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In situ performance assessment of vacuum insulation panels in a flat roof construction

Samuel Brunner, Hans Simmler*

Empa, Swiss Federal Laboratories for Materials Testing, Research Laboratory for Building Technologies, CH-8600 Duebendorf, Switzerland

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Abstract

The recently introduced vacuum insulation panel (VIP) is a space saving alternative to conventional thermal insulation, thanks to its five to eight times higher thermal resistivity. As gas permeation through the envelope barrier may drastically reduce the insulation efficiency, aging effects and service life expectation are crucial aspects of those high performance insulation units. In the present paper, monitoring data from a terrace construction over more than 3 years are reported. The results are compared with laboratory aging data at constant conditions by linear and Arrhenius weighting of the dynamic boundary conditions. Based on satisfactory agreement, a similar approach is applied for the prediction of the thermal performance after an installation time of 25 years, the common time used for building design regarding energy performance.
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Keywords: Vacuum insulation panel; High-performance thermal insulation; Building envelope; Monitoring; Aging; Service life prediction

1. Introduction

The vacuum insulation panel (VIP) is a high-performance thermal insulation component for the building envelope that was introduced into construction technology in the last few years [1]. Its high thermal resistivity, which is five to eight times higher compared to conventional insulation materials, makes it suitable for designing energy efficient buildings even with slim insulation layers. Big potentials also exist in building renovation, where often little space is available for thermal insulation. In Switzerland, VIP are frequently installed in terrace areas of apartment houses in recent years, since the indoor and outdoor floor level can be kept equal, while maintaining the required low U-value for terrace areas with heated space underneath (Fig. 1).

A VIP consists of a micro-porous core material that is sealed in a gas tight envelope at low air pressure. While open cell organic foams were used earlier by the refrigeration industry, fumed silica powder (SiO_2 agglomerates) has become the favorite core component in VIP for building application [2,3]. With this core material, the gaseous conduction is negligible even at gas pressures up to 10 mbar, which is a benefit of the pore size below 0.3 μm (Fig. 2). In contrast to organic foams, which are in use for transportation units, SiO_2 shows no outgassing, is chemically stable, non-combustible and does not require metallic getters. Additional core ingredients are polymer or glass fibers for structural reasons and opacifier to eliminate radiative heat transfer, yielding a thermal conductivity of about $4\times10^{-3}\,W\,m^{-1}\,K^{-1}$ for the dry core at 1 mbar. Massive aluminum foils used as gas barrier in the early stage of VIP production are favorable regarding the permeation properties, but thermal bridge effects around the panel edges strongly affect the overall thermal performance in building applications [4]. Actual barrier materials used for SiO_2-VIP are laminates of up to three aluminum coated polymer films made of polyethylene terephthalate (PET) and/or polypropylene (PP), and an additional polyethylene (PE) sealing layer [5].

Laboratory-based aging experiments and service life prediction models suggest sufficient service life for this type of VIP in building applications [6,7], as pressure increase

*Corresponding author. Tel.: +41 44 823 4276; fax: +41 44 823 4009.
E-mail address: hans.simmler@empa.ch (H. Simmler).

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rates up to 2 mbar yr^{-1} are acceptable with fumed silica. However, since long-term experience with installed VIP is almost missing, there is a need to verify laboratory-based service life prediction by performance data from real applications. In the following, we present measurements on a VIP-insulated flat roof construction that has been monitored from June 2004 till June 2007. The results are compared with values obtained by laboratory aging measurements under defined temperature und humidity conditions. A simplified time dependence of the center-of-panel thermal conductivity is given that allows an estimation of the long-term thermal performance. It is shown that a service life of several decades can be expected for this VIP construction, where aging in terms of a continuous increment of the thermal conductivity is taken into account. Monitoring and comparative aging modeling results of other construction applications are described e.g. by Schwab et al. [8].

Fig. 1. Example of a slim balcony insulation with VIP giving equal levels for indoor and outdoor zones (2003). Today, panels for on-site installation are normally shipped with glued-on protection layers.

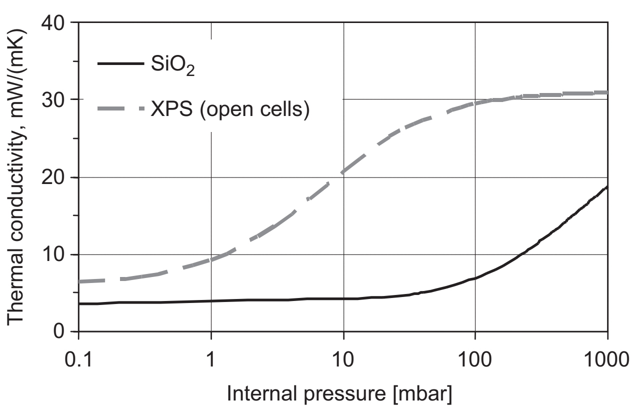
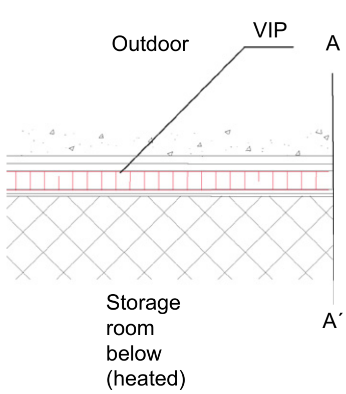


Fig. 2. Thermal conductivity of nano-porous fumed silica (SiO_2) and open cell extruded polystyrene foam (XPS) as a function of gas pressure.

2. Experimental set-up

An existing flat roof construction as illustrated in Fig. 3 was chosen for investigation. The location of the building is in Regensdorf, near Zurich (Switzerland). SiO_2-VIPs with a three-fold metallized polymer laminate barrier, and dimensions of $25 \times 25\,cm^2$ or $50 \times 50\,cm^2$ and a thickness of 20 mm, were installed in two square areas of about $200 \times 200\,cm^2$. Larger VIP formats are normally used to reduce the pressure increase. For the test set-up, small formats were chosen in order to get more significant aging effects. The sequence of material layers in vertical direction is listed in Fig. 3. Pictures from the installation process are shown in Fig. 4. In one area, temperature and humidity sensors were installed in the indoor and the outdoor surfaces near the center and at the cross joints of a number of VIP surrounded by a guard area consisting of similar panels. Details of the area layout, sensor locations and labeling are shown in Fig. 5. Combined temperature–relative humidity (RH) sensors labeled "*TF* x/y", where x indicates the inside and y the outside surface of the VIP layer, were used at specific locations such as center-of-panel, joint and cross joint. These sensors ("Rotronic Hygroclip SC04", diameter 4 mm) were installed on both sides at the center-of-panel location and at the central cross joint of the test area. The temperature is measured by a



Layer (A-A')	2 [mm]	d
Crushed gravel	4	30
Bituminous water barrier (3 layers)	6	10
Protective layer	8	7
VIP	10	20
Protective layer	12	5
Water barrier (existing construction)	14	10
Porous concrete (existing construction)	16	200

Fig. 3. Cross-section of the flat roof construction used for monitoring and sequence of the material layers including VIP insulation (A–A′ from outside to inside).

Fig. 4. Pictures from the installation process of the two VIP test areas.

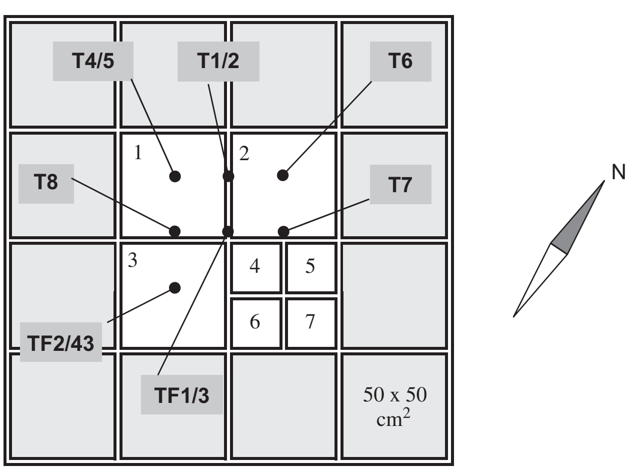


Fig. 5. Schematic outline of the in situ monitored test area with location and labeling of the sensors. *T* stands for temperature, *F* for humidity. Outside/inside positions are indicated by x/y. The gray shaded surrounding VIPs were installed to shield the monitored ones, shown in white.

standard PT100 resistor, and the RH is measured by a calibrated moisture sensitive capacitance element. In addition, 0.3 mm type *T* thermocouple (TC) temperature sensors were installed at other locations. They are labeled "$T\ x/y$", where x/y is used as before. Data from the built-in sensors as well as climate parameters on the inside and the outside of the test areas were recorded in an hourly basis with a logger ("Squirrel"). This unit includes an internal reference temperature measurement and direct transformation of the TC voltages into a correct temperature reading in degree Celsius.

The other area was not equipped with sensors but prepared for repeated opening, because the internal pressure and moisture content had to be determined in the laboratory. The internal pressure was determined by measuring the "critical" pressure, at which the flexible envelope of a panel starts blowing in a depressurization chamber. The lift-off as a function of chamber pressure is recorded by several optical distance sensors; this allows a mathematical evaluation of the lift-off pressure with a repeatability of about 0.1 mbar at pressures from 0.5 to 20 mbar [6]. Every time when VIPs were removed from the construction, they were conditioned to room temperature for more than 3 h in order to enable pressure measurements at a constant temperature. The overall uncertainty is about 0.2 mbar at a confidence level of 1σ (standard deviation). The moisture content was determined by an electronic balance with an accuracy of 0.01 g. As a remark: the fact that, after several removal and re-installation processes, all monitored panels are still intact indicates that even bare VIP can be handled on site without damage, if the persons involved are aware of specific risks. As often in Swiss climate there were some raindrops before the initial installation, so that the underlying protective PE foam layer was slightly wetted. It was dried manually as far as possible before the laying of the VIP. After the installation, the test areas were sealed by means of a multiple bituminous water barrier, so that the panels were fully surrounded by a water barrier layer.

3. Monitoring results

The data recording started in June 2004 and will continue for several years. Fig. 6 shows the temperature evolution during 3 years at the center-of-panel location *TF* 2/4 for both sides of the VIP surface. The yearly temperature cycle on the outside surface covers a temperature range between -10 and $+60\,^{\circ}$C. This means temporarily rather high temperatures in summertime, in spite of the heat buffering capacity of the gravel layer. The temperature variation on the inside surface is much smaller. The inside temperatures were relatively low in winter because the subjacent room was not fully heated. The RH on both sides of the VIP is depicted in Fig. 7. The RH on the VIP surfaces is rather independent from temperature variations, which is typical for a cavity containing moisture-buffering materials (protective layer in Fig. 3). On the inside VIP surface (F2, center-of-panel), the RH value is in continuous saturation. The RH sensor F1 (Fig. 7), located below the cross joint of two panels, is only partly in saturation during the first year, and then reaches continuous saturation too. At first, the observed condensation effects may be associated with the slight

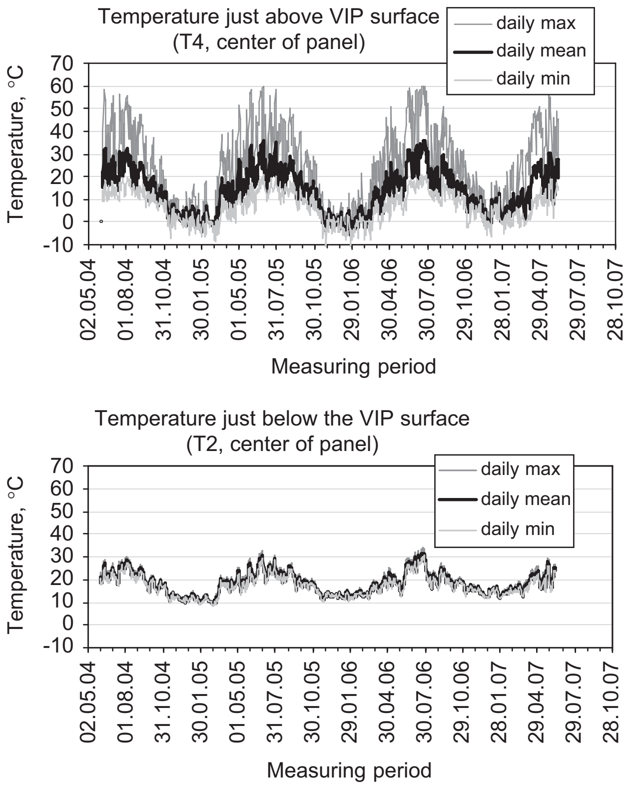


Fig. 6. Monitored temperatures at the center-of-panel location on the outside (left) and the inside (right) VIP surface.

wetting during the installation. However, even after opening the test area several times under dry conditions, condensation still occurs. Wetness has been observed also in a test area nearby that was never exposed to rain loads. Therefore, it is assumed that permeation through the water barrier gives the main contribution to the water found inside the sealed space enclosing the panels. A continuous RH increase occurs on the outside (just above the VIP surface), which may be due to moisture transfer from the high humidity zone at the inside (just below the VIP surface). The second test area was opened repeatedly in order to determine the moisture content and the internal pressure of test specimens in the laboratory. In agreement with the RH measurements of the in situ monitored test area, condensation was observed below the panels upon the first removal of the bituminous barrier. In subsequent opening procedures condensation was observed partly, primarily at the inside of the VIP layer. Evaporation of moisture during the opening periods did happen, since removal and re-installation were done under dry conditions. Yearly pressure increase rates p_a are shown in Fig. 8 for the two VIP sizes. The time evolution of the yearly rates was determined by dividing the difference of the actual and the first reading by the time difference (in years). As indicated in Fig. 8, the uncertainty decreases with increasing time due to the absolute measurement uncertainty of $p_a \approx 0.5$ mbar (2σ interval). There is also a transient effect which seems to be associated with seasonal variation of the in situ boundary conditions, despite the conditioning of the VIP to room temperature before measuring. The latest evaluation based on data after 774 days gives the average values $p_a = 2.7\,\text{mbar}\,\text{yr}^{-1}$ for the format $25 \times 25\,\text{cm}^2$, and $2.1\,\text{mbar}\,\text{yr}^{-1}$ for the format $50 \times 50\,\text{cm}^2$. The statistical uncertainty is $0.2\,\text{mbar}\,\text{yr}^{-1}$. Similar graphs for the yearly moisture content increase rate X_{wa} are shown in Fig. 9. Again a large uncertainty is seen for early evaluations. A clear decrease, visible in the time development of the rates X_{wa}, is probably due to an adhesive tape on the panel surfaces acting as a moisture buffer after installation. After a reasonable time period, this bias is eliminated in the evaluation. A second contribution to the decrease of X_{wa} may be a reduction of the moisture level in the insulation layer as a result of drying in periods with open test area. Averages of the yearly moisture content increase rates for the two VIP sizes are 0.15 and $0.10\,\text{mass\%}\,\text{yr}^{-1}$, with a relative uncertainty of 15–20% (Table 1). The measurements show a significant size dependence of the rates, indicating that permeation takes place through the surface as well as through the perimeter of the panels.

4. Analysis

In order to compare the monitoring results with laboratory-based aging data, permeation data were determined in the laboratory at various temperatures at about 80% RH. This corresponds approximately to the cavity in the situation described above, where the mean monitored humidity was about 85% RH (Fig. 7). The yearly pressure increase rate p_a as a function of temperature is indicated in Fig. 10 in a $\log(p_a)$ versus $1/T$ plot. The linear shape of the plotted data clearly indicates an Arrhenius-like temperature dependence of the pressure increase rate.

The Arrhenius fit parameters A and E_a (the apparent activation energy) were used to determine an effective temperature $T_{\text{effective}}$ and to estimate the yearly rate p_a with respect to dynamic boundary conditions according to the following Arrhenius weighting:

$$p_a = \sum_i A \exp\left(-\frac{E_a}{RT_i}\right)\Delta t_i \bigg/ \sum_i \Delta t_i \equiv A \exp\left(\frac{-E_a}{RT_{\text{effective}}}\right). \tag{1}$$

Eq. (1) includes the assumption that the dynamic case can be approximated by adding up fractional contributions at respective static conditions. The yearly moisture content increase rate X_{wa} shows a similar Arrhenius-like temperature dependence at constant RH, according to the exponential temperature dependence of the driving vapor pressure. As a consequence, Eq. (1) was used in a similar way to calculate the weighted average rate X_{wa} for the dynamic boundary temperatures in the application. In non-sealed constructions, where the vapor pressure is not linked to the temperature as in sealed cavities, the dynamic vapor pressure boundary conditions and the related permeability of the barrier must be considered. The temperature

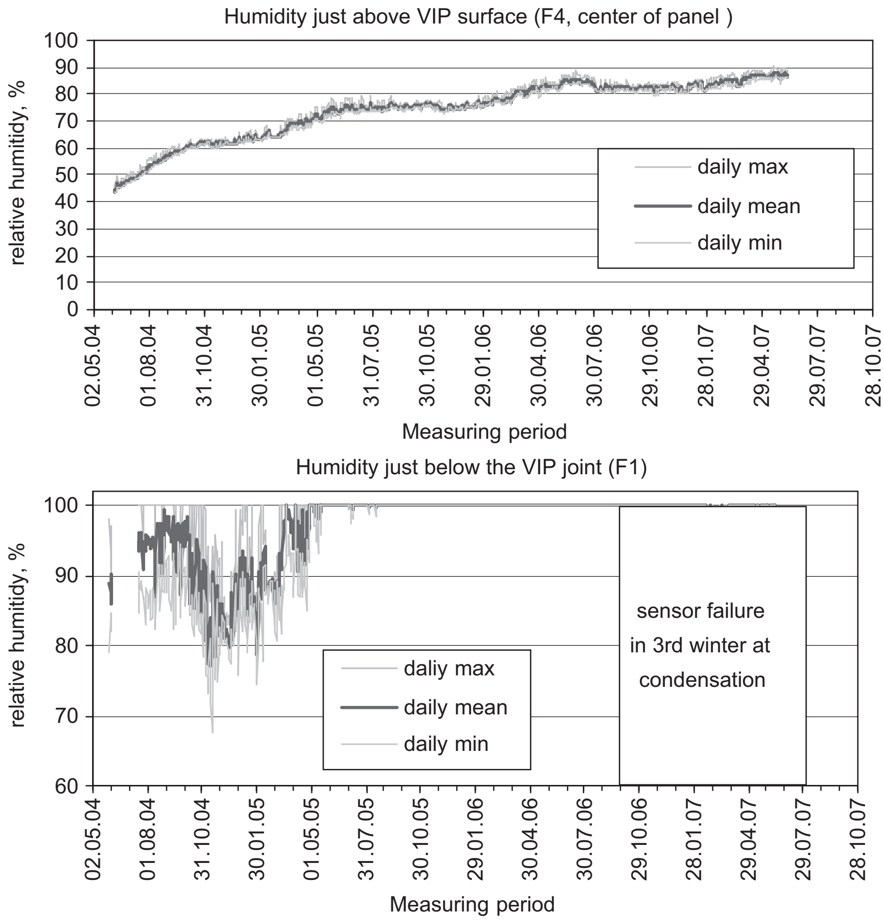


Fig. 7. Monitored relative humidity at the center-of-panel location on the outside (left) and at the joint between two panels on the inside of the VIP layer (right).

histogram obtained from the monitoring data is shown in Fig. 11 for the outside surface. A frequency peak is caused by the melting temperature of snow, which, however, has no important influence on the results.

The effective temperatures, $T_{\text{effective}}$, are 18.6 °C on the inside and 18.8 °C on the outside VIP surface. A comparison with the common average temperatures 17.7 °C (inside) and 12.4 °C (outside) shows that the non-linearity of the exponential weighting has a larger influence on the pressure increase at the outside surface. The increase of 6.4 K due to the high temperature peaks (Fig. 6) equals the influence of the conditions at both sides on the aging in this case. Calculated pressure and moisture content increase rates are summarized in Table 1 together with the measured values for the two panel sizes. Based on the effective temperatures, the pressure increase rates are in good correspondence with the measured values. The uncertainty of the calculated value is thought to be significantly higher than that of the measurement. On the other hand, if the average temperature is used, the result is lower compared to the measured value, thus underestimating the non-linear weight of high temperatures. Regarding moisture content increase, the agreement between calculated and measured values is less than above, but still useful for prediction. One reason for this may be a drying effect due to the repeated opening of the test area, indicated by the disappearance of condensation. Therefore, the humidity level around the VIPs in the opened test area has been reduced to some extent, in contrast to those of the monitored test area. A second reason may be the transient character of the short high temperature—high vapor pressure periods. In those periods, the assumed steady state moisture transfer is not fully established within the high barrier film, as was demonstrated by time dependent measurements of the water vapor transmission rate [1]. In addition, the water vapor permeability is dependent on temperature and moisture content in a nonlinear way [9]. It should be noted that the humidity related rates are really small, so that a rather large uncertainty has to be accepted for those results. In summary, averaging steady state permeation data to approximate dynamic boundary conditions seems to be justified within the range of boundary conditions described here. Arithmetic averaging disregards the disproportional contribution of temperature peaks. Coherently, simply averaged rates tend to underestimate the real behavior. Arrhenius-like weighting is in good agreement with real data regarding pressure increase, and is on the safe side regarding moisture content increase. In

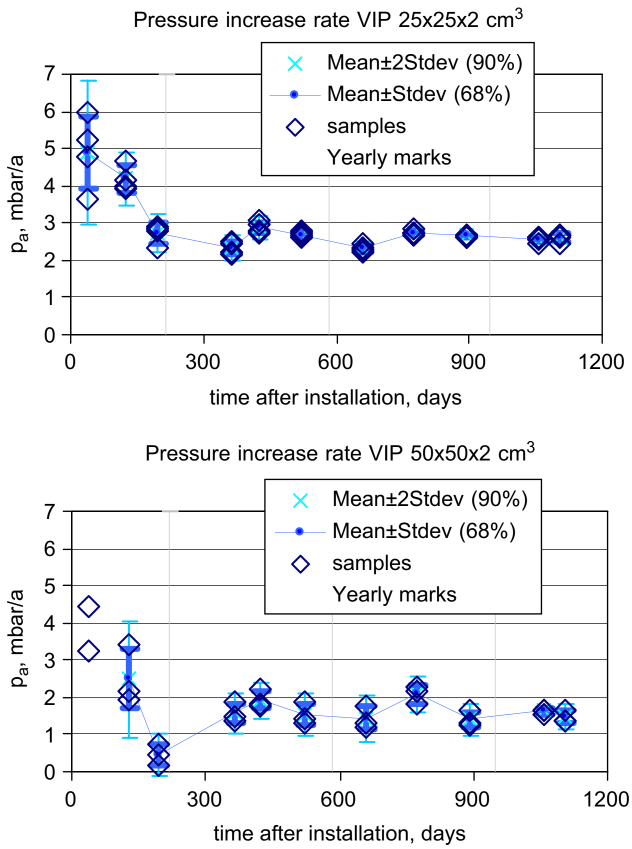


Fig. 8. Yearly pressure increase rates as determined for the two VIP formats during the monitoring period.

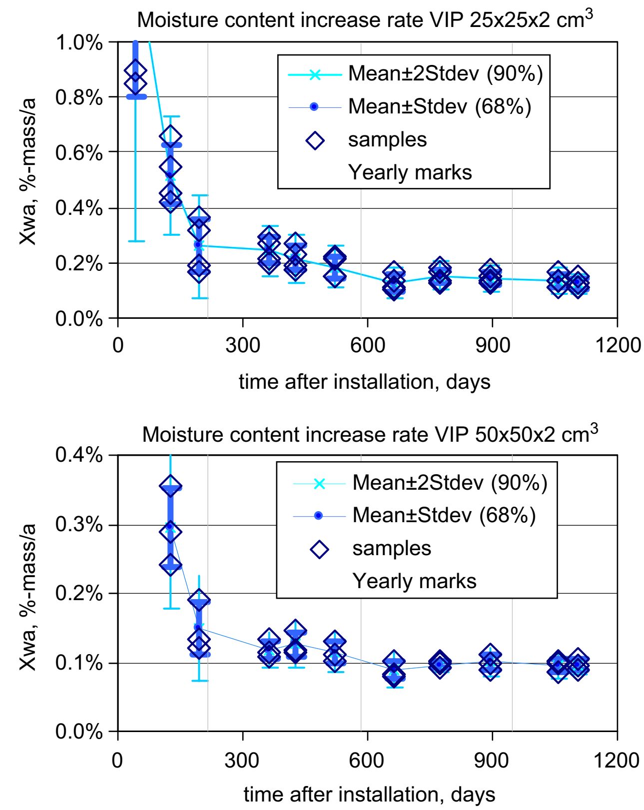


Fig. 9. Yearly moisture content increase rates as determined for the two VIP formats during the monitoring period.

the described application, mechanical or chemical stress does not seem to accelerate aging during the observation period. However, the occurrence of 60 °C combined with high humidity must be considered in the development of laminated barrier materials, as the typically used polyurethane adhesive is not necessarily stable against hydrolysis at these conditions [10]. Therefore, with actual barrier materials, temperatures in sealed constructions containing moisture should be limited to a level around 60 °C by constructive means.

5. Service life prediction

Under the assumption that other aging mechanisms are negligible, continuous degradation of a VIP as described in the previous sections will take place. Thus, service life may be understood as the time period until a certain performance criterion is no longer fulfilled. From a practical point of view, the main performance parameter is the thermal conductivity. The relation between gas permeance properties and the thermal conductivity of fumed SiO_2 can be expressed by the following simplified equation [6]:

$$\lambda(t) \cong \lambda_0 + \frac{\partial\lambda}{\partial p} p_a t + \frac{\partial\lambda}{\partial X_w} X_{w,eq}\left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \quad (2)$$

Additional symbols are:

λ_0, initial thermal conductivity, $10^{-3}\,W\,m^{-1}\,K^{-1}$; $\partial\lambda/\partial p \cong 0.035\times10^{-3}\,W\,m^{-1}\,K^{-1}\,mbar^{-1}$, for $p \leqslant 100\,mbar$; $\partial\lambda/\partial X_w \cong 0.50\times10^{-3}\,W\,m^{-1}\,K^{-1}\,mass\%^{-1}$; $X_{w,eq}$, equilibrium moisture content $\cong$ 6.4 mass% at 80% RH; τ, moisture saturation time constant $\cong X_{w,eq}/X_{wa}$ (in years).

In Eq. (2), the gas pressure is assumed to increase linearly with time t, which is a reasonable approximation up to 100 mbar [1]. Moreover, an experimentally determined proportionality constant between pressure and thermal conductivity is used for the pressure range under consideration. The moisture content may approach equilibrium according to the hygroscopic sorption isotherm. To apply Eq. (2) in a realistic way some changes in the boundary conditions were made. The inside boundary temperature is set at 21.5 °C to have a typical average surface temperature in a domestic building, and a common panel format is chosen. Therefore, the laboratory-based data for the selected surface temperatures are up-scaled to the typical product format $100\times60\times2\,cm^3$. Thus, we get the parameters $p_a = 1.5\,mbar\,yr^{-1}$, $X_{wa} = 0.17\,mass\%\,yr^{-1}$, and $\tau = 37.6\,yr$.

The increase of the thermal conductivity according to Eq. (2) is depicted in Fig. 12. The expected change of the thermal conductivity becomes $2.9\times10^{-3}\,W\,m^{-1}\,K^{-1}$ after 25 years, which is the standard period for the specification of long-term properties of thermal insulation products in

Table 1
Measured and calculated permeation data of VIP elements in the flat roof construction

Panel size	Quantity	Calculation based on the temperature data (2 years)			Measurement (774 days)	
		Inside	Outside	Mean		
In mbar yr^{-1}						
$25 \times 25 \times 2\,cm^3$	p_a ($T_{effective}$)	2.70	2.75	2.73	2.7	±0.2
	p_a ($T_{average}$)	2.50	1.63	2.07		
$50 \times 50 \times 2\,cm^3$	p_a ($T_{effective}$)	2.03	2.06	2.05	2.1	±0.2
	p_a ($T_{average}$)	1.88	1.23	1.56		
In mass% yr^{-1}						
$25 \times 25 \times 2\,cm^3$	X_{wa} ($T_{effective}$)	0.25	0.27	0.26	0.15	±0.03
	X_{wa} ($T_{average}$)	0.23	0.15	0.19		
$50 \times 50 \times 2\,cm^3$	X_{wa} ($T_{effective}$)	0.17	0.18	0.18	0.10	±0.01
	X_{wa} ($T_{average}$)	0.16	0.10	0.13		

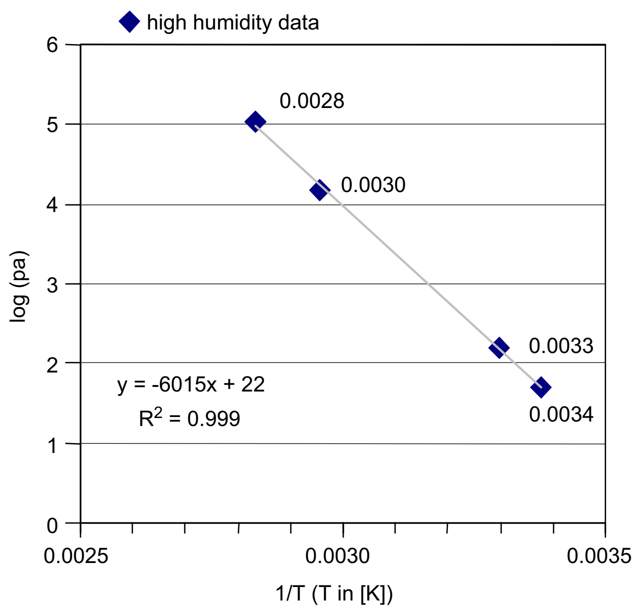


Fig. 10. Arrhenius plot of lab determined pressure increase rates at about 80% RH (panel format $25 \times 25 \times 2\,cm^3$).

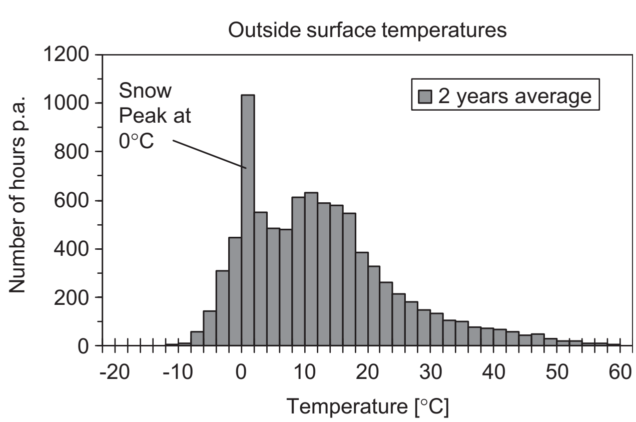


Fig. 11. Histogram of hourly values of the outside surface temperature measured over 2 years (average for 1 year).

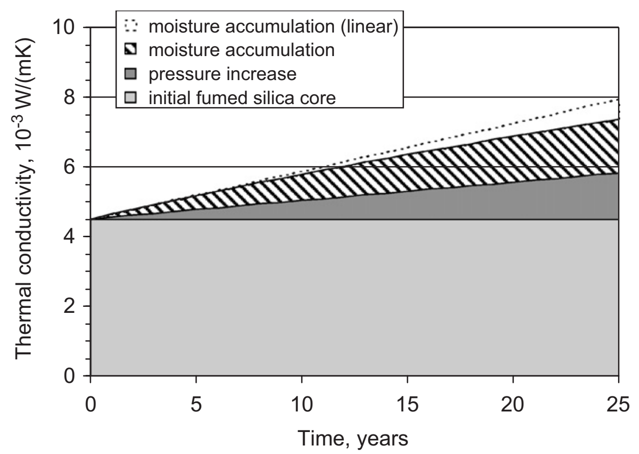


Fig. 12. Effect of pressure increase and moisture accumulation on the thermal conductivity of VIP (format $100 \times 60 \times 2\,cm^3$) over a period of 25 years. The dotted line indicates the increment omitting moisture saturation.

Europe (see, e.g. Ref. [11]). Assuming an initial value $4.5 \times 10^{-3}\,W\,m^{-1}\,K^{-1}$ the thermal conductivity after 25 years will be $7.4 \times 10^{-3}\,W\,m^{-1}\,K^{-1}$. Using common terms in building technology, with a design value $\lambda_D = 8 \times 10^{-3}\,W\,m^{-1}\,K^{-1}$ for this type of applications, a service life of 25 years can be expected under the conditions described. At present, there are no approved means to quantify the uncertainty of this prediction. An error propagation analysis on the influence of parameter deviations in Eq. (2) gives a relative uncertainty of 10–15% for the predicted thermal conductivity after 25 years.

6. Conclusions

Monitoring data from a flat roof with VIPs show non-negligible aging effects of the panels within a period of 2 years. Aging characteristics derived from laboratory experiments at defined temperature and humidity conditions can be related to the in situ behavior by weighting the experimental boundary conditions. The pressure increase rate obtained by non-linear (Arrhenius) weighting is in good correspondence with the experimental data. The moisture content increase seems to be overestimated to some extent. Experimental effects and the assumption of steady state behavior may contribute to the deviation between measurement and prediction. Both in situ and laboratory-based aging results suggest a service life of several decades in building applications, provided that the long-term increase of the thermal conductivity is taken into account at the design stage. The increment depends on barrier properties, panel dimensions, and boundary conditions. For the described application, a long-term value of $8\times10^{-3}\,\mathrm{W\,m^{-1}\,K^{-1}}$ may be appropriate for state-of-the-art VIP with fumed silica core and polymer-based barriers. In applications with lower moisture loads, e.g. in façades, the design value may be $7\times10^{-3}\,\mathrm{W\,m^{-1}\,K^{-1}}$. Monitoring results from periods of several years are still needed to clarify remaining uncertainties and to quantify possible supplementary aging effects. Strengthening confidence in the vacuum insulation technology is an important prerequisite to further propagate this promising technique in improving the energy efficiency of buildings with space constraints.

Acknowledgments

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