Smart Vapour Barriers in Compact Wood Frame Roofs

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ABSTRACT

Compact wood frame roofs typically need a vapor and air barrier at the warm side to avoid interstitial condensation due to vapor diffusion and air leakage from the interior. A vapour barrier such as a polyethylene foil does not, however, allow drying of moisture to the interior, making the construction vulnerable to moisture damages. A so-called smart vapour barrier or retarder could allow condensed moisture, built-in moisture, or moisture from minor leakages to dry to the interior. The concept of smart vapour barriers has been known for some time; such a barrier consists of a material that changes its vapour resistance according to the level of relative humidity in the surrounding air.

The application of smart vapour barriers and retarders in compact wood frame roofs was investigated in this study. The study was performed by laboratory measurements. The concept was to investigate how four different types of smart vapour barriers/retarders performed during typical summer conditions, including an innovative product that has a much broader variation in its vapour resistance than previously known commercial products. The rate of drying was measured and internal humidity conditions within the roof structures were monitored. The various smart vapour barriers were found to function quite differently in regard to their ability to enhance the drying to the interior.

INTRODUCTION

In Nordic climates a vapour and air barrier is typically used on the warm side of the building envelope to avoid interstitial condensation during the heating season due to vapour diffusion and air leakages from the interior. Often a polyethylene (PE) foil is used, which has a very high vapour resistance. Such a vapour-tight product does not, however, allow moisture to dry to the interior. A more vapour-open product could allow condensed moisture, built-in moisture, or moisture from minor leakages to dry to the interior. This could be especially useful for constructions with reduced or no possibility to dry to the exterior, such as unventilated flat roofs. It might allow cheaper solutions, making it possible to use organic (wooden) materials in such constructions or skip the use of wooden preservatives.

The term *vapour retarder*, as opposed to *vapour barrier*, is often used for products that have a lower vapour resistance than recommended for vapour barriers. Such products may allow for some drying to the interior. Different commercial products vary quite a lot in regard to their level of vapour resistance, typically somewhere between s_d = 2–10 m (0,34–1,7 Perm) for products sold on the European market. For North American climates, Lstiburek (2002) defines vapour retarders as having the following rage: 0,34 m < s_d < 3,4 m (1–10 Perm).

However, Geving and Holme (2012) concluded that vapour retarders had little effect on the total drying of ordinary wood frame walls with relatively vapour-open exterior sides. To get an inward drying of built-in moisture of some significance (25% or more of the total drying), the vapour resistance on the warm side should be rather low, typically with an s_d value lower than 1–2 m (1,7–3,4 Perm). However, with such a low vapour resistance on the warm side the risk for interstitial condensation increases. While a wood frame wall has good drying possibilities to the exterior, and thereby needs very

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vapour-open vapor retarders to have a significant drying to the interior, it seems obvious that for constructions with low or no drying to the exterior one might get a significant drying to the interior even with higher s_d values on the warm side. In a simulation study using climate data for various places in Northern Europe and Northern America, Bludau and Künzel (2009) found for instance that for an unvented flat roof a vapour retarder with a constant s_d value down to 3 m (1,1 Perm) could be acceptable for moderate heating climates (not too far north) without risk of interstitial condensation and mould growth.

While a vapour retarder has a given constant vapour resistance, some vapour barriers or retarders[1] are sold on the European and North American markets with adaptable vapour resistance. Popular terms for these products are *smart*, *intelligent*, *moisture-adaptive*, and *humidity-dependent* vapor barriers. The physical behavior of these products varies, but the main principle is that the vapour barrier should function as an ordinary vapour-tight vapour barrier most of the time, preventing vapour diffusion into the construction from the indoor air. If, on the other hand, the construction is wet, for example due to built-in moisture or leakages, so that the relative humidity (RH) on the exterior side of the vapour retarder gets high, the vapour resistance will be reduced so that there may be possibilities for drying inwards. Another possibility may be that the barrier layer has capillary properties with possibilities to transport condensed water to the interior surface.

Probably the first commercial product that can be put under the term *smart vapour barrier* (SVB) was a capillary active product that was developed in Denmark during the 1980s (Korsgaard 1985). It consisted of synthetic fibres sandwiched between stripes of polyethylene, giving it a constant very high vapour resistance similar to the polyethylene film. If, on the other hand, moisture condensed on the exterior side of the vapour barrier, the water would be transported sideways through the fibres by the wicking action and be allowed to evaporate to the interior side. Research on the practical use of this product was performed in both Denmark and the U.S. in the late 1980s and early 1990s (Korsgaard and Pedersen 1990; Rode et al. 1993; Pedersen et al. 1992), and it was found to give a significant drying effect of unvented lightweight roofs.

In the mid 1990s another type of SVB was developed in Germany (Künzel 1996). It is now sold both in Europe and in North America under several different names. It consists of a polyamide film with no capillary properties but with a pronounced difference in vapour resistance for high and low ambient RH. The s_d value is approximately 4–5 m (0,68–0,85 Perm) when the RH is below about 40% and 0,1–0,2 (17–34 Perm) when the RH is above 80% (Künzel 1996). Also this product was first introduced as beneficial for unvented roofs. Most research since then has been focused on the use of this product. There are a lot of studies on unvented roof systems with this product (Künzel 1996; Künzel 1998; Künzel 1999; Künzel and Leimer 2001; Ghazi Wakili et al. 2004; Kaufmann et al. 2006; Bludau and Künzel 2009; Bludau et al. 2010).

Since then there have been developed various similar products with varying levels of vapour resistance. Some of these new products may have a higher resulting vapour resistance for winter conditions compared to the polyamide SVB, reducing the risk for interstitial conditions. Some may have a lower resulting vapour resistance for summer conditions, resulting in higher drying rate to the interior. This study investigates and compares the performance of three newer products with the polyamide SVB.

LABORATORY TESTS

General

The purpose of the laboratory tests was to investigate and compare the drying conditions in compact wood frame roofs when applying different types of commercially available SVBs. The drying typically takes place during the summer season, when the external surface is heated by the sun and the driving potential for inward vapour flow is highest. A typical diurnal variation of external roof surface temperatures during a sunny summer day was repeated during 144 days.

The following type of compact unventilated wood frame roof was tested (from the exterior side):

- Roofing membrane
- 21 mm (0,83 in.) plywood (spruce) sheathing
- 200 mm (7,9 in.) glass wool or expanded polystyrene (EPS)
- SVB or PE foil
- 13 mm (0,5 in.) gypsum board
- Latex paint (high permeance)

The measurements took place in the laboratories of the Department of Civil and Transport Engineering at the Norwegian University of Science and Technology during spring 2012.

Experimental Set-Up/Test Rig

Six different configurations of the wood frame roof were tested where the only differences were the type of SVB or PE foil used and whether glass wool or EPS were used as insulation. Five configurations had glass wool; four types of SVBs and PE foil were used as the barrier layer among these five. One configuration with SVB had EPS insulation (see later description). For better accuracy each configuration was tested with two specimens, i.e., there was a total of 12 specimens. The roof specimens were built up in storage boxes of polypropylene, where the bottom of the box was used to imitate the roofing membrane and the rest of the materials were adjusted to fit the box (see Figure 1a). The boxes had interior dimensions b = 0,28 m (10,6 in.), l = 0,40 m (15,3 in.), and h = 0,22 m (8,7 in.) and flanges onto which the SVBs and gypsum board were taped. The corners of the boxes were curved so the resulting “light opening” of the boxes had an

[1] *Vapour barrier* is used in the rest of this paper for simplification.

area of 0,1053 m^2 (1,13 ft^2). The boxes were placed in a lifted test rig with the bottoms up, with insulation on all sides to get isothermal conditions and a heating foil that could be controlled to give the wanted surface temperature on the roofing membrane (i.e., the bottom of the polypropylene box) (see Figure 1b). Each test box could be dismounted during the experiment to monitor the continuous weight loss. See details in Figure 2.

Materials

The four types of SVBs are anonymized: A, B, C, and D. SVB-A is a polyethylene copolymer, where the copolymer is an acrylic with hygroscopic properties. The s_d value ranges from 0,25–26 m (0,13–13,6 Perm). SVB-B is a polyamide with an s_d value ranging from 0,2–5 m (0,68–17 Perm). This product is manufactured under many different names in Europe and North America. It was originally developed in Germany in the late 1990s (Künzel 1996) and was the first commercially available humidity-dependent vapour barrier product for building applications. Most scientific studies on use of SVBs in building applications are limited to this product only, together with studies on the previously mentioned capillary active product (Korsgaard 1985). SVB-C is composed of a fabric of synthetic fibres with good capillary properties laminated with stripes of perforated PE foil and polyamide foil. It should be noted that this product is a further development of the original capillary active SVB (Korsgaard 1985) mentioned previously. The s_d value ranges from 1–20 m (0,17–3,4 Perm). SVB-D is a polyvinylalcohol film (with spunbonded polypropylene as a reinforcement and protecting layer) with an s_d value ranging from 0,02–102 m (0,03–170 Perm).

The PE foil has a thickness of 0,15 mm (6 mil) and an estimated s_d value of 70 m (0,05 Perm). The EPS has an estimated vapour resistance factor μ = 50 (5,45E–6 Perm-in). The gypsum board and latex paint has a combined s_d value that was measured with the cup method of 0,13 m (26 Perm).

Figure 1 *Test box and test rig: a) test box with gypsum board and measurement cables on top and b) test rig seen from below.*

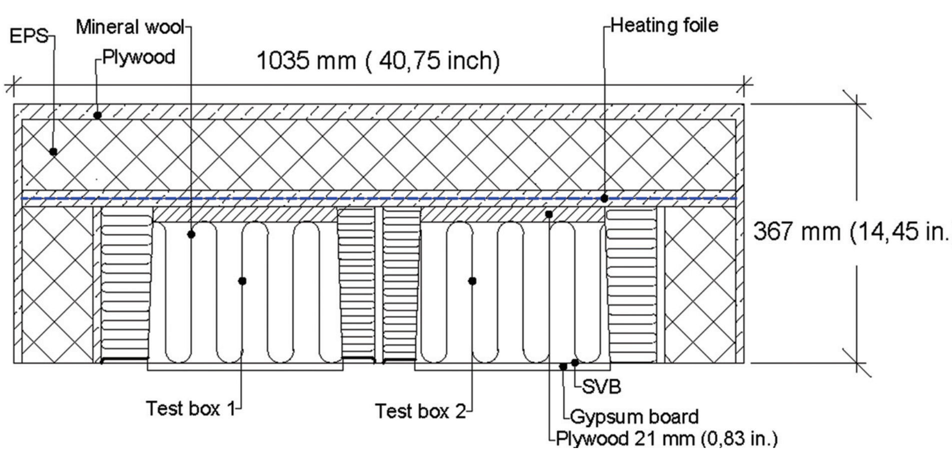

Figure 2 *Section of the test rig showing the two parallel test boxes.*

Boundary and Initial Conditions

The external boundary conditions were given by the temperature controlled by the heating foil in the test rig. During sunny summer days the temperature on flat roofs may reach 50°C–60°C (122°F–140°F). However, to use a constant value would not be realistic. To find a realistic diurnal variation for the external temperature, measured external surface temperature on an unventilated flat wood frame roof at a test house in Trondheim, Norway, was used as a basis (see Figure 3). It was decided to try to imitate the diurnal temperature cycle given by the roof with a light membrane on June 7 with a maximum surface temperature of 49°C (120°F). It was, however, difficult to use the heating foil to recreate the exact temperature cycle given in Figure 3. Figure 4 compares the temperature profile that was chosen to the test house profile from June 7. The driving potential for inward vapour flow was calculated for the two profiles in Figure 4, assuming an RH of 100% both at the external and internal parts of the insulation cavity, and the laboratory test cycle was adjusted to give it almost similar inward driving potential as that of the test house cycle. It was difficult to get a sufficiently quick temperature drop at the heating foil due to the thermal mass of the test rig, so a slightly lower maximum temperature was chosen, 45°C (113°F), so that the evening and nighttime temperatures would not be too high.

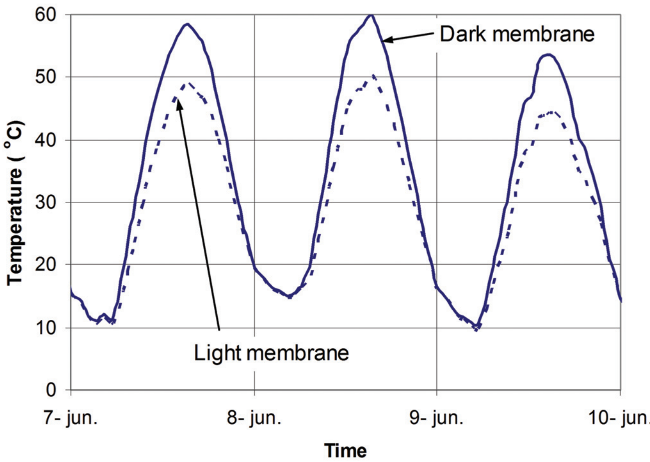

Figure 3 *Typical measured external temperature variations of a flat roof at a test house during three sunny summer days for an element with a dark roofing membrane and a light (solar absorption factor ≈ 0.65) roofing membrane (Geving and Holme 2010).*

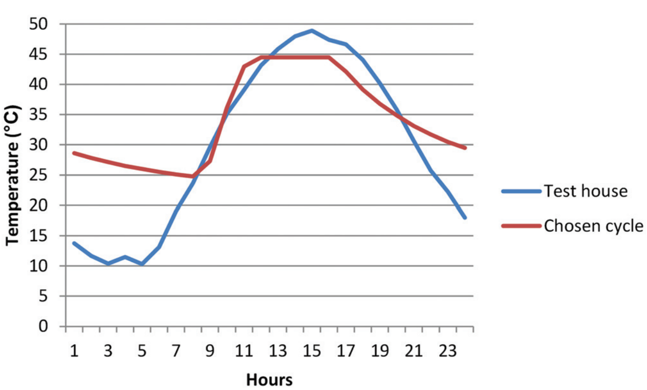

Figure 4 *Comparison of chosen temperature cycle with the measured surface temperature at a test house in Trondheim.*

The test rig was placed in a climatic chamber with a constant indoor temperature of 23°C (73°F) and 50% RH.

To simulate built-in moisture or an accidental leak, the plywood sheathing was given an initial moisture content varying between 23 and 32 weight % by immersion in water for 20 h; see the detailed initial moisture content of each plywood specimen in Table 1. The sides of the plywood were sealed to get a uniform moisture uptake in the specimens. This initial moisture content was determined by the gravimetric method by measuring both wet weight and finally the dry weight when the measurement series were finished.

Measurements

The rig and test boxes were constructed so that the boxes could be dismounted and weighed regularly, to follow the total drying of the configurations. In addition the temperatures and RHs at the interfaces between the SVB and insulation were measured (logged each sixth minute) in one of the two test boxes of each configuration. The moisture content of the plywood board was measured manually once a day by traditional resistance measurements, using screws (dimensions 3.5 × 9.5 mm) with a distance of 25 mm (1 in.) as electrodes—

Table 1. Initial Moisture Content in Each Plywood Specimen

Configuration/ Specimen	Weight %, %	Total Moisture, kg
SVB-A #1	24,7	0,199
SVB-A #2	25,0	0,197
SVB-B #1	29,7	0,238
SVB-B #2	28,9	0,226
SVB-C #1	30,6	0,245
SVB-C #2	32,5	0,255
SVB-D #1	26,9	0,214
SVB-D #2	29,7	0,238
PE foil #1	23,7	0,190
PE foil #2	27,5	0,219
SVB-D/EPS #1	22,8	0,184
SVB-D/EPS #2	29,7	0,230

one measurement point with the two screws mounted from the top of the board and another point with two screws mounted from the bottom (see Figure 5). The screws were sealed with epoxy on top to avoid extra capillary water uptake during the immersion in water. As for the RH measurements, the wood moisture content was only measured in one of the boxes for each roof configuration. The wood moisture meter was set at Scandinavian Spruce. Both the weighing of the boxes and the measurement of wood moisture content were made just before the heating foil was turned on, i.e., when the temperature of the boxes was uniform and close to laboratory temperature.

The RHs and temperatures of the indoor climate were also continuously logged.

RESULTS

The drying of the built-in moisture of the six roof configurations are illustrated in Figures 6, 7, and 8. Figures 6 and 7 show the total water content of the boxes during the test period, i.e. the total water content (kg) divided by drying opening (area) at the SVB level. The total water content is determined from the initial water content in Table 1 and the weight loss determined by weighing the boxes throughout the test period. Figure 6 shows the average of the two parallel specimens for each configuration, while Figure 7 shows each specimen to give an impression of the variance. From Figure 6 we see that the configurations with SVB-B and SVB-D have a much faster rate of drying than the rest of the configurations, followed by SVB-C and SVB-A. As expected, the PE foil has a very slow rate of drying. When comparing the two configurations with SVB-D, one with glass wool insulation and the other with EPS insulation, we see that the one with EPS has a much slower rate of drying. This is as expected since the vapour resistance of the EPS is rather high, slowing down the vapour flow from the plywood layer to the interior.

We also see that at the end of the test period all configurations are approaching the same level of total water content.

Figure 8 shows the total drying from the start at several different points of time. We see that the configuration with SVB-D has a faster drying rate after 10 days compared to the one with SVB-B. This is logical since SVB-D has a lower

Figure 5 *Screws used as electrodes for wood resistance measurements.*

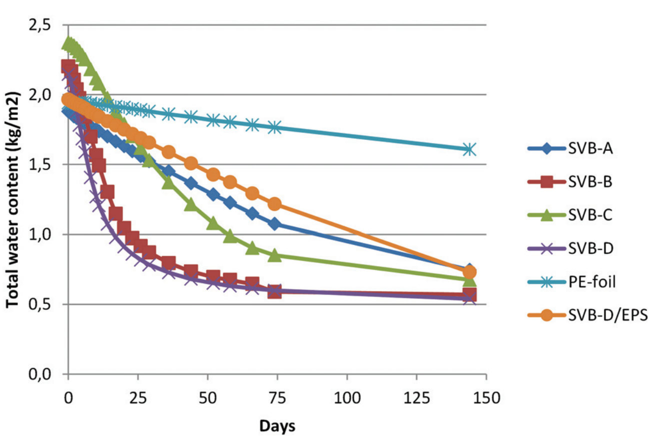

Figure 6 *Total water content in the six roof configurations during the test period. Each curve represents the average of two test boxes.*

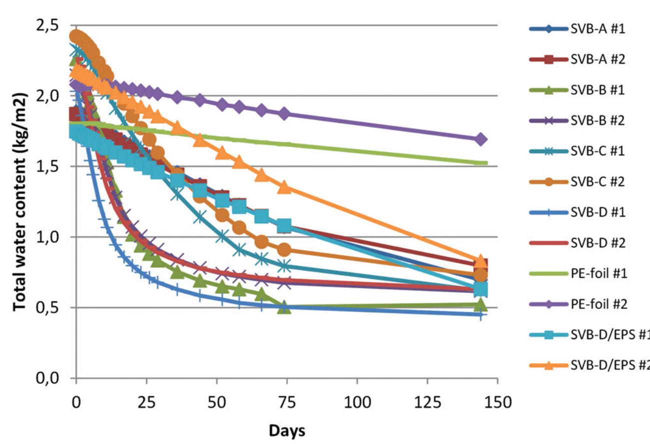

Figure 7 *Total water content for all the 12 specimens during the test period.*

s_d value than SVB-B at high RH levels. We also note that both configurations have a relative high part of the total drying during the first 10 days. That fact makes them very effective in regard to drying of built-in moisture in a Nordic climate, where the number of summer days with high external surface temperatures may be limited. Even though the other configurations finally reach the same level of total moisture content, this will take much more time, increasing the risk for mould growth and rot.

Figure 9 shows the measured RH at the interface between the SVB and insulation level for the first month of the test. We see that the configurations with SVB-D (with glass wool insulation) and SVB-B reach an RH of 100% in one to two days. The RH in the roof with SVB-D does, however, start to drop after 1 week, while for SVB-B it stays at 100% for 2,5 weeks. This high initial RH is probably due to condensation at the SVB, which dries up after the initial period. After this initial period we see that the RH is fluctuating, being high at midday (when the external temperature is high) and low during nighttime. After approximately two months the RH curves for SVB-B and SVB-D are practically equal (not shown here). A more detailed illustration of the diurnal variation of the RH, compared to the external surface temperature, is given for one day after four weeks of testing in Figure 10. We can see that the RH follows the temperature curve with only one to two hours' delay.

It should be noted that the RH curves for PE foil, SVB-C, and SVB-A are not shown in Figure 9 since they reached 100% after only approximately eight hours and stayed at 100% during the whole measurement period. That is partly as expected, due to their higher levels of vapour resistance, but may also be caused by a malfunction of the RH sensors after a prolonged period at 100%. All RH sensors were, however, controlled after finishing the experiment, and they all functioned well. Especially for SVB-A you could expect some dropping in RH during the later part of the test period. But it should be mentioned that the sensor at the SVB-C started having daily fluctuations between 0 and 100% after 75 days, indicating at least that the RH level was not 100% during "nighttime."

The moisture content (measured by the electrical resistance method) in the plywood layer is shown in Figure 11. Except for the configuration with EPS insulation, which has a slow drying rate, the difference between the various SVBs is not big. We see, for instance, that the roof with the PE foil has one of the highest drying rates, indicating that internal redistribution of moisture within the insulation cavity is an important factor. Since the external surface temperature always is higher or equal to the indoor air temperature, the plywood will tend to dry to the interior side of the insulation layer—even for the PE foil configuration. What we can read out of Figure 11, in combination with Figures 6 and 9 is the following: due to the high temperatures on the external side, the vapour pressure in the plywood layer will be very high the first weeks. This will

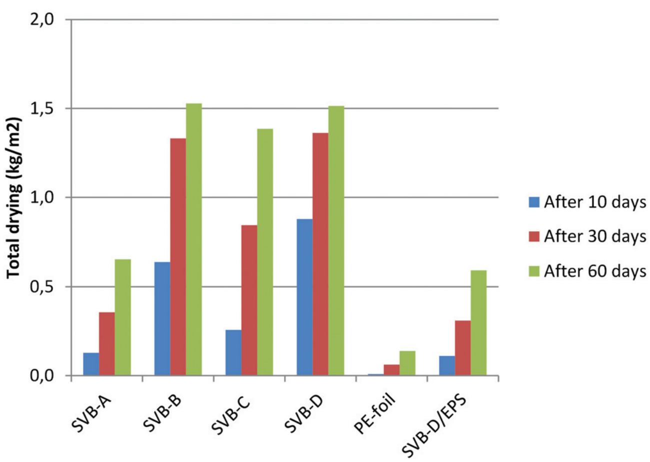

Figure 8 *Total drying from the start and after 10, 30, and 60 days for the six roof configurations; average values for two test boxes.*

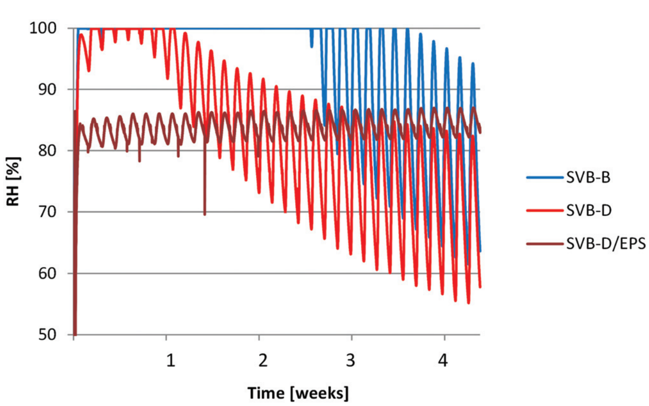

Figure 9 *RH at the interface between the insulation material and SVB.*

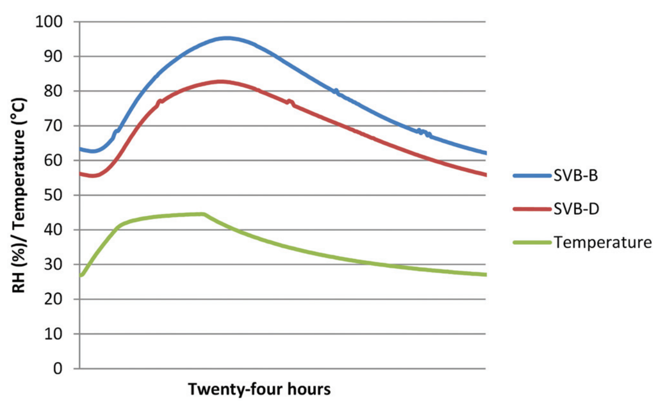

Figure 10 *RH at interface between glass wool and SVB with temperature at exterior surface; shown for one day after four weeks of testing. The starting point is when the heating foil is turned on.*

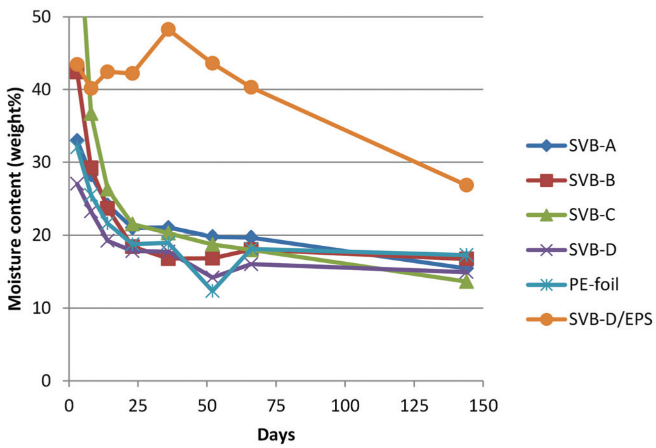

Figure 11 *Moisture content in plywood board (measured with the electrical resistance method); average of measurement points on the top and bottom of the board.*

give a high inward-directed vapour flux—even if the RH at the interface between the SVB/PE foil is somewhere close to 100% as shown in Figure 9. After a few weeks most of the moisture in the plywood layer will probably either have dried to the indoor air, as we see for the vapour-open SVB-B and SVB-D in Figure 6, or partly have condensed in the interior part of the mineral wool for the SVBs with higher vapour resistance and the PE foil. This explains why we do not see the differences between the different SVBs in Figure 11 as we see in Figure 6. In a real case this may be different, however, due to nighttime undercooling of the roof surface caused by black-body radiation to the sky. As shown in Figure 4, the exterior surface temperatures drops to 10°C (50°F) during the night on the test house measurements. This will give an outward-directed vapour flow during the night, which will probably be higher for those configurations with an RH close to 100% in the interface between the insulation and SVB, such as the one with PE foil and SVB-A. It should be mentioned that the measurement uncertainties are relatively high when measuring in plywood. Even if the wood moisture meter is set on a calibration curve for spruce, you will usually measure higher moisture contents than the real ones, this difference being higher for higher moisture contents (Geving and Holme 2010). This means that the high moisture contents measured at the start of the test period, most well above 30 weight %, in reality will be considerably lower and closer to the initial moisture contents given in Table 1.

DISCUSSION

An aspect that is not investigated in this study is the RH occurring between the SVB and the interior lining during the most intense drying period. While it may be advantageous having an SVB with a high permeance (at a high RH level) giving a fast drying, it may also be a disadvantage if this leads to an increased RH level and mould risk for the interior lining during periods with inward-directed drying. The most vapour-open SVB will obviously give a lower RH level and mould risk at the exterior side of the SVB, as illustrated in Figure 9, while at the same time it may lead to a higher RH level and mould risk between the SVB and interior lining. Whether there will be any problems also depend strongly on the vapour permeance of the interior lining itself. In general the lining should be of high-permeance materials to decrease this risk, such as gypsum board with high-permeance paint.

An interesting aspect demonstrated by this experiment is that if only looking at the moisture content of the plywood layer in Figure 11 there seems to be no difference in the rate of drying between the various SVBs and PE foil. The most reasonable explanation for this is that there will be an internal redistribution of moisture from the plywood to the internal part of the insulation (as condensation) the first few weeks, the size of this redistribution being almost independent of the vapour resistance of the vapour barrier. The drying of the roof can therefore only be observed when looking on the total water content in the roof as given in Figure 6—or the RH at the interface between the insulation and vapour barrier, where we see that the condensed moisture in the interior part of the insulation dries to the interior air at very different rates depending on the type of SVB or PE foil used.

There are several limitations or shortcomings with this laboratory experiment. One is that the effect of undercooling of the external surface during the night caused by black-body radiation to the sky is not included. This overestimates the drying to the interior. In addition, the geometry of the experiment is a simplification, since rafters are not included in the test boxes. The rafters will represent an absorptive material in the insulation layer and may influence the moisture distribution and diurnal fluctuations. It should also be mentioned that in this study we have repeated a summer day continuously, which is far from reality. On the other hand, a flat roof with a very dark roofing membrane may have higher maximum external roof temperatures than used in this study. How fast the drying will be in reality will be investigated in a separate simulation study.

The most efficient SVBs for use in flat roofs seem to be the most vapour-open (at high RH levels) products such as SVB-B and SVB-D. Which one of those two performs best cannot, however, be concluded before drying at lower external surface temperatures (shaded summer conditions) and the risk for interstitial condensation during winter conditions are investigated.

In Autumn 2012 a similar laboratory study was performed, this time using lower external surface temperature, as if the roof was shaded from direct solar radiation. Preliminary results seem to indicate slower drying, approximately a reduction of 50% of the drying rate. We are currently also investigating the risk for interstitial condensation during wintertime. This is also very interesting, since one of the benefits of the newer SVBs such as SVB-A and SVB-D, as compared to the older polyamide product SVB-B (Künzel 1996), is that they have a higher resulting vapour resistance during winter conditions.

CONCLUSIONS

Nowadays there exist several types of SVBs. They have various properties in regard to their range of vapour resistance at various RH levels. In this study a laboratory experiment was performed to investigate the drying rates for various types of SVBs during summer conditions for an unventilated compact wood frame roof. The results showed that the various SVBs performed differently in regard to drying rate, depending on the vapour resistance and its dependance on RH.

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