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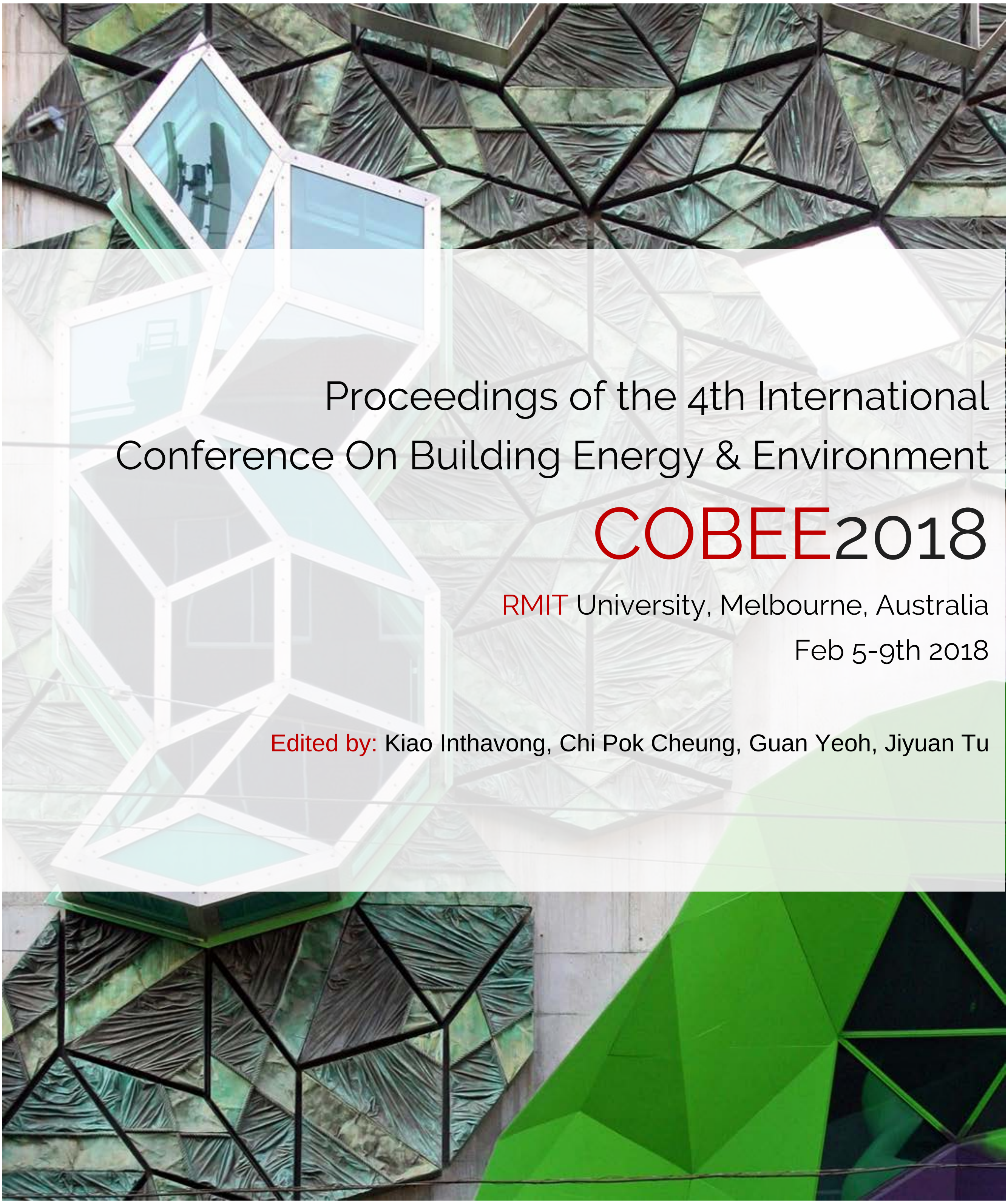

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Edited by: Kiao Inthavong, Chi Pok Cheung, Guan Yeoh, Jiyuan Tu

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Preface

The building sector consumes a staggering 40% of the world's energy and is a major generator of greenhouse gas as it heats, cools, and ventilates the indoor environment. This makes it a critical target for reducing energy consumption as we face sustainability challenges regarding energy use and environmental damage.

The International Conference On Energy & Environment series was first hosted in Dailin in 2008 (initiated by Tianjin University and Dalian University of Technology), and has since moved throughout the world tri-annually to become a truly international conference.

We have had the pleasure to host the 4th COBEE conference held during February 5-9th in the most liveable city in the world, Melbourne, Australia – with RMIT University as the host. The conference brought together researchers from all over the world to address the negative impact of increased building energy consumption.

The submitted papers demonstrated strong interest in the fol-lowing fields: Advanced Modelling & CFD, Heat Exchange Sys-tems, Indoor Air Quality & Health, Building Energy, Urban Buildings & Environment, Ventilation, Thermal Comfort.

Other topics of interest included: Building Envelope & Phase Change Materials, Passive Building Design, Sensors, Controls & Monitoring, Cooling & Air Conditioning, Experimental Meas-urements, Acoustic & Noise. The diversity of themes highlight-ed the need for greater collaboration which will deliver high lev-el outcomes through multi-disciplinary approach.

On behalf of the COBEE2018 Committee, we thank all delegates for their strong contributions towards a fruitful conference.

Editors:

Dr Kiao Inthavong, *RMIT University*
Ass.Prof Chi Pok Cheung, *RMIT University*
Prof Guan Yeoh, *UNSW*
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Development of aerogel based internal thermal plasters for the energy retrofit of existing buildings: First results

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SUMMARY

A relevant part of research activities dealing with the energy retrofitting of existing buildings is currently focused on the development of highly insulating plasters, which represent a feasible and effective solution as far as thermal bridges, mold growth risk and heat loss reduction are concerned.
Within this framework, the EU funded research project "Wall-ACE" started in October 2016. The project involves industrial partners, research centres and public bodies, with the aim of developing, testing and implementing, a new set of high performance aerogel based insulating products.
In this first stage, the activity carried out by the authors was mainly focused on internal insulating plasters. The first blends of lightweight samples were experimentally characterized as far as thermohygrometric and mechanical properties are concerned. Moreover, the thermal behavior of typical wall assemblies retrofitted using the developed aerogel based plasters, were assessed through numerical simulations. The first results and the technical issues which have arisen during the initial stage of the research, are here presented.

INTRODUCTION

European countries agreed a 2030 framework for climate and energy, including common targets and objectives, such as a 40% reduction of GHG emissions compared to 1990 levels and at least a 27% energy saving compared to the business-as-usual scenario. These represent intermediate targets to Union's 2050 goals of reducing European GHG emissions by 85-90%.
Buildings are responsible for the 40% of European energy consumption and for the 36% of CO_2 emissions. An intensive energy renovation of the existing buildings can cut up to 36% the buildings energy consumption, strongly contributing to the mid and long term European climatic goals. The European Union encourages the development of innovative technologies to reach climate objectives at a wide scale.

Wall-ACE is an international collaborative research project, started in October 2016, funded under a EU H2020 program. The scope of the project is the market uptake of five aerogel based products aimed at significantly improving the insulating behaviour of the building envelope: external insulating render, internal insulating plaster, interior thermal coating-finishing, interior insulating patching filler and insulated clay bricks. The products are suitable for new constructions and renovations of existing buildings and can be combined to reach higher insulating performances.

The paper focuses on the early development stages of one of the products: the thermal plaster for indoor applications. The work mainly addresses the methodological approach, provides the technical context and relative issues and highlights how the products performance can be improved.

Several base formulas were tested following three main objectives: i) identifying the ideal aerogel particle size to be used as insulating component in the mix, ii) providing basic formulas for developing the product at laboratory scale and iii) setting the base for the next phase of industrial production.

The insulating performance of the product is provided by incorporating a high performance silica aerogel in the plaster mix, which contains more than 95% of air, captured in nanometre-sized pores. To reach a suitable mechanical resistance, several attempts were made to identify the ideal binder: eventually a combination of special hydraulic binders was chosen. The first plaster samples, manually blended, were dried and thermal performances were investigated in laboratory, reaching quite encouraging results. A key issue for the material development was the suitability for spray machine application in order to allow the application of the plaster in buildings.

State of the art of aerogel plasters

Many studies focused on the possibilities of improving thermal properties of plaster with different types of light weight aggregates. In particular Barbero et al. 2014 defined the target value for new insulating material for the EU market: they declared that a density of about 250 kg/m^3, low water absorption and high transpiration are desirable properties. Since traditional light-weight aggregates may be not sufficient to reach this lower value of density, great research efforts have been done in order to identify new types of Light Weight Aggregates (LWA) and among the others aerogels present very promising properties.
Several studies are indeed highlighting the great increase of the thermal resistance of aerogel based thermal plaster when compared to conventional thermal plasters.
Stahl et al. (2012) developed a new lime-cement plaster with aerogel characterised by a thermal conductivity λ of 25±2 mW/mK and a density of about 200 kg/m^3.
Density of about 156 kg/m^3 is obtained by Ibrahim et al. (2014) with a thermal conductivity reaching value of 26.8 mW/mK.
According to Schuss et al. (2017), the application of the aerogel plaster (thickness 4cm) at building scale, makes the thermal transmittance (U-value) equal to 0.46 W/m^{2}K (from the initial value of 1.25 W/m^{2}K of the bare wall).
The influence of the aerogel content on the plaster thermal properties was experimentally investigated by Buratti et al. (2014).
As far as the relation among thermal and mechanical properties of an aerogel plaster are concerned, Liu et al. (2016) showed that a 0-60% aerogel content causes a noticeable λ improvement (from 0.6 to 0.152 W/mK) but a contemporary drastic reduction of the compressive strength (from 40 to 2.15 MPa).
De Fátima Júlio et al. (2016) evaluated if other traditional LWA mixed with aerogel can positively contribute to improve

the thermal properties of cement plaster. Results show that a mixture of aerogel, cork, expanded clay and expanded perlite can reduce λ of about fifteen times from the initial value of about 1.5 W/mK.
Nosrati et. al (2017) carried out a series of ageing tests on Aerogel Based Products (ABPs). The plaster shows larger increase of thermal conductivity than other ABPs. Nevertheless, even after a 20 years ageing, the final λ value is about 33 mW/mK that can be considered an acceptable value for insulation purposes.

The above presented overview points out that the research about this new building product is in constant development, but some aspects (e.g. mechanical properties), need to be further improved.

METHODS

In this study, preliminary experimental campaigns and numerical analyses were carried out to assess the thermal plaster performance at the material and component scale.
A first series of products based on aerogel and different mineral lightweight aggregates were developed and measured to evaluate their thermal properties (Samples A, B and C). The opportunity to use less aerogel and thus to maintain lower prices, was assessed as starting point.

In a second phase a new insulating thermal plaster based on aerogel was developed in order to reach higher performance and thermal conductivity measurements and mechanical tests were complementarily performed.

Finally the same formula was tested as well. Samples were made with two different application methods: one by manual application (Sample D) and the other one sprayed through a plastering machine (Sample E).
A simulation model was then set up to evaluate the influence of the two different application methods at the component scale and under dynamic hygrothermal conditions.

THERMAL PLASTERS CHARACTERISATION

Conductivity measurement

A heat flow meter apparatus was used to perform thermal conductivity measurements on the aerogel thermal plaster samples (5 cm of thickness and 40x40 cm size). The measurements were carried out according to UNI EN 12667:2001 international standard through a Lasercomp FOX600 apparatus (Figure 1). Technical specifications are shown in Table 1.

Both the handmade and the machine-made samples were tested. For each sample, two thermal conductivity measurements were performed: first using the dry samples and then using the moisted ones. Before the measurement in dry condition, samples were dried using a ventilated oven at 100°C. Each sample was weighted every 24 hours for about two weeks. After the thermal conductivity measurement in dry conditions, the samples were placed in a plastic vessel and then submerged in water until saturation. The thermal conductivity measurements were performed at three different mean temperatures (10, 25 and 40 °C) with a temperature difference between the two measuring plates of 20 °C.

Since the samples surfaces are not perfectly planar, two rubber sheets were placed between each sample face and the respective measurements plate. Each rubber sheet is 2 mm thick and has a thermal resistance of 0.029 m^2K/W.
The heat flow meter apparatus sets the upper and the lower plates at predefined temperatures, so a constant heat flow occurs. The equivalent thermal conductivity of the samples is calculated using Equation 1:

$$\lambda_{eq}\left[\frac{W}{mK}\right] = \frac{s \cdot \phi}{\Delta\theta} \qquad (1)$$

Where λ is the equivalent thermal conductivity, s is the sample thickness [m], ϕ is the specific heat flux [W/m^2] and $\Delta\theta$ is the temperature difference between the plates [°C].

Figure 1 The equipment used for the thermal experiment

Table 1. Experimental apparatus specifications.

Thermal conductivity range	~0.01–0.2	W/(m K)
Accuracy	~1	%
Reproducibility	~0.5	%
Temperature control stability	~±0.03	°C
Thickness measurement precision	~±0.025	mm
Maximum sample size	~610 × 610	mm
Actual measuring area	254 × 254	mm
Maximum sample thickness	~203	mm

Results and discussion

Results of thermal conductivity and dry bulk density (ρ_{dry}) for the first three plaster samples are reported in Table 2.

Table 2. First series of sample investigated (Sample A, B and C differs from the aerogel and the mineral expanded aggregates type)

	ρ_{dry}	λ
	[kg/m^3]	[W/mK]
Sample A	387	0.093
Sample B	343	0.071
Sample C	321	0.066

The results, despite showing an improvement due to presence of aerogel in the mix, were not considered satisfactory. The thermal conductivity was quite far from the value 0.04 W/mK, which was set as the minimum required value to be reached before starting the optimisation process and the key issues identification.

A new mix, using only aerogel into the mix was thus developed and tested (Sample D and E).
The material surfaces of the two thermal plasters are shown in Figure 2.

Figure 2 The sample measured: (a) Sample D by hand (b) Sample E by plastering machine. [scale ▬▬ 1cm]

Results of these two samples are presented in Table 3, showing both the mechanical and hygrometric properties Laboratory test to evaluate the mechanical properties of the new insulating plaster are so far carried out only for the specimens made by manual mixing (Sample D).

Table 3. Properties of the specimens

	ρ_{dry}	R_c	R_t	Air	μ
	[kg/m^3]	[N/mm^2]	[N/mm^2]	[%]	[-]
Sample D	249	0.5	0.18	23	11
Sample E	314	-	-	7	-

The mechanical resistance obtained for sample D are in accordance with the minimum requirements of UNI EN 998-1. Further improvements are thus necessary to allow the external use of the mixture.

The conductivity measurements are carried out for both the samples. The results of λ as a function of the average temperature of the plates are shown in Figure 3.

The results show an increase of the thermal conductivity as a function of temperature of about 5%, from 10°C to 40°C, for both the samples. Moreover, the thermal conductivity of sample E is about 25% higher than sample D, meaning that the spraying process seems to negatively impact on the overall thermal performance.

A thermal conductivity increase due to the plastering machine application is also reported by Stahl et al. 2012. The authors show a correlation between the pressure of the plastering machine and the reduction of the thermal performance: increasing the pressure from 0 to 8 bar, an increase of thermal conductivity from 23% to 66% was found in different plaster mixtures.

This phenomenon can be due to a porosity reduction (Table 3) of the mixture, caused by aerogel grains breaking, mechanically stressed by the industrial mixer and the plastering machine. In Figure 2 it is possible to observe that the surface appearance of the two samples is quite different: the one produced by manual mixing is visibly rougher, since the grain size is significatly bigger.

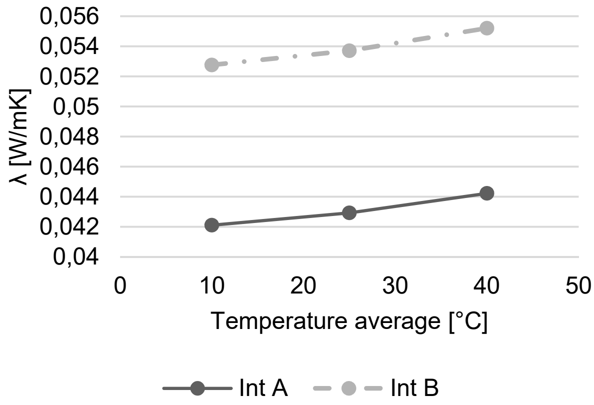

Figure 3 Conductivity as a function of temperature

In Figure 4, the dependence of thermal conductivity as a function of water content can be observed. Sample D shows a thermal conductivity ranging between 0.18 W/mK and 0.23 W/mK in saturated conditions (262 kg/m^3 of water content), while sample E, in the same conditions (368 kg/m^3 of water content), shows a λ variation from 0.23 W/mK to 0.31 W/mK.

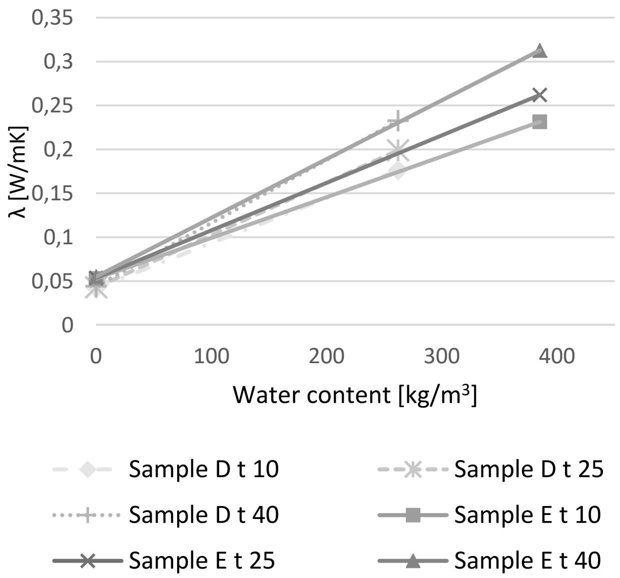

Figure 4 Thermal conductivity as function of water content

The completely saturated condition hardly occurs in real situations. However, not negligible increments of the thermal conductivity can be observed at much lowerwater contents. For example, a certainly realistic condition of about 50 kg/m^3 of water content leads to thermal conductivity percentage differences of about 70% for sample D and 52% for sample E with respect to the dryed case.

THERMAL PERFORMANCE AT COMPONENT SCALE

Numerical analyses

The numerical analyses were carried out with the aim of investigating the thermal performance (U-value) of a conventional solid wall retrofitted with the aerogel plaster (Figure 5), under dynamic hygrothermal conditions.

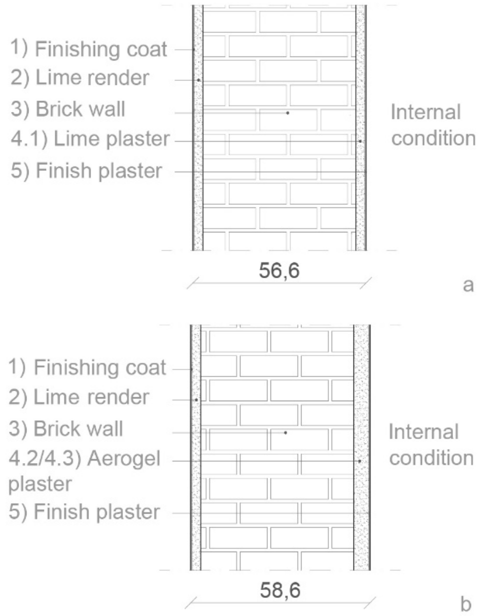

Figure 5 Simulated wall structure: a. Reference wall, b. Refurbished wall.

Heat and Moisture Transfer (HMT) simulations were carried out using WUFI® Pro. Simulations were performed considering data obtained by the two different aerogel plaster samples previously measured in the laboratory (Sample D and Sample E). The basic thermophysical properties of the wall assembly are reported in Table 4.

Table 4. Thermophysical properties of the reference wall layers

layer	Material	D	ρ	c	λ	μ
		(mm)	(kg/m^3)	(J/kgK)	(W/mK)	[-]
Outdoor climate conditions						
1	Finishing coat	3	1482	850	0.954	17
2	Lime render	15	1475	850	0.641	17
3	Brick wall	500	1952	863	0.955	19
4.1	Lime plaster (ref.)	15	1475	850	0.641	17
5	Finish plaster	3	1482	850	0.954	17
Indoor climate conditions						

Simulation were carried out considering a north-east oriented wall located in Northern Italy (Cuneo, 44°23′N, 7°33′E), which is quite representative of the Italian building envelope needed to be refurbished and constituting a case study in the authors research activity. The wall was considered exposed to the driving rain, the rain load was calculated assuming a wall below a steep sloped roof with height <10 m, and medium exposure according to ASHRAE 160. Moreover, the indoor hygrothermal conditions were calculated according to EN 15026 with an internal medium moisture load. Simulations were repeated for four years, and only the last year of simulation was considered for the analysis of the winter monthly thermal performance (U-value). Main results are summarised in Table 5.

Table 5. Thermophysical properties of the refurbished wall layers

layer	Material	D	ρ	c	λ	μ
		(mm)	(kg/m^3)	(J/kgK)	(W/mK)	[-]
Outdoor climate conditions						
1	Finishing coat	3	1482	850	0.954	17
2	Lime render	15	1475	850	0.641	17
3	Brick wall	500	1952	863	0.955	19
4.2	Aerogel plaster (D)	50	249	1100	0.042	11
4.3	Aerogel plaster (E)	50	314	1100	0.053	11
5	Finish plaster	3	1482	850	0.954	17
Indoor climate conditions						

Results and discussion

The wall thermal transmittance (U-value) calculated according to EN ISO 6946:2008 (steady conditions) is 1.34 W/m^{2}K for the reference configuration, 0.52 and 0.60 W/m^{2}K for the wall retrofitted with the aerogel plaster (D) and (E) respectively. Results of the steady state U-value calculated for dry materials show that a reduction of the U-value between 61% (config. D) and 55% (config. E) are achievable with a retrofit strategy based on interior aerogel thermal plaster.

The results of HMT simulations were statistically analysed through a box plot analysis (Figure 6). Results highlight that the actual monthly median U-value ranges between 0.56 W/m^{2}K and 0.69 W/m^{2}K for configuration D and between 0.61 W/m^{2}K and 0.74 W/m^{2}K for configuration E, depending on the moisture content of the wall during the different period of the year. As expected, the wall under actual operating conditions presents an increment of the U-value due to the changes of the thermal properties that are dependent on temperature and moisture content. Nevertheless, it is possible to highlight that, for most of the time (1st to 3rd quartile), the simulated thermal performance of the wall under actual operating conditions does not present a significant decay if compared to the U-values calculated in steady state conditions on dry materials (EN ISO 6946:2008). The observed increase of the U-value ranges between 8% and 33% for configuration D, and between 2 and 23% for configuration E.

The production of the mixtures and the application method has a small but not completely negligible influence on the actual thermal performance. Configuration E (plastering machine) always presents lower thermal performance if compared to configuration D (hand mixture), with a difference in the median U-values of about 8%.

These results highlight that the manufacture of a high performance thermal insulating plaster is not the only important phase. It is also of paramount importance to take into account the production phase and the application method in order to exploit the thermal performance of the plaster mixture.

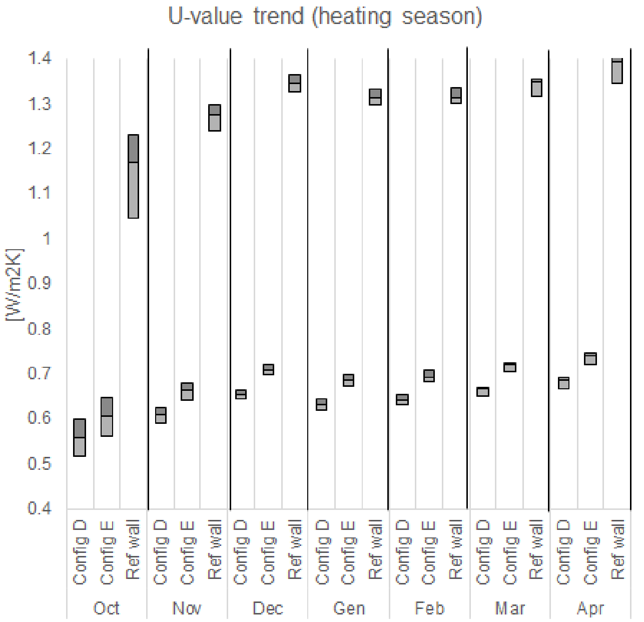

Figure 6 Transmittance trend during heating season

CONCLUSIONS

The first steps of the development of a high-performance aerogel based thermal insulating plaster for internal applications, carried out within an EU funded H2020 Research Project, have been described. A mixture of aerogel and different mineral lightweight aggregates was previously tested, showing interesting but not satisfactory results in term of thermal performance. Further analyses were thus performed on a new developed thermal plaster containing only aerogel as insulating aggregate, showing a thermal conductivity ranging between 0.042 and 0.044 W/mK, near to the value of 0.04 W/mK and presenting mechanical properties in accordance with limit values set by UNI EN 998-1.
The promising properties obtained testing the manually created sample were then verified by realising and testing a new sample made using the spraying machine. An increase of the thermal conductivity of about 25% was observed, meaning that the spraying process affected the thermal conductivity probably by damaging the aerogel grain and thus reducing the material porosity.

The Heat and Moisture Transfer simulations of a solid brick wall retrofitted with the developed aerogel plaster showed that:

- a decrease of the wall U-value between 61% (hand-made mixture) an 55% (plastering machine mixture) are respectively achievable.
- under operating hygrothermal conditions, the performance are not significantly lower if compared to the values calculated in steady-state conditions on dry plaster samples. The increase of the U-value ranges between 8% and 33% (hand-made mixture), and 2 to 23% (plaster machine mixture).

As far as the thermohygrometric properties are concerned, the developed aerogel plaster shows high potentials and good compatibility as internal insulating solution for the retrofit of existing buildings. Lower thermal conductivity and lower water absorption coefficients seems to be achievable, allowing the adoption of the plaster even for external use.

The application process can lead to several issues that need to be carefully faced, as initial investigations performed on the product applied to a pilot surface have demonstrated.

The mechanical mixing and the spraying machine application has highlighted two important aspects: on the one hand, the mixture formulation should consider that the maximum grain sizes needs to take into account the spraying gun characteristics, in order to avoid the aerogel grain breaking; on the other hand, the pressure applied to the material should be set so to avoid significant thermal performance drop.

Further research activity is thus necessary before starting the industrial phase. Nevertheless, the presented results are referred to the very early stages of the research and are useful to stress and identify the key aspects which will constitute the basis for the future steps.

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