.g., the risk of mold) and, during springtime, the drying effectiveness of structures.

TABLE 1
The Test Conditions During the First Test Series (1997-1998)*

Variable	Winter
T indoor	+20°C (+68°F)
T outdoor	–10°C (+14°F)
ϕ indoor (RH)	50%
ϕ outdoor (RH)	90%
Δp	–10, 0, +10 Pa (–0.21, 0, +0.21 lb/ft^2)
Test period	3×9 d = 27 d

* Indoor moisture increase was about 6.7 g/m^3 (2.9 gr/ft^3) (humidity by volume).

TABLE 2
The Test Conditions During the Second Test Series (2000-)*

Variable	Autumn	Winter	Spring
T indoor	+20°C (+68°F)	+20°C (+68°F)	+20°C (+68°F)
T outdoor	+7°C (+45°F)	−10°C (+14°F)	−6…+10°C (+21…+50°F) 1 cycle/ day
ϕ indoor (RH)	62%	35%	46%
ϕ outdoor (RH)	85%	90%	50…90% 1 cycle/ day
Δp	0 Pa (0 lb/ft^2)	0 Pa (0 lb/ft^2)	0 Pa (0 lb/ft^2)
Test period	6 to 8 weeks together		

* Indoor moisture increase was about 4.0 g/m^3 (1.8 gr/ft^3) (humidity by volume). During the spring period, indoor moisture increase was typically a little bit higher, about 5.0 g/m^3 (2.2 gr/ft^3).

The material layers of the tested wall structures are shown in Tables 3 and 4. The same external cladding was in all wall structures: horizontal paneling 22 mm (0.87 in.) with ventilation gap 25 mm (0.98 in.) behind it. The vapor permeability/ resistance values of test materials used are shown in Table 5.

In the first test series, the initial humidity levels in the pores of the insulation materials and windshields of test walls 1, 3, 5, and 7 were RH 35%; in test walls 2 and 4, RH 85%; and in test walls 6 and 8, RH 55% (shown in Figures 2 and 3). The inner sheets always had the same initial humidity (RH about 30% to 40%).

Three 3.5-mm (0.14-in.) holes were drilled to the left of the bracing in test walls 2, 4, and 6; the holes extended through the inner sheet and the air/vapor barrier. Corresponding holes were drilled to the right of the bracing, but they extended only through the air/vapor barrier. These test walls also had a joint of the inner sheet and air/vapor barrier at the bracing. Filler was applied to the joint of the inner sheet and an overlap of 200 mm was used in the air/vapor barrier, but the joints were not taped. In test wall 8, holes were drilled only to the left of the bracing: six 5.0-mm (0.20-in.) holes, which extended through both the inner sheet and the air barrier. Other test walls were not perforated.

In the second test series, the initial humidity levels in the pores of the insulation materials and windshields of test walls were RH 55% and 86%. The inner sheets and timber frame always had the same initial humidity (RH about 65%). These test walls were not perforated.

RESULTS

Test results that are essential from the viewpoint of the water vapor transmission due to diffusion and convection between permeable walls (walls with air barrier) and impermeable walls (walls with air and vapor barrier) are presented in this connection. Most of the results are from the first test series, but there are also some from the second test series. All test results from the first test series have been presented in Vinha and Käkelä (1999).

Impact of Diffusion and Structural Moisture in Winter Conditions (Test Series 1)

Permeable Walls. Due to diffusion, the RH values on the external surface of Test Wall 1 increased throughout the test. As a result of the low level of initial moisture, the moisture contents in the structure never reached the stationary state during the test. In other words, the cellulose insulation had sufficient capacity to retain all of the moisture transmitted into the wall (Figure 2). Actually, Test Wall 1 is a borderline case in that the internal surface of the structure may be just permeable enough to prevent condensation in a diffusion situation under conditions used in the test. In this structure, condensation begins when it contains extra structural moisture (Test Wall 2) or moisture enters it by convection.

Test Wall 2 also contained extra moisture, which tended to move both inside and out when the test began. The outward transmission was, however, stronger since the outward potential difference was larger. Due to the extra structural moisture, condensation on Test Wall 2 had already begun about three days into the test. A major part of moisture transmitted by diffusion condensed on the windshield since the cellulose insulation had no moisture-retention capacity left after the steady state had been reached (14 days).

Test Walls 7 and 8 were similar in structure except that they had different types of insulation. In Test 7, condensation began seven days into the test and in Test 8, condensation started after 21 days. Although the initial moisture content of Test Wall 8 was somewhat higher at the start of testing, it can be concluded that the moisture-retaining capacity provided by the cellulose insulation did not delay the start of condensation significantly. This is due to the fact that the internal surface of the wall was highly permeable. In other words, the moisture-retaining capacity of cellulose insulation is limited.

Impermeable Walls. Let us then look at Test Walls 3 and 4 (Figure 3). The RH values for Test Wall 3 were very low and moisture contents reached steady state two days into the test. Moisture did not move into the structure by diffusion or convection, which means that there was no condensation of water in the structure. Test Wall 3 behaved extremely well in the test.

TABLE 3
Material Layers of Examined Wall Structures in Test Series 1*

Test Wall	Inner Board	Air/Vapor Barrier	Thermal Insulation	Windshield
1, 2	Gypsum board 13 mm (0,51 in.)	Bitumen paper	Cellulose insulation 145 mm (5.71 in.)	Wood fiberboard 25 mm (0.98 in.)
3, 4	Gypsum board 13 mm (0.51 in.)	Plastic	Mineral wool 145 mm (5.71 in.)	Mineral wool 25 mm (0.98 in.)
5	Gypsum board 13 mm (0.51 in.) + Fir plywood 9 mm (0.35 in.)	Bitumen paper between inside boards	Cellulose insulation 145 mm (5.71 in.)	Fir plywood 9 mm (0.35 in.)
6	Gypsum board 13 mm (0.51 in.)	Plastic	Cellulose insulation 145 mm (5.71 in.)	Wood fiberboard 25 mm (0.98 in.)
7	Wood fiberboard 12 mm (0.47 in.)	Building paper	Mineral wool 200 mm (7.87 in.)	Wood fiberboard 12 mm (0.47 in.)
8	Wood fiberboard 12 mm (0.47 in.)	Building paper	Cellulose insulation 200 mm (7.87 in.)	Wood fiberboard 12 mm (0.47 in.)

* The area of each structure was about 1185 × 1185 mm^2 (46.7 × 46.7 $in.^2$)

TABLE 4
Material Layers of Examined Wall Structures in Test Series 2*

Test Wall	Inner Board	Air/Vapor Barrier	Thermal Insulation	Windshield
9	Gypsum board 13 mm (0.51 in.)	Plastic	Mineral wool 173 mm (6.81 in.)	Mineral wool 30 mm (0.12 in.)
10	Gypsum board 13 mm (0.51 in.)	Plastic	Mineral wool 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
11	Gypsum board 13 mm (0.51 in.)	Bitumen paper	Cellulose insulation 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)
12	Gypsum board 13 mm (0.51 in.)	Plastic	Cellulose insulation 173 mm (6.81 in.)	Wood fiberboard 25 mm (0.98 in.)

* The area of each structure was about 590 × 590 mm^2 (23.2 × 23.2 $in.^2$).

TABLE 5
The Water Vapor Permeability and Resistance Values of Test Materials at Temperature +23°C (+73.4°F) When Average Relative Humidity Has Been Changed from 35% to 95%*

Test Material	Water Vapor Permeability δ_p $\times 10^{-12}$ kg/m s Pa (gr in./ft^2 s in. Hg)	Water Vapor Resistance Z_p $\times 10^9$ m^2 s Pa/kg ($\times 10^3$ ft^2 s in. Hg/gr)
Gypsum board	26…33 (17.9…22.7)	
Fir plywood	0.9…8 (0.62…5.51)	
Wood fiberboard	42 (28.9)	
Plastic		~ 450 (~93)
Bitumen paper		1.5…0.15 (0.31…0.031)
Building paper		0.12 (0.025)
Mineral wool (windshield)	140 (96.4)	
Mineral wool	50…400 (34.4…275)	
Cellulose insulation	50…350 (34.4…241)	

* These test results were also determined during the same research project by the cup method.

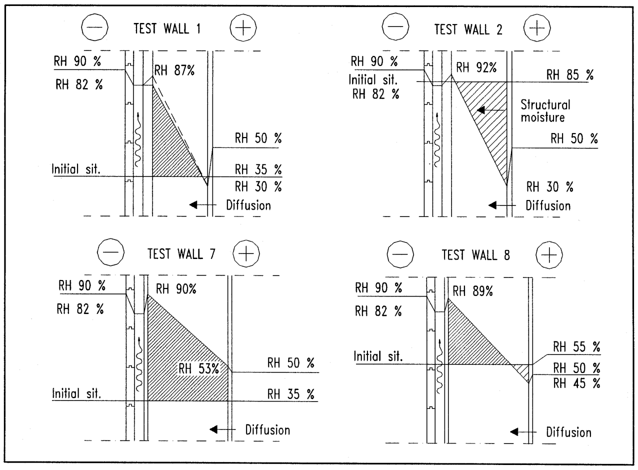

Figure 2 *Relative humidity values (RH%) of Test Walls 1, 2, 7, and 8 pore air at the end of a one-month test.*

It took longer (16 days) to reach the steady state in the case of Test Wall 4 since the moisture contents of the structural materials were higher at the start of the test. Yet no condensation occurred in the structure since the amount of moisture retained by mineral wool is small independent of the RH of pore air. Thus, Test Wall 4 also behaved well in the test. Test Wall 4 (mineral wool) had about 40 g/m^2 (57 gr/ft^2) extra moisture in the initial situation, whereas Test Wall 2 (cellulose insulation) had about 400 g/m^2 (570 gr/ft^2). This explains why condensation started quite rapidly in Test Wall 2.

Figure 3 shows that RH was essentially lower also behind the windshield of Test Wall 6 since no moisture was transmitted to the structure by diffusion. The steady state was reached after ten days in this case. In this test, the cellulose insulation performed flawlessly. In other words, the tightness of the inner wall surface is much more important for the moisture behavior of the wall than the insulation material used.

The test results indicate that RH values within Test Wall 5 increased considerably slower than with Test Wall 1 due to the more impermeable inner surface. In this test, much of the moisture-retention capacity of cellulose insulation was still unused after a one-month test. The speed of change of RH values at the end of the test further indicates that the moisture contents of the structure would not have presented a risk of condensation even in a steady-state situation. The test showed that the inner surface of the wall can be made sufficiently impermeable by means of other materials than a plastic vapor barrier. However, Test Wall 5 has high risk since the external plywood has quite high water vapor resistance, especially when the temperature is under 0°C.

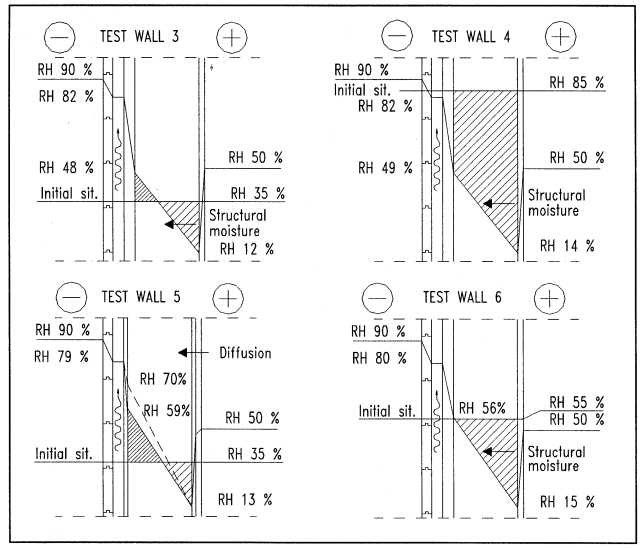

Figure 3 *Relative humidity values (RH%) of Test Walls 3, 4, 5, and 6 pore air at the end of a one-month test.*

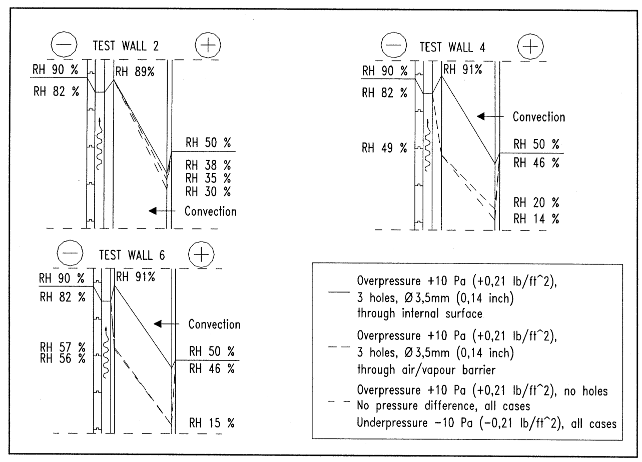

Figure 4 *Changes in relative humidity values (RH%) of Test Walls 2, 4, and 6 pore air due to convection.*

Impact of Convection in Winter Conditions (Test Series 1)

Let us examine Test Walls 2 and 4 (Figure 4). The RH values of Test Wall 2 rose high close to the outer surface merely due to diffusion, while convection had little effect on the values near the holes. The RH values of Test Wall 4 remained generally low, but in an overpressure situation, they climbed high in that part of the structure where the holes extended through the whole internal surface. There, the RH values attained the same level as with Test Wall 2.

Test 6 was intended to determine how the behavior of a structure incorporating a vapor barrier changes in the presence of convection when the mineral wool insulation is replaced by cellulose insulation. The end result of this test was similar to that on Test Wall 4: in overpressure conditions, RH values were high near holes that penetrated the internal surface. The only difference was that the moisture content values for Test Wall 6 rose somewhat slower (steady state after about 14 days) than those for Test Wall 4 (steady state after 1 day).

In Test Wall 8, pressure difference was used to determine the extent to which underpressure can lower the moisture contents of a wall structure. In the case of Test Walls 2, 4, and 6, the RH values of structures did not differ significantly in underpressure and no pressure difference situations. Double the number of holes were drilled in Test Wall 8—they were also larger than in other tests (6 × 5 mm) (6 × 0.2 in.). In this test, the moisture contents of the thermal insulation under equilibrium were somewhat lower (about 10% RH) in an underpressure situation than when there was no pressure difference. However, in actual structures, the reduction in moisture contents from underpressure is quite limited. Yet, underpressure ensures that overpressure does not develop in the building.

Wall Tests in Autumn, Winter, and Spring Conditions (Test Series 2)

In the second test series, indoor moisture increase was lower (4.0 g/m^3) (1.8 gr/ft^3). This is also a more typical value in detached houses in Finland. Figures 5, 6, and 7 show relative humidity values (RH%) behind the windshields in Test Walls 9,10, 11, and 12.

Before the beginning of the test, each type of structure was humidified at two initial RH levels (55% and 86%). However, during the autumn period, the values balanced to almost the same level despite the initial RH values. Therefore, the behavior of the same type of structures is quite similar despite the summer conditions before the autumn period (wet or dry summer). The small differences of moisture levels between same type of structures caused, e.g., different thermal conductivity values of windshields (due to different moisture content).

It took longer to reach the stationary state in the case of the Test Walls 11 and 12 because of the higher moisture-retention capacity of cellulose insulation. The steady state was reached in mineral wool insulated walls after about two days, but in the cellulose insulated walls this time was two to three weeks. If, e.g., sawdust is used to thermal insulation, the time when the steady state has been reached is still longer—even one or two months.

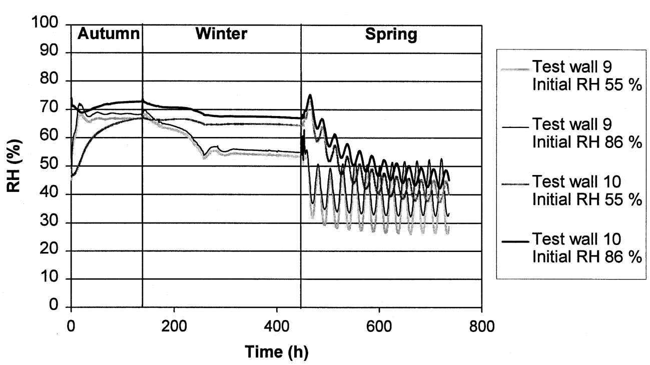

Figure 5 *Changes in relative humidity values (RH%) of Test Walls 9 and 10 pore air behind the windshield during a three-season test.*

In a permeable wall (Test Wall 11), RH values are clearly higher than in impermeable walls (Test Walls 9, 10, and 12) in every season. The difference was about 10% to 15% RH during the autumn period, 15% to 25% RH during winter, and 10% to 15% RH during springtime. In permeable structure 11, which had an initial RH value of 86%, RH values were also slightly over the critical mold risk values (mold is possible) during the autumn period.

It seems that the mineral wool windshield was also slightly better than porous fiberboard because RH values of Test Wall 9 were a bit lower (0% to 10% RH) than RH values of Test Wall 10. The drying time of Test Wall 9 was also shorter than that of Test Wall 10, but, on the other hand, the moisture absorption time was also shorter. In addition, in Test Wall 9, the change of relative humidity during the cyclic spring period was three times bigger than in other Test Walls. These test results show that changes in indoor and outdoor air relative humidity influence rapidly on RH values in mineral wool insulated structure.

The test results also illustrate that drying time in the spring is not longer in permeable wall structure 11 than impermeable wall structure 12.

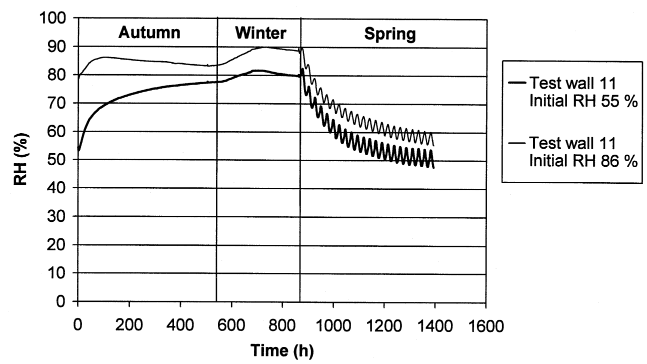

Figure 6 *Changes in relative humidity values (RH%) of Test Wall 11 pore air behind the windshield during a three-season test.*

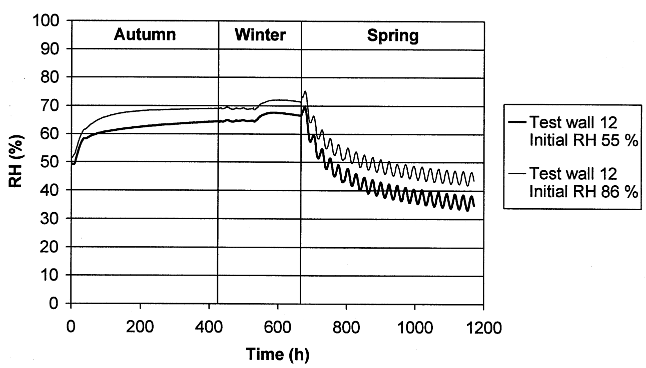

Figure 7 *Changes in relative humidity values (RH%) of Test Wall 12 pore air behind the windshield during a three-season test.*

CONCLUSIONS

A structure permeable to moisture is clearly more at risk for condensation and mold than one with a vapor barrier. It means that the internal wall surface must have sufficient water vapor resistance. In Nordic countries, the autumn period is even more critical than the winter period because mold risk is higher than condensation risk. Water vapor resistance of the inner surface should be at least five times greater than the resistance of the outer surface when the indoor moisture increase is lower than 4.0 g/m^3 (1.8 gr/ft^3). The same resistance ratio has been calculated at the Technical Research Centre of Finland (Kokko et al. 1999) and it is also mentioned in Finnish water and moisture sheltering introductions (RIL 2000).

If the internal wall surface has a proper air and vapor barriers, both cellulose and mineral wool insulation can be used. The use of cellulose insulation slows down increases in RH values behind the windshield during the autumn and winter periods, but RH values are finally higher in permeable walls than in impermeable walls. So, the moisture-retention capacity of wood-based materials delays the onset of condensation and molding but is not always enough to prevent these effects. Surplus moisture retained by materials increases the risk of condensation and molding. In the case of wood-based materials, the risk is high since they can retain a lot of moisture.

A windshield sufficiently permeable to water vapor must be attached to the external wall surface in order to allow surplus moisture to exit. There must also be a functioning ventilation gap outside the windshield. The test results have also shown that drying time in the spring is not longer in wall structures with a water vapor barrier inside than wall structures with only an air barrier inside.

In addition, convection tests have shown that the risk of condensation and mold exists in a wall structure if the structure has holes clear through the internal surfaces and if there is overpressure inside the building. The use of cellulose insulation slows down increases in RH values in overpressure situations at holes but, in the end, the moisture rates of the structure correspond to those of a mineral wool wall. If the structure is permeable to water vapor, condensation is possible despite pressure difference because there is diffusion through the structure.

When holes penetrate only the air/vapor barrier, RH values are not affected by pressure difference if the joints of the inner board are airtight. This also applies to the attachment of the inner board to the bracing through an air/vapor barrier. A 200 mm overlap is sufficient at the joint of an air/vapor barrier. Taping of joints is always recommended but is not necessary at the bracing if the inner board is installed carefully.

DISCUSSION

The moisture behavior of a wall structure depends on the moisture load to which it is subjected. All wall structures perform well from the viewpoint of diffusion, if the moisture increase of the indoor air is small and water cannot enter the structure as a result of moisture leaks. Convection is not a problem either if underpressure prevails in the building or the structure has a solid air barrier. However, the latter condition is not easy to carry out in practice.

In relation to diffusion, the most essential thing to know is the difference in humidity by volume of indoor and outdoor air in various seasons. The outdoor air determines the level of RH value outside the envelope structure. The more permeable the internal surface is, the more the RH value goes up behind the windshield and the risk for condensation and mold increases.

If RH 50% is selected as the design value in winter, as in the first part of this study, the difference between inside and outside humidity by volume is about 6.5 g/m^3 (2.9 gr/ft^3). This is such a high value that many of the permeable wall structures used today in Finland are at risk for moisture damage. When the moisture increase is lower, more wall structures function sufficiently well.

Actually, the humidity of the indoor air of most buildings decreases in winter, but there are also many buildings where that does not happen (families with many children and use of a humidifier). It is also recommended, for health reasons, that the RH value of indoor air be selected between 25% and 45% in the winter. The ventilation system and the moisture retained by wooden structures also affect the RH of indoor air.

Even if the internal surface has sufficient water vapor resistance, it should be kept in mind that the windshield must not be too impermeable. If there are some kind of moisture leaks from outside to inside the structure, then the structure cannot dry and extra moisture may cause moisture damages.

It is not necessary to use a plastic vapor barrier in the internal surface because its vapor resistance is many times higher than needed. However, use of plastic does not cause problems if the structure can dry through the outer surface. On the other hand, there are no significant benefits to using too permeable internal surface material either.

Although many results have been acquired from these laboratory tests, it must always be kept in mind that the general view of the moisture behavior of wall structures presumes that structures have been analyzed also with calculation methods using whole year climatic data and, in addition, measurements have been done in real buildings. Therefore, during this research, material property tests will also be done with the same materials that have been used in the tested structures. Material properties will be compared to the other references (e.g., CEN 2000 and Kumaran 1996). Laboratory test results will also be analyzed with the calculation program in a whole-year period. Moisture performance of permeable and impermeable structures have also been measured in a Finnish detached house and these results will be used for one part of the analysis as well.

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