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Hygrothermal Behaviour of Three Internal Retrofit Prototype Solutions

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Abstract

Although the application of internal insulation to existing perimeter walls poses significant challenges in terms of building physics and loss of habitable space, it is sometimes an inevitable choice because of practical or legislative constraints. Innovative solutions are then required to deliver satisfying performances and reduce nuisance to inhabitants of residential buildings in case they are going to remain in their flats during the retrofit works.

Three systems for inner thermal retrofitting purposes have been designed and produced as prototypes. Two of them are composed by silica aerogel containing fibrous material: the first one is a rigid flat laminated panel, the second one is a rollable solution with a fabric finishing layer. The third insulating system is a perlite based board with a hydrophobic layer. All the materials composing the retrofit solutions have been characterized by means of laboratory tests in order to measure their main hygrothermal properties. In fact, some parameters are fundamental for determining the hygrothermal performance of the composite systems: thermal conductivity, at dry and wet state (moisture dependant), water vapour diffusion resistance factor, hygroscopic sorption at isotherm condition and water absorption coefficient. All those measured data were necessary for optimizing the solutions, guaranteeing energy efficiency and vapour open layers to systems that are intended for installation on existing walls.

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Keywords: retrofit; thermal insulation; hygrothermal performance; perlite; silica aerogel.

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1. Introduction

The energy retrofit of existing buildings is a key priority if the EU is to meet the ambitious carbon emissions reduction and energy efficiency goals it set for 2020 and beyond [1]. In Europe there are currently around 80 million buildings dating from between 1925 and 1970, with very poor energy performance [2]. These include 10 million multi-owner, multi-storey residential buildings [3], where the improvement of the envelope performances can often be achieved only with insulating solutions applied on the internal side of the perimeter walls.

The aim of the following collaborative research (developed within the FP7 EASEE project [4] as part of a specific work package) was to develop innovative and reliable solutions for the inner thermal retrofitting of perimeter walls. The second step within the project was to assess their performance over time after installation on a demo wall, as going to be published soon, in order to prove the reliability of solutions at real scale. In most cases, we know technical data of commercial insulating materials or we know their initial properties from laboratory testing [5,6] but we do not know their real performance after installation. In other cases, we know performance by in-situ monitoring [7]. In general, we do not have enough hygrothermal data to explain the relation between properties and final behaviour, especially for innovative materials. For those reasons, the development process started with the design, production and testing of the three retrofit kits.

2. Description of retrofit kits

The three prototyped solutions of multilayer retrofit kits, for the inner surface of traditional assemblies (as solid masonry or cavity wall), are: a natural perlite-based board with hydrophobic layer and renders (kit A.1); a flat laminated panel with multilayer silica aerogel reinforced by the fibers of a non-woven textile (kit B.1) and a flexible single-layer silica aerogel non-woven textile with a fabric finishing layer (kit B.2).

2.1. Retrofit kit A.1: improved perlite board

This represents the most conventional solution compared to the other ones. The insulating board (thickness of 55 mm, area of 500 mm x 500 mm and weight of about 12 kg m^{-2}) is composed by hydrophilic natural perlite, with mineral binders and additives. In order to limit the absorption of liquid water from outside layers of the wall but guarantee water vapor transfer and drying from both direction, we added a hydrophobic layer in the middle of the thickness of panel using a specific procedure under non-disclosure protection. Cement based glue and filler was prepared on purpose by Schwenk, one of the partners of the consortium to apply the insulating board without any mechanical fixing system.

2.2. Retrofit kit B.1: aerogel flat laminated panel

This solution is composed by three layers of silica aerogel composites reinforced by impregnating silica sols into polyester unwoven fibrous blanket. The insulating composite mat is obtained by allowing sol-gel synthesis among cross-linked fibers using silicon-based compounds (polyethoxydisiloxane, PEDS) as precursors through ageing, hexamethyldisiloxane silylation and subcritical drying. As result of the process, the air space between the fibers has been filled by aerogel structure. The silica-aerogel is a low weight, and generally translucent, nanoporous material with very high porosity (>90%), high surface area (>600 m^2/g) and low density (0.08 – 0.2 g/cm^3). The advantages are a thermal conductivity reduction of the fibrous material and a solution to mechanical limitations of aerogel structure, giving also a kind of flexibility and more adaptability in building application. More details on silica aerogel properties can be found in Koebel et al [8] and Wong et al [9].

The three layers of aerogel with non-woven textile (with a total thickness of about 20 mm, each 500 mm x 500 mm large) are coupled together with a discontinuous layer of melted polyethylene powder. Then, the insulating mat was glued on a flat panel (expanded recycled glass based, thickness of 10 mm) by means of “water-glass” based adhesive mat, especially developed. The use of this water-glass mat permits a stable and adhesive interface between the hydrophobic aerogel and the rigid panel. Resin-based glue and filler has been instead developed by one of the partner and used for the installation on the demo wall. The whole system composed by rigid panels (weight of about

9 kg m^{-2}) can be applied either as a seamless flat surface by filling in the joints, or as a modular solution with panels connected by visible profiles.

2.3. Retrofit kit B.2: aerogel-based permeable wallpaper

The third solution was designed to be a lightweight (1.7 kg m^{-2}), flexible product that can be installed like traditional wallpaper, and in principle also by users with limited construction abilities (do-it-yourself).
The kit is composed by a single layer of silica aerogel, reinforced with fibres (thickness of 6 mm) and a tri-laminated polyester textile as the top surface. A discontinuous layer of polyethylene powder (the same as used in kit B.1) has been melted on both sides, in order to permit the adhesion with finishing textile layers. The discontinuity of polyethylene powder is important for guaranteeing water vapour permeability. Protecting the insulating layers, a finishing tensioned fabric, which guarantees a homogeneous and permeable inner surface, is installed by means of tensioning elements, which allow the fabric customized and stretched on the upper and lower part of the wall (patent on going).

3. Hygrothermal characterization tests

All materials composing retrofit kits have been tested following the main directives of the reference standards in order to have enough complete data set to describe the hygrothermal behavior. The sizes of specimens are according to the minimum dimension required in standards for each test and it depends on thickness and type of tested materials.

3.1. Thermal conductivity measurement at dry and moist condition

In order to assess the thermal conductivity of materials by means of guarded hot plate, (UNI EN 12667) a custom built device working with single specimen has been used for the measurements on small flat samples with high thermal resistance. The optimal dimension of the sample is 65x65 mm, which corresponds to the dimension of the device plates. The warm side at 30°C has a measurement area of 25 x 25 mm, the cold plate was cooled to 12°C.

The thermal conductivity λ_{dry} has been measured at dry state (*RH* 0%), after drying the samples at 65°C until equilibrium. Thermal conductivity λ got measured at different steps of relative humidity and after water immersion, in order to evaluate the increasing of the thermal conductivity at moist conditions. The samples have been conditioned at *T* 23 ±0.5°C and *RH* 30%, 50%, 80% and 87% in the climatic room until the equilibrium has been reached, typically 2-3 days, and after immersed into water (for 1h and 24h), measuring the change in mass at each step (see also chapter 3.3 and 3.4). After the achievement of the equilibrium, the samples have been inserted in a vapour tight plastic envelope in order to limit water vapour migration during the test on guarded hot plate apparatus.

3.2. Vapor permeability test

The test procedure is based on the reference standard EN ISO 12572:2001 using the cup tests method for determining the water vapour permeability of building materials under isothermal conditions. We carried out ‘dry cup 0/50’ test, using molecular sieve desiccant to reach 0% of relative humidity inside the cup, and ‘wet cup 50/93’ tests, using ammoniumdihydroxide solution to reach 93% of relative humidity inside the cup. In both case the cups have been placed in a climatic room at constant temperature 23 ± 0.5 °C and constant humidity 50 ± 3%.

The aim is to have the data of permeance respectively at low humidity, by mainly vapour diffusion, and at higher humidity, when the vapour transport is decreased due to the liquid water transport within the pores. The samples have been placed on the cup and sealed in order to have moisture flux perpendicular to the main water vapour exchange area.

Tests lasted until having stable measures respectively of the increasing of the weight for dry cup and the decreasing for the wet cup for the calculation the rate of water vapour flow (mg h^{-1}) and water vapour resistance μ.

3.3. Hygroscopic sorption test

Based on ISO 12571:2000, the hygroscopic sorption properties, which represent exchange of water vapour between ambient air and a porous material until the point of equilibrium is reached, have been assessed by means of the climatic chamber method. All the samples have been dried at 65°C to constant mass, complying with ISO 12570:2000, and then conditioned at *RH* 30%, 50%, 80%, 87% and 95% at isotherm condition with T_{amb} 23 ± 0.5 °C. The equilibrium at each humidity stage is reached when the specimen have constant mass by weighing, typically at 2 and 3 days in the maximal case. The adsorption curve, with moisture content, w_{cont} (kg m^{-3}) of material in function of environmental relative humidity, is obtained.

3.4. Long term water absorption by total immersion

The long-term water absorption by total immersion, according to EN 12087:2013,is determined by measuring the change in mass of the test specimen, totally immersed in water, over a period of 28 days (it has been measured also after 7,14 and 21 days). The excess water adhering to the surface, not absorbed by the test specimen, is removed by drainage following the defined method in standard. The result W_{28} might be expressed in volume percent, mass percent or kg m^{-3} while the last one has been preferred. The total immersion has been used also for approximating the free water saturation. We carried out measurements even after 1 hour and 24 hours for finding moisture-induced thermal conductivity increment factor.

3.5. Water absorption coefficient by partial immersion

The water absorption coefficient W_{w24} (kg $m^{-2}h^{-0.5}$) is the mass of the water absorbed by a test specimen per face area and per square root of time based on ISO 15148:2002. It has been assessed by means of partial immersion with no temperature gradient, keeping the water level constant at 5±2 mm above the base of sample. It is intended to assess the rate of absorption of water, by capillary action. The scope is measuring the change in mass of the test specimen over a period of 24 h measuring at each defined time step (in function of response of the tested material), the increasing of water content.

4. Results and discussion

From the laboratory results, those most interesting in terms of performance response of thermal insulating material are discussed here. The measurement of thermal conductivity of aerogel based material at moist condition following the procedure mentioned in section 3.1 revealed to be fundamental. The reasons are the hardy anywhere discussed properties of such nano-porous material as function of moisture. For such aerogel blanket for building application some might expect the effect of the increasing λ on the thermal transmittance is expected as for all insulation material on one hand, on other hand, these aerogels have well hydrophobised internal surfaces. The *U-value* of the retrofitted wall will vary as a function of the moisture content, as the values of λ (mW $m^{-1}K^{-1}$) vary in function of water content (kg m^{-3}), see Fig. 1a. On the right hand, Fig. 1b shows the moisture storage function (hygroscopic sorption and free water saturation) in order to correlate water content w_{cont} to relative humidity *RH*.

The points with uncertainties in Fig. 1a are the average values of λ in function of the average of w_{cont}, calculated from measurements on five square specimens (area 65 x 65mm and mean thickness 16.6 mm), with mean density ρ_{dry} of 136 kg m^{-3}. All samples have been conditioned at each step of relative humidity 0%, 30%, 50%, 80%, 87% *RH* and put under water immersion for 1 hour, $w_{t\text{-}im1\text{h}}$, and 24 h, $w_{t\text{-}im24\text{h}}$. The thermal conductivity λ_{dry} at dry condition is equal to 25.0±0.5 mW $m^{-1}K^{-1}$ (starting value at 0%) and the samples reaches 35.4±2.7 mW $m^{-1}K^{-}$. λ with higher moisture. At each measurement, the average has been calculated within the same interval (from 35 to 50 minutes), of the reading data from the device, as in the temperature gradient of the measurement, the moisture has started to migrate. Standard deviation at each point (x-axis and y-axis) is higher for higher values of water content. The reason is the decreasing of thermal conductivity during the test with the time, as the warmer part of the sample is drying, like in the real applications temperature gradient. Water vapor transfer through the material and latent heat of local evaporation/condensation can occur, despite the presence of tight envelope around the sample. In fact, at the end of the test water drops, are visible on the lower part of the sample (side in contact with cold plate at 12°C). For having reliable data, the samples were weighted before and after the test, to ensure that loss of water during test was lower than 0.1% of the weight. The general increasing of λ is small due to low water content because of the hydrophobic nature of that aerogel-based material, but well measurable. The regression is not linear - a quadratic polynomial curve fits well the trend with coefficient of determination R^2=0.999.

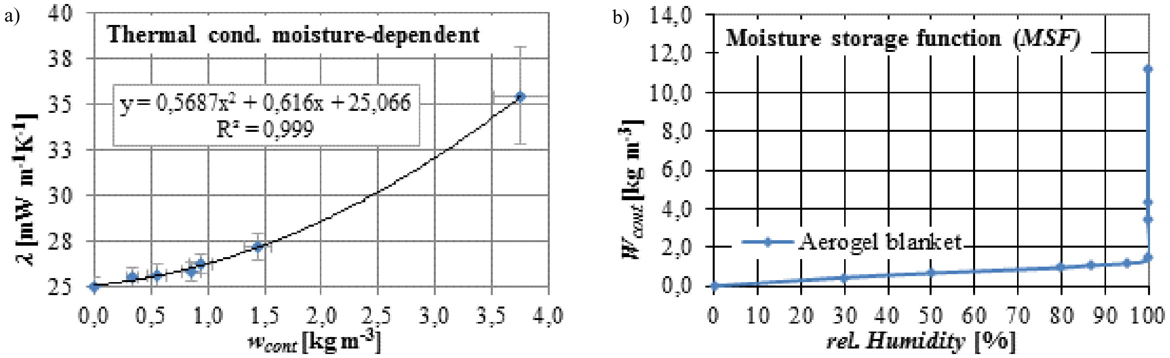

Fig. 1. (a) The thermal conductivity of aerogel sheets with non-woven polyester fibers is moisture-dependent. Plotted are the average of the values with standard deviation and regression line; (b) Moisture storage function obtained by hygroscopic sorption test and water immersion of these aerogel sheets mechanically reinforced with non-woven polyester fibers.

One of the most important features of the aerogel-based wallpaper is the permeability to water vapor. The permeability of the aerogel sheets containing fibers got measured first alone, secondly with the discontinuous polyethylene layer and also when glued to the finishing fabric. By means of the dry and wet cup method, as described in section 3.2, the water resistance factor, μ (-) of the three configurations was measured. In case of water vapor diffusion, the equivalent air layer thickness values s_d (m) is less than 0.1 m, like in our case, an increasing of uncertainty in the results has been expected. The values are collected and compared in Tab.1.

Table 1. Vapor resistance factor μ and vapor diffusion thickness s_d of aerogel-based polyester fibers with complementary layers.

	μ_{dry} (-),	$s_{d\,dry}$(m)	μ_{wet} (-)	$s_{d\,wet}$ (m)
Silica Aerogel containing polyester fibers (no added layer)	4 - 6	0.022 - 0.033	2 - 4	0.011 - 0.022
Aerogel-polyester fiber with polyethylene discontinuous layer	4 - 6	0.024 - 0.036	2 - 4	0.012 - 0.024
Aerogel-polyester fiber with polyethylene layer and finishing fabric	12	0.084	-	-

In brief, no difference has been seen with or without polyethylene due to discontinuity of the layer, guaranteeing low value of water vapor resistance μ_{dry} between 4 and 6 (-) at dry condition and μ_{wet} between 2 and 4 (-) at wet condition. The chosen finishing polyester fabric rises μ_{dry} at 12 (-), but remaining low and satisfying value for application as inner retrofit.

The hydrophilic nature of natural perlite based board (kit A.1), with density ρ_{dry} of 198 kg m^{-3} and λ_{dry} of 62.5±0.4 mW m^{-1}K has been limited by providing a hydrophobic core zone, while keeping the main surface unchanged. In order to evaluate the performance of added hydrophobic liquid at a define depth of the board, we measured water absorption coefficient W_{w24} (kg $m^{-2}h^{-0.5}$), on two samples of 100mmx100mm and thickness of 55mm, with and without the hydrophobic layer, following the procedure described in section 3.5. The curves of both types of samples are in Fig.2a. During the test, water is visible on the top surface of the specimen without hydrophobic layer at the third measurement, after 5 minutes. So the consecutive data, which gives W_{w24} of 1.13 kg $m^{-2}h^{-0.5}$ (slope of the straight-line) are not valid for calculation, according to the standard ISO 15148, because of the high increase of water content (25.64 kg m^{-2}) due to fast capillary suction at the beginning of the test. On the contrary, hydrophobic samples (see Fig.2.b), show a good performance in terms of water absorption with W_{w24} of 0.14 kg $m^{-2}h^{-0.5}$.

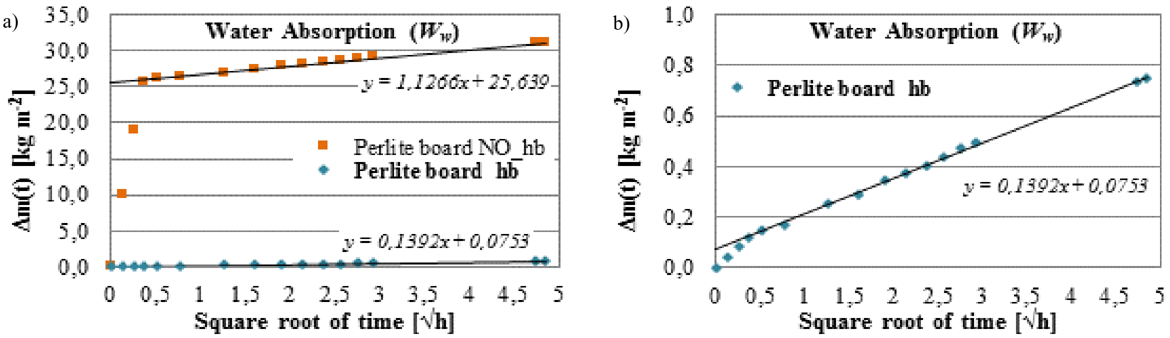

Fig. 2. (a) Water absorption curves of hydrophilic sample (perlite board No_hb) and hydrophobic sample (perlite board hb) in comparison; (b) Water absorption curve of perlite board with hydrophobic layer and straight-line equation for determine water absorption coefficient W_{w24}

5. Conclusions and outlook

Three prototypes of multilayer components for inner retrofit have been developed and characterized. They are 1) a natural perlite-based board with hydrophobic layer, 2) a flat laminated panel with silica aerogel reinforced by unwoven textile and 3) a flexible single-layer silica aerogel reinforced by unwoven textile with a fabric finishing layer. The experimental work carried out at the material scale was useful to assess the main hygrothermal properties that can affect the thermal performance of solutions over time after installation as interior retrofit. Based on these results, the kits are suitable for this kind of application, demonstrating vapor permeability, low liquid water absorption and almost stable thermal conductivity even at moist condition of the main insulating material. On the other hand, a complete data set is available, useful for numerical simulation for verifying and forecasting the response at different boundary conditions. The following step was to study the in situ performances of the solutions by monitoring their behavior on a demo wall, proving also the applicability and reliability of the considered installation system. Improvements are on the way to obtain better performances (initial lower value of thermal conductivity) and optimize the process to proceed from lab scale prototypes to pilot (industrial) scale production.

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