Journal of Building Engineering 12 (2017) 140–146

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Temperature and moisture evolution beneath an aerogel based rendering applied to a historic building

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A R T I C L E I N F O

Keywords:
Aerogel based rendering
Restoration
Historic building
External rendering
Vapor permeability
Random stone wall

A B S T R A C T

Retrofitting of buildings defined as cultural heritage with respect to energy consumption and thermal comfort of the occupants is a demanding endeavor due to the additional requirements of the conservation aspect. Within a pilot project an inhabited mill in Sissach/Switzerland whose first mention dates back to the 14th century has been retrofitted by using a highly insulating external rendering containing SiO_2 aerogel and mainly mineral admixtures namely hydraulic lime, calcium hydroxide, white cement, aerogel granules, light mineral aggregate, water retaining agent, air-entraining agent, except the organic hydrophobic agent. By a rendering thickness of 5–6 cm, the thermal transmittance through the walls was reduced to one third of its original value and the thermal comfort in the 6 apartments improved substantially including a reduction in mold growth risk. The characteristics of the aerogel based rendering have been discussed especially with respect to preservation aspects. By installing temperature and moisture sensors on the original wall and beneath the insulating rendering it was shown that its application on the original walls fulfils the requirement for avoiding moisture accumulation. Further, hygro-thermic simulations were performed extrapolating temperature evolution and water content for a period of 5 years. The object represents a new paradigm in the energy efficient restoration of the built heritage and simultaneously respecting the conservation aspects. The project has been carefully monitored by the state office (Basel-Landschaft) for preservation of monuments.

1. Introduction

Article 5 of the Venice Charter [1] states that “the conservation of monuments is always facilitated by making use of them for some socially useful purpose” adding that this should be done without changing the “lay-out or decoration of the building”. Adaptation and preservation of historical buildings has been recognized as vital for the conservation of construction, culture and history [2] and it has been argued that making a building usable is the guarantee to preserve it [3]. In order to make use of listed old buildings as residential or office buildings in the 21st century a number of requirements have to be fulfilled dealing with diverse aspects such as energy consumption, comfort, stability, sustainability and life expectancy simultaneously to the very demanding aspects of preservation. A large number of the existing literature concerning retrofit of old and protected buildings deals mainly with the structural stability of these constructions [3,4].

The most straight-forward strategy to retrofit existing buildings with respect to their energy consumption and the improvement of the thermal comfort is the use of external insulation. This solution is not applicable to retrofit protected/listed buildings as it will not comply with the requirement of leaving the outer façade unchanged or at least apparently unchanged. The alternative concept of internal insulation cannot be transposed directly to this kind of buildings either because of the following aspects. First, there is the reduction in the internal space which has to be dealt with, especially if heating and cooling installations have to be removed, reinstalled or replaced. There are also the thermal bridges occurring mainly at the junctions between external walls and floors / ceilings which have to be considered and dealt with. Another aspect is the temperature drop during the cold period of the year of the whole original wall which will become thermally separated from the warm interior due to the inner insulation layer as well as the change to the thermal inertia of the whole building. This leads to a

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http://dx.doi.org/10.1016/j.jobe.2017.05.016
Received 12 March 2016; Received in revised form 23 May 2017; Accepted 24 May 2017
Available online 25 May 2017
2352-7102/

slower drying of the accumulated moisture, shorter drying periods or even to new accumulations at the external layers enabling eventually frost damage on the external façade. Finally, the expectations of inhabitants regarding thermal comfort have also to be met to encourage them to live or work in retrofitted old buildings. All of these conditions have to be balanced with respect to conservation requirements. It goes without saying that there is no general solution but rather a careful case by case analysis of the feasibility of retrofitting old buildings to modern living standards. A rather important economical aspect which has to be kept in mind is the impact of energy efficient retrofit measures on the market price of the building [5]. It has been argued [6] that higher prices for energetically advantageous performing buildings is a market driven argumentation which has to be included in energy policies. The socio-technical issues of dwelling retrofit are important too [7] but beyond the subject of this study. The present investigation is a special case of an external insulation keeping the appearance of the historic building unchanged by means of a 5–6 cm high performance thermal insulation rendering containing SiO_2 aerogel granules (already on the market for 3 years) to improve the thermal behavior of the random stone walls of a historic building. The development of such high-performance rendering is spreading over Europe and new developments are underway [8–10]. The present paper reports on in-situ measurements of temperature and moisture at critical points and numerical simulations used for the hygro-thermic analysis of the wall before and after the retrofit procedure for different assumed initial conditions showing the robustness of this retrofit procedure.

2. The historic mill of Sissach

The investigated mill is situated in the historic town center of Sissach in Canton Basel-Landschaft belonging to the flatlands of north-western Switzerland. The mill of Sissach is listed in the Federal Inventory of Swiss Heritage Site (ISOS) by the Swiss Federal Office of Culture (FOC) as of national importance. The oldest parts of the mill date back to the 14th century. Throughout the centuries, a complex building arose with an impressive pitched roof so that its architectural substance represents an important testimony of the historic character of the town center of Sissach. The present-day shape and size has remained nearly unchanged since 1672. It was in 1905 that for the last time grain was milled to flour and since then the mill was turned into a residential building. It was used as a dwelling for workers of a nearby silk ribbon weaving mill, a major industry in Switzerland during the early years of the 20th century. In 1974, the building was subjected to its latest renovation. The old historical rendering on the external side which had been in a ruined state and covered with metal sheets was removed and replaced by a very hard Portland cement rendering. This was possible because at that time only the appearance of the building was of interest to the state office for the preservation of monuments and the original materials and production techniques were not a concern. This circumstance allowed the removal of the above-mentioned external rendering in 2012 without compromising the conservation rules and replacing it with the present aerogel based insulation rendering consisting of mainly mineral ingredients. Nevertheless, all kind of changes on the façade remained subject to tight restrictions hence, forbidding any conventional external insulation right from the beginning. Fig. 1 shows the eastern façade of the building before and after the new retrofit respectively. The same is shown for the southern façade in Fig. 2. Today the dwelling is inhabited by 13 people living in 6 apartments spread over three floors.

3. Retrofit with aerogel based rendering

The analysis of the operating energy losses prior to realizing the energy efficiency measures, showed that 48% of the overall energy loss occurred through the external walls, 25% through the roof, 17% through floors and only 5% through the windows. These were calculated according to the Swiss Standard SIA 380/1 [11]. In order to realize substantial operating energy savings, it was essential to find a solution to insulate the historic external walls.

In case of conventional insulations several problems would have arisen. The historical window casings would have either to disappear beneath an insulation layer or a new casing would have been needed for doubling on top of the existing casings both not acceptable for the preservation office. Further, usage of plastic based materials such as expanded or extruded polystyrene was not accepted by the preservation office. Last but not least, the mainly uneven surfaces of the façades make it nearly impossible to apply rigid insulation boards especially when rounding and corners have to be followed to maintain appearance of the historical surface and the respective light and shadow effects. It has to be mentioned that wooden profiles were used to ensure a more or less homogeneous thickness as it is done for conventional renderings. Besides, large air gaps between a rigid vapor tight insulation layer and the original uneven external walls could cause moisture accumulation and condensation risk.

Until now it was not possible to find an insulating rendering with these special compositions for historical buildings and a thermal conductivity of 0.028 W / (m K) on the market. The invention of the aerogel based rendering opened new perspectives for owners of historic buildings, as it allowed very efficient insulation with only 5–6 cm of insulation thickness. Up to now, this product has been applied to a total surface of approximately 30,000 m^2 in Switzerland [12] without any problems regarding adherence or compressive strength.

At a first glance the external application of the aerogel based rendering does not seem adequate for restoration of listed buildings as its ingredients do not comply with those of a historical rendering and moreover there is the necessity to use a glass fiber reinforcing mesh to compensate for temperature induced stress. Nevertheless, the approval for this pilot project was given first because there was no historic rendering on the façades and second under the strict condition that the thickness of the new rendering does not exceed the thickness of the old one. This made it possible for the stone frame of the windows to continue clearly to protrude and act as decorative elements. Even under these restrictive preconditions the aerogel based rendering enabled an efficient thermal insulation of the façade. Hence, the rendering allowed an external insulation compatible with the overall appearance of the building. Due to the thin layer needed, window and door frames as well as other typical design characteristics essential for a distinctive appearance of a building in the locality remained completely visible after the retrofit procedure.

4. Characteristics of the aerogel based rendering

The aerogel based rendering has been available on the market since January 2013 (Fig. 3). A first summary of the hygro-thermal properties has already been published by the authors [13,14]. The most important of these properties are the thermal conductivity of 0.028 W / (m K) at 23 °C / 50% relative humidity according to EN 12667 [15] and the water vapor permeability resistance factor [16] of as low as 4 (Fig. 4). This low resistance to vapor transfer helps to avoid moisture induced deterioration on the outer façade by concentration of soluble salts [2]. The ingredients of the aerogel based rendering are listed in Table 1. The ingredients mainly responsible for the low thermal conductivity of the rendering are SiO_2 aerogel granules with a porosity of more than 90% and a nano-porous structure. Due to the nano-porous structure the air molecules are trapped in pores smaller than their free mean path length which reduces their contribution to the heat transfer by conduction. A small dried sample of the rendering is shown in Fig. 3 where the aerogel granules are clearly visible. Further, the term “Nano” is defining solely the air-filled pores and there are no nano-sized particles emanating from this rendering which eventually would have implied health related concerns. A human-toxicological investigation of the aerogel based rendering resulted in the following statements [17]: The inves-

Fig. 1. Eastern façade of the building before retrofit with the portland cement rendering (left) and after retrofit with the new aerogel based rendering (right).

tigated aerogel based rendering is by definition of ISO/TS 800004-1:2010 a nano-product to be attributed to the group of nanostructured nano-porous systems (with pore size below 100 nm). The majority of the particles contained in the aerogel based rendering have a size larger than 100 nm and the particle size distribution is situated at the upper Micrometer and lower Millimeter scale. Further, SiO_2 aerogel is nontoxic and does not represent a health risk. The main ingredient i.e. amorphous silica is a well-known comestible additive E551. An elaborate overview on toxicology of engineered nanomaterials is given in the often-cited review of Kunzmann et al. [18]. Finally, the presented rendering is fire resistant and does not develop any smoke or burning droplets. According to EN 998–1: 2010 the whole system achieves the classification A2-s1-d0. Fig. 5 shows the impact a flame of about 1800 °C has on a specimen of this material. This property is important mainly for indoor applications where fire reaction of the innermost layer of the walls has a decisive role in the time of evacuation and the spread of the fire as well as the protection of the layers and materials beneath. As an external application, the fire reaction has also a considerable importance in suppressing the fire spread to upper floors trough broken windows as well as between buildings especially in old town districts where alleys are narrow and buildings have been built very near to each other. The price of the here investigated aerogel based rendering has dropped by 50% since January 2016 and will change further in the future. So, it is advised to ask directly at the producer Fixit about the latest developments.

5. In-situ measurement and numerical simulation

There are some practical points in evaluating the retrofit of a many centuries old building which has to be taken into account when comparing measured and calculated results:

– The external walls do not have the same thickness throughout the whole building. According to the investigations of the owner (one of the authors) the external walls of the ground floor were about 700 mm in thickness. This value reduces to 600 mm for the external walls of the first floor and to 450 mm of the second floor. This fluctuation of wall thickness strongly influences the U-value (thermal transmittance coefficient) of the external walls before as well as after the retrofit. Table 2 shows the calculated one-dimensional U-values for three different thicknesses of the random stone wall before and after retrofitting. A thermal conductivity of 0.80 W / (m K) has been assumed for the wall itself. This is a U-value reported by prior in-situ investigations by Baker et al. [19] for a 600-mm thick traditional stonewalls. It has to be kept in mind that the inhomogeneity of the wall and the age of the walls does not allow a precise determination of the thermal properties as it would be the case for modern constructions. The calculations made have to be seen as comparative and not absolute results.

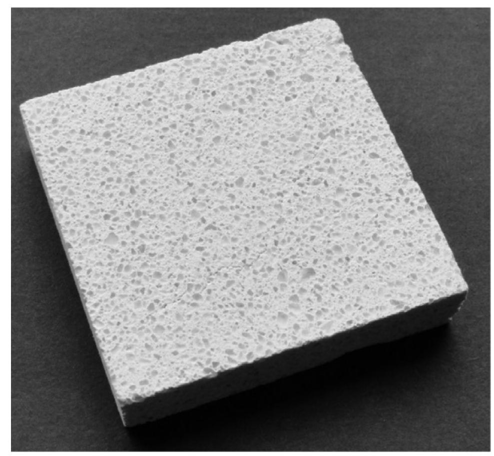

Fig. 3. A sample of 65 × 65 × 15 mm^3 of the high performance aerogel based rendering. The visible particles are SiO_2 aerogel granules.

Fig. 2. Southern façade of the building before retrofit with the portland cement rendering (left) and after retrofit with the new aerogel based rendering (right).

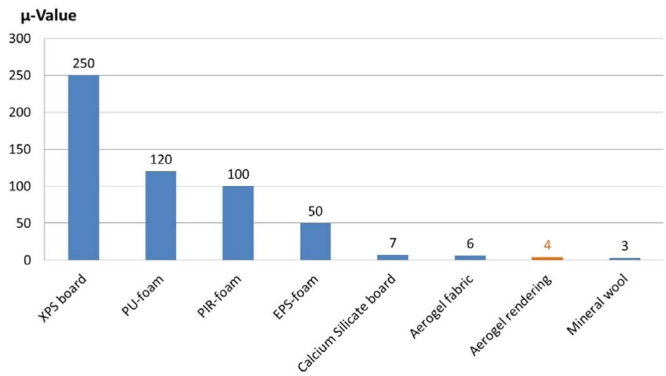

Fig. 4. Water vapor permeability resistance of different insulation materials compared with the aerogel based rendering measured by the dry cup method [16].

Table 1
Main ingredients to the aerogel based rendering (FIXIT 222).

Hydraulic lime
Hydrated lime
Aerogel (SiO_2)
Mineral aggregates
White cement
Water retaining agent
Air-entraining agent
Hydrophobic agent

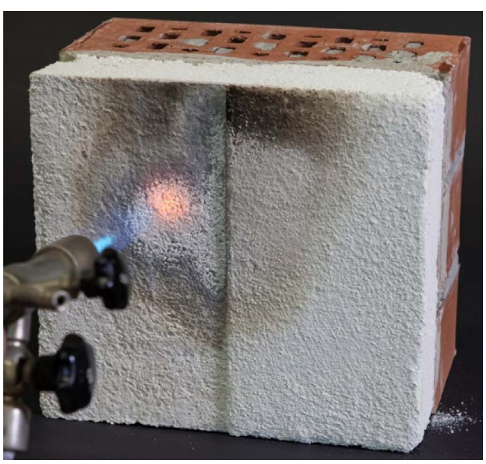

Fig. 5. Simple fire resistance test (not standard) showing that the applied aerogel-based mortar including the finishing layer of the render is non-flammable and non-combustible. The flame temperature is around 1200 °C.

Table 2
Calculated one dimensional U-value before and after retrofitting for three different thicknesses of the random stone wall. A rendering thickness of 50 mm and a thermal conductivity of 0.80 W / (m K) for the wall has been assumed.

Wall thickness [mm]	U-Value prior to retrofit [W / (m^2 K)]	Rendering thickness [mm]	U-Value after retrofit [W / (m^2 K)]	U-Value reduction [%]
450	1.37	50	0.40	approx. 71
600	1.09	50	0.37	approx. 66
700	0.96	50	0.35	approx. 63

– The surfaces of the random stone walls are very uneven due to different stone sizes used (Fig. 6). It is obvious that applying an external rendering will not result in a homogeneous thickness of the latter as it would be the case for modern concrete or brickwork walls. This means that for an average value of 50 mm on top of the external walls fluctuation of ± 10 mm might occur. This unevenness causes at the same time a large uncertainty for the position of the sensor which has to be considered in the numerical simulations by varying the distance between the sensor and the surface of the original wall.

Fig. 6. Position of the air and humidity sensor on the wall before applying the highly insulating aerogel based rendering.

The hygro-thermal conditions between the original external wall and the applied rendering is of major importance. This is because the largest temperature gradient will be over the thickness of the aerogel based rendering due to its very low thermal conductivity compared to the conductivity of the random stone wall. Moisture accumulation and condensation at this part of the retrofitted wall would cause frost damage and consequently the destruction of the rendering's micro-structure. Hence, temperature and humidity sensors were installed to measure temperature and relative humidity at the interface between wall and rendering besides the respective values for the external air. The two Figs. 7 and 8 show the evolution of the measured temperature and the measured relative humidity on the western façade representing the weather side, i.e. the most critical orientation with respect to moisture due to driving rain, for a period of approximately 15 months starting from the day of application at end of August 2012. The temperature beneath the rendering (black curve Fig. 7) is clearly above the external air temperature (grey curve Fig. 7) during the cold period of the year and below it during the hot period. A criterion for avoiding condensation risk beneath the applied rendering is that the corresponding dew point temperature remains well below the measured temperature. As the relative humidity was measured with a sensor integrated in the same element with the temperature sensor, the corresponding dew point temperature could be determined. The dotted curve in Fig. 7 shows that the dew point temperature remains clearly below the measured temperature beneath the rendering layer. An exception to this is the very starting period where these two temperatures are near each other caused by the primary wetness of the applied rendering. As can be seen the latter dries out after a couple of weeks. This is also supported by the measured relative humidity beneath the insulation rendering (Fig. 8 dark line) which remains mostly beneath the relative humidity of the external air (Fig. 8 Gy line) with the exception of the short drying period at the beginning of the measurements. This means that there is no moisture accumulation detected beneath the insulating rendering which may have caused deterioration of its thermal properties or any falling off of the rendering. Laboratory tests on samples of the rendering showed a water content of 3.54 kg / m^3 at an equilibrium of 50% relative humidity. In absence of in-situ measurement of the hygro-thermic conditions prior to the retrofit, numerical simulations of the hygro-thermic behavior of the wall with and without the aerogel based rendering have been performed using the software WUFI-Pro ® Version 5.2 [20] in order to overcome this shortage. For this purpose, the weather data corresponding to an average cold year of Zurich (available on the mentioned software) was applied to the external

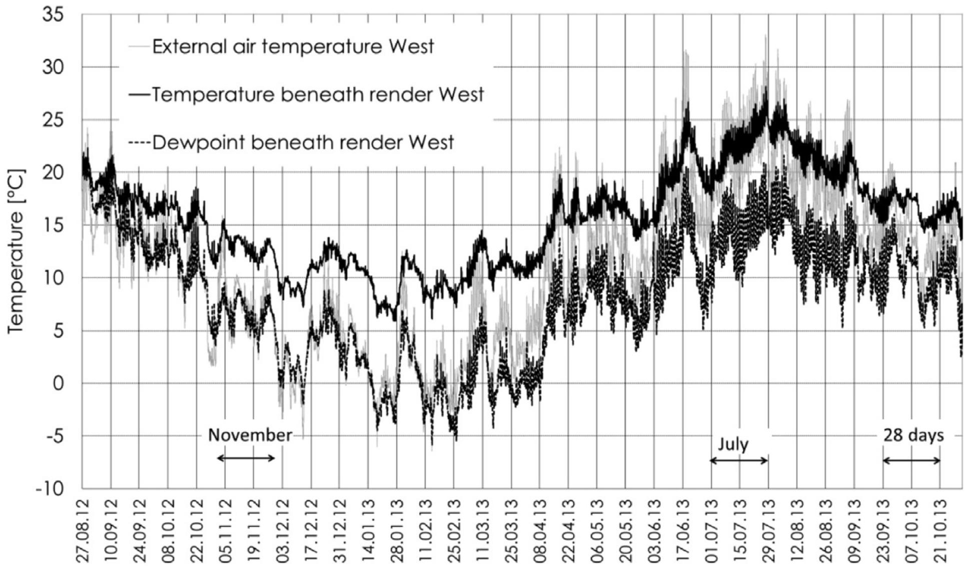

Fig. 7. Measured temperature of the external air and beneath the aerogel based rendering on the western façade for a period of approximately 15 months. The dew point temperature beneath the rendering is calculated based on the measured relative humidity.

surface. On the internal side of the building a constant air temperature of 20 °C and 50% relative humidity has been assumed. A further assumption regarding the weather side was that 1 vol% of the wind-driven rain was allowed to penetrate beneath the aerogel based rendering. This represents the occurrence of rainwater leakage [21] due to cracks in the rendering when moisture can reach directly by convection (and not by slow diffusion) the interface between the wall and the rendering. A summary of the investigated cases is given below:

Case A. – Random stone wall prior to retrofit. This case represents the wall in its initial condition (no render) and gives hints regarding the probable inner surface temperature before retrofit. The values of the hygro-thermic properties used herein are those stated in Table 3.

Case B. – Random stone wall retrofitted with 50 mm aerogel based rendering and a low initial moisture content of the wall: 7.0 kg / m^3 corresponding to an equilibrium relative humidity of 80% representing to the most probable situation on site. This case represents the original wall in a dry state to which an aerogel based rendering layer of 50 mm has been added. In addition, a moisture dependence of the thermal conductivity of the aerogel containing rendering was taken into account for the WUFI calculations (Table 4).

Table 3
The equivalent air layer thickness s_d (= μ × d) of water vapor diffusion for each layer of the investigated wall (according to EN 12086 [16]).

Material layer	Thickness [mm]	s_d value [m]	Sum [m]
Mineral paint	0.15	0.06	
Interior rendering	20	0.16	
Ruble stone masonry	500	10.0	10.22
Preparatory mortar	3	0.05	
Aerogel-based rendering	50	0.20	0.41
Reinforcement layer	6	0.04	
Finishing layer	3	0.02	
Mineral paint	0.2	0.10	

Case C. – Random stone wall retrofitted with 50 mm aerogel based rendering with a high initial moisture content of the wall 42.8 kg / m^{3}corresponding to an equilibrium relative humidity of 99.9%. This is a rather extreme case of an initially very wet wall corresponding to a case when the retrofit would have been done shortly after a long rainy

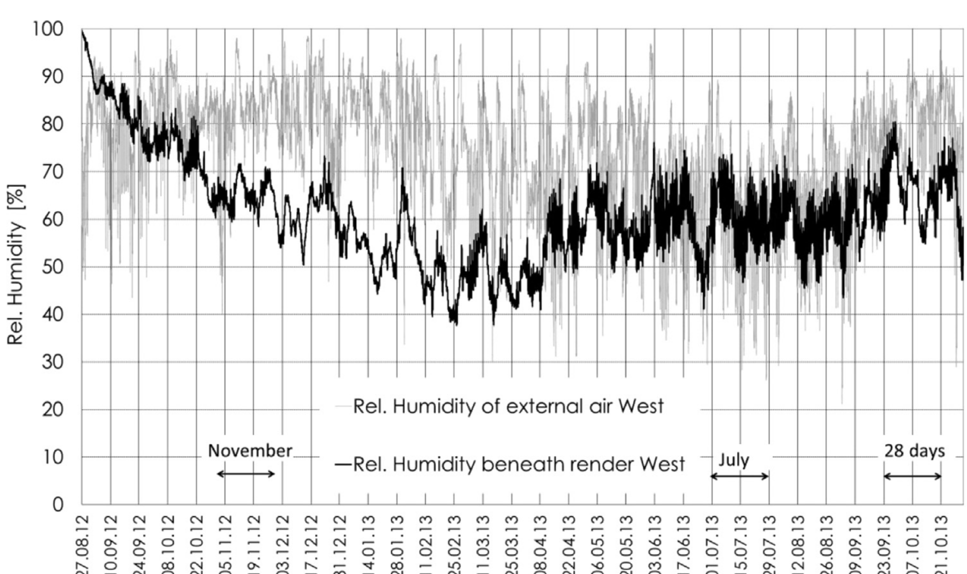

Fig. 8. Measured relative humidity of the external air and beneath the aerogel based rendering on the western façade for a period of approximately 15 months.

Table 4
Measured thermal conductivity of the aerogel containing rendering as a function of rel. humidity.

Rel. humidity	Water content [kg / m^3]	Therm. conductivity [W / (m K)]
0%	0.00	0.0270
50%	3.54	0.0274
80%	8.51	0.0286
Fully water saturated	526	0.364

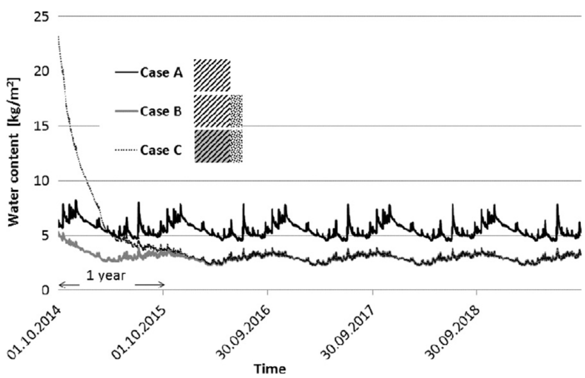

Fig. 9. Calculated/predicted evolution of the water content per unit surface for the 3 investigated cases for a period of 5 years.

period causing a high relative humidity for the internal and the external air.

As moisture transport, due to annual temperature fluctuation is a slow process, the weather data of Zurich for one representative cold year has been repeated 5 consecutive times for all three cases in order to get simulations for a period of five years. By this a prediction of possible moisture accumulation can be made possible. Fig. 9 shows the calculated evolution of the water content per unit surface during a period of 5 years. Prior to retrofit (Case A), the mean temperature of the wall was lower and hence, its average moisture content was higher. After retrofitting (Case B) the mean wall temperature increased due to the insulating effect of the aerogel based rendering and dried out to lower moisture content by the unhindered permeation of moisture through the vapor open aerogel rendering. This is where the vapor permeability of the applied rendering plays a decisive role. Finally, an additional calculation with a completely wetted wall in its initial state (Case C) was carried out to quantify the time period needed for the drying out process after the rendering had been added. Fig. 9 (dotted curve) shows that the wet wall dries out over a period of about 1.5 years and reaches the equilibrium value of Case B. This means that even if the wall would have been completely wetted prior to the retrofit the vapor open rendering allows a rather rapid drying out avoiding interstitial condensation risks. All three calculation cases reached a so called quasi steady state after 2 years irrespective of their initial hygro-thermic conditions. A further prediction made possible by the above calculation is related to the comfort of the inhabitants. A decisive parameter influencing thermal comfort is the relation between the room air temperature and the temperature on the inner surface of the coldest walls. The smaller the difference between room temperature and wall surface temperature the higher the comfort feeling. Fig. 10 shows the calculated inner surface temperature of the wall for Case A (before retrofit) and B (after retrofit of the dry wall). During the cold period when the temperature difference between room side and outdoor is highest, the inner surface of the retrofitted wall is permanently higher than prior to retrofit by 3–4 K. In other words, the difference to the inner air temperature is smaller by 3–4 K which results in a higher comfort. During the warm period the temperature difference between indoor and outdoor is much less at this geographical position which

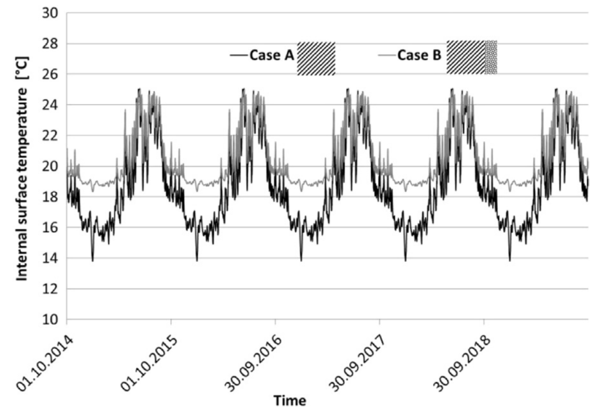

Fig. 10. Calculated / predicted evolution of the internal surface temperature of the building for Case A (black curve) and B (grey curve) for a period of 5 years.

leads also to smaller difference between the inner surface temperature before and after the retrofit. It has to be mentioned that the above calculation may result in other values for the temperature differences if weather data strongly differing from the Zurich data would have been used. The risk of mold growth is also strongly related to the surface temperature of inner surfaces. At low temperatures, this risk will be considerable even at medium relative humidity of the internal air. Higher internal surface temperatures push this risk to higher and hence less probable humidity of the internal air. As an additional qualitative controlling, infrared pictures were taken in the early morning of a winter day in 2013, before direct sun rays could reach the façades, to investigate the temperature distribution on the outer surface of the building. As the temperature difference between indoor and outdoor in this period of time is the highest, the thermal bridges (weak points) on the façade will become better visible. Fig. 11 shows two representative infrared pictures taken from eastern façade (left) and the southern façade (right) with an assumed emissivity of 0.9 (the windows are not relevant). The wall surfaces show a low temperature between − 5 and − 7 °C close to the external air temperature of − 8.4 °C indicating a good insulation. The stripe of the wall beneath the roof has a clearly higher temperature as it is shielded from the heat loss to the cold sky by the eave. The lower parts of the wall show a rather inhomogeneous temperature distribution which is partly due to the inhomogeneity of the wall material itself as well as thermal bridges at the connection to the ground. The stone frames around the windows are clearly the weak points and show higher temperatures around + 1 °C, i.e. low thermal insulation. This has been expected as these parts could neither be removed nor covered externally by an insulation layer. A precise evaluation of the absolute values of the measured temperatures is of minor importance and needs not to be tackled at this stage. Nevertheless, an extended study on the influence of different climatic parameters such as wind, solar irradiation and thermal transmittance on the evaluation of infrared pictures can be found in [22].

6. Conclusions and outlook

The application of a newly developed aerogel based rendering to the whole external façade of an inhabited historic mill in Sissach, a town near the city of Basel in Switzerland, has been a full success with respect to reducing energy demand and avoiding moisture accumulations between the applied rendering and the original wall. As a main requirement, the old character of this protected building has been maintained. Temperature and moisture measurements at critical sites showed no trespassing of the threshold given by the respective dew point and hence, no deterioration or detachment of the rendering occurred. The Hygro-thermic simulations coupled with parametric studies show that even if the walls are wet they will dry out as the high-performance rendering is vapor permeable and hence does not

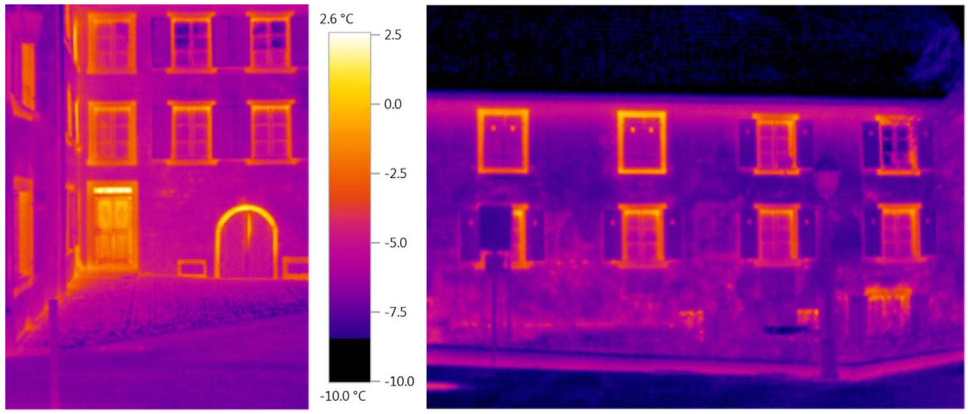

Fig. 11. Infrared pictures on an early morning of a winter day in 2013 of the retrofitted eastern façade (left) and southern façade (right).

induce any moisture accumulation over a long period of time. Additional infrared images supported the effectiveness of the applied high performance insulting rendering.

This investigation lacked the measurement of the heat flux at the inner surface which would have resulted in a measured post retrofit U-value and enable the quantification of energy savings. In order to get more detailed information on these aspects for such a heterogeneous construction, a robust in-situ measurement campaign including hygro-thermic simulations are needed for an acquisition period of several years [23,24,25].

Acknowledgment

The above investigation is part of the project "Sustainable Renovation of Historical Buildings SuRHiB" which has partially been supported by the Commission for Technology and Innovation CTI of the Swiss federal government under the grant Number 10987.

References

[1] ICOMOS, International charter for the conservation and restoration of monuments and sites (The Venice Charter), 1964.
[2] J.A. Garcia-Esparza, Revitalization of architectural and Ethnological heritage: recovery of vernacular building techniques in a 19th century winery, Int. J. Archit. Herit. 8 (2014) 140–159.
[3] M. Philokyprou, Adaptation of new university uses in old buildings: the case of rehabilitation of listed buildings in Limassol Cyprus for university purposes, Int. J. Archit. Herit. 8 (2014) 758–782.
[4] M. Tomaževič, M. Lutman, Heritage masonry buildings in urban settlements and the requirements for eurocodes: experience of Slovenia, Int. J. Archit. Herit. 1 (2007) 108–130.
[5] G. Dall'O, A. Galante, G. Pasetti, A methodology for evaluating the potential energy savings of residential building stocks, Sustain. Cities Soc. 4 (2012) 12–21.
[6] D. Popescu, S. Bienert, C. Schützenhofer, R. Boazu, Impact of energy efficiency measures on the economic value of the buildings, Appl. Energy 89 (2012) 454–463.
[7] Ch. Tweed, Socio-technical issues in dwelling retrofit, Build. Res. Inf. 41 (2013) 551–562.
[8] R. Galliano, K. Ghazi Wakili, Th Stahl, B. Binder, B. Daniotti, Performance evaluation of aerogel-based and perlite-based prototyped insulations for internal thermal retrofitting: HMT model validation by monitoring at demo scale, Energy Build. 126 (2016) 275–286.
[9] M. Ibrahim, E. Wurtz, P.H. Biwole, P. Achard, H. Sallee, Hygrothermal performance of exterior walls covered with aerogel-based insulating rendering, Energy Build. 84 (2014) 241–251.
[10] C. Buratti, E. Moretti, E. Belloni, F. Agosti, Development of innovative aerogel based renderings: preliminary thermal and acoustic performance evaluation, Sustainability 6, 2104, pp. 5839–5852.
[11] SIA380/1, Thermische Energie im Hochbau (in German, French and Italian), SIA Zurich, 2009.
[12] Th Stahl, K. Ghazi Wakili, Bewährungsprobe mit Bravour bestanden (in German), Appl. Sonderausg. (2016) 56–59.
[13] T. Stahl, S. Brunner, M. Zimmermann, K. Ghazi Wakili, , Hygro-thermic properties of a newly developed aerogel based insulation rendering for both exterior and interior applications, Energy Build. 44 (2012) 114–117.
[14] T. Stahl, First practical experiences with the newly developed thermal insulating rendering (in german: Erste Praxiserfahrung mit einem neu entwickelten Wärmedämm-putzsystem), 24. Hanseatische Sanierungstage, Heringsdorf, Germany, 7–9 Nov. 2013, pp. 127–142.
[15] EN 12667, Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance, Brussels, 2001.
[16] EN 12086, Thermal insulating products for building applications - Determination of water vapour transmission properties, Brussels, 2013.
[17] H. Krug, H, Personal communication. Empa, Materials meet life, CH-9014 St. Gallen, Switzerland, 2014.
[18] A. Kunzmann, B. Andersson, T. Turnherr, H. Krug, A. Scheynius, B. Fadeel, Toxicology of engineered nanomaterials: focus on biocompatibility, biodistribution and biodegradation, Biochim. Biophys. Acta General. Subj. 2011 (1810) 361–373.
[19] P. Baker, U-values and traditional buildings. In situ measurements and their comparisons to calculated values. Historic Scotland Technical Paper 10, Edinburgh, 2011.
[20] WUIFI-Pro® Version 5.2, PC-Program for calculating the coupled heat and moisture transfer in building components. The Fraunhofer Institute for Building Physics, Stuttgart, Germany.
[21] H.M. Künzel, D. Zirkelbach, Advances in hygro-thermal building component simulation: modelling moisture sources likely to occur due to rain water leakage, J. Build. Perform. Simul. 5 (2013) 346–353.
[22] B. Lehmann, K. Ghazi Wakili, Th Frank, B. Vera Collado, Ch Tanner, Parameters affecting the infrared thermography results of building façades, Appl. Energy 110 (2013) 29–43.
[23] K. Ghazi Wakili, B. Binder, M. Zimmermann, Ch Tanner, Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building, Energy Build. 82 (2014) 237–242.
[24] K. Ghazi Wakili, Th Stahl, E. Heiduk, M. Schuss, R. Vonbank, U. Pont, C. Sustr, D. Wolosiuk, A. Mahdavi, High performance aerogel containing rendering for historic buildings with structured façades, Energy Procedia 78 (2015) 949–954.
[25] R. Garrido, J.D. Silvestre, I. Flores-Colen, Economic and energy life cycle assessment of aerogel-based thermal renders, J. Clean. Prod. 151 (2017) 537–545.