OVERVIEW OF THE PERFORMANCE OF AN EXTERNAL VACUUM INSULATION COMPOSITE SYSTEM

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ABSTRACT
The external thermal insulation composite system (ETICS) is a construction technology commonly used for insulating building walls. Incorporating a super-insulation material, such as vacuum insulation panel (VIP), ETICS is a solution with great potential for improving the thermal performance of façades towards achieving nearly-zero energy buildings. However, the application of VIPs in buildings presents several challenges that need to be taken into account. Namely, those associated with handling and installation issues, design factors, as well as with the edge thermal bridging that occurs between panels, the doubts surrounding long-term performance and the high investment costs of vacuum technology. Also, conventional ETICS often presents early-signs of anomalies that could be worsened by using VIPs. Thus, many aspects need to be evaluated before VIP based ETICS become a viable solution. The main goal of this paper was to study the feasibility of incorporating a VIP solution into ETICS. For this purpose, an extensive investigation into the solution was carried out, following mainly experimental approaches. First, focus was put on the VIP thermal performance, in particular regarding the edge thermal bridging effect. Then, VIP-based ETICS walls were evaluated in terms of the whole system hygrothermal performance and durability. Real onsite walls and laboratory large-scale test specimens were assessed. New experimental procedures were defined to evaluate the durability of the solution and to enable the early identification of potential anomalies, in particular when exposed to solar radiation. Lastly, the cost-effectiveness of vacuum technology was analysed by means of a life cycle costing assessment. This research indicates that VIPs can be successfully used in ETICS. Nevertheless, such integration needs to be meticulously performed, since concerns specific to VIP installation need to be taken into account.
Keywords: vacuum insulation panels, ETICS, hygrothermal performance, experimental testing, onsite monitoring, life cycle costing.

1 INTRODUCTION

The EU 2030 Climate Target Plan is now aiming at reducing greenhouse emissions in at least 55% (from 1990 levels) and improving energy efficiency in at least 32.5% [1]. These ambitious targets are leading to increase the thermal requirements for buildings envelope over the last years. As a consequence, there is a need to use high thicknesses of thermal insulation materials, especially in cold climates, to accomplish the requirements of nearly-zero energy buildings. However, a thick envelope may not be desirable for several reasons, including architectural/design limitations and reduction of available floor area. Hence, there is growing interest in developing products using materials that are able to present a high thermal performance at a reduced thickness. In this field, emphasis is given to vacuum insulation panels (VIPs). The VIP consists in an evacuated open core material surrounded by thin laminates, composed of a barrier envelope (multi-film layer), used to maintain the vacuum. Typical values of VIP thermal conductivity (measured at centre of the panel) can be less than 5 mW/(m·K) in initial state, and 7 to 8 mW/(m·K) after 25 years [2]. These values are much lower than that of conventional thermal insulation materials, such as expanded polystyrene (EPS) that usually have thermal conductivity values around 35 mW/(m·K).

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Using this super insulating material in solutions widely spread in buildings could be a key factor to improve the thermal performance of buildings walls. For example, combine the benefits of external thermal insulation composite systems (ETICS) with the outstanding thermal performance of VIPs could have a great potential. Nevertheless, the use of VIPs in buildings have specific challenges that needs to be taken into account. For example, the panels: cannot be cut or adapted on-site; are very sensitive to mechanical damage; raise doubts regarding their service life performance; and have a high cost, as previously identified by Gonçalves et al. [3].

The present work aimed to study the feasibility of incorporating a VIP solution into ETICS. For this purpose, experimental approaches were conducted in order to evaluate the hygrothermal behaviour of the solution and its durability. First, the thermal performance of the VIP product was investigated, with particular attention to the edge thermal bridging effects. Then, two real VIP-based ETICS were built in different climates, namely in Warsaw (Poland) and Coimbra (Portugal). These case studies were monitored during two years, looking to evaluate long-term performance and detect early anomalies such as cracking, vacuum loss, blistering and biological growth. In laboratorial environment, the hygrothermal performance of the innovative solution was carried out for evaluating its durability and for enabling early identification of potential anomalies. In this context, a new test procedure that includes multiple dynamic boundary conditions, such as air temperature, relative humidity, rain and solar radiation simulation, was proposed and carried out on a large-scale test specimen. Additionally, since the high cost of vacuum technology is one of the most issues of it using in buildings, a life cycle costing analysis of the VIP is presented. Finally, some final remarks are taken.

During this research work, the VIP performance was often compared with a conventional thermal insulation material in order to evaluate the competitiveness of this innovative solution against the most commonly used ETICS solution, namely EPS based ETICS. Given the extension of the research, this paper only presents some of the main results achieved in this investigation.

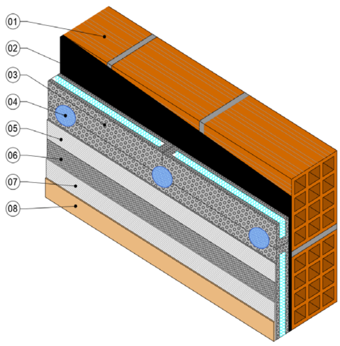
2 MATERIALS AND METHODS

2.1 Description of the solution

The product used in this study consists in a vacuum insulation panel composed by fumed silica powder encapsulated in a metallized high barrier film. The nominal thickness of the panel is 20 mm. To allow for an ETICS application, the VIP product is fully encapsulated with a protective cover layer made of graphite expanded polystyrene with a thickness of 10 mm on each side and 20 mm along the edges. The EPS cover layer allows for the adhesive bonding of the panels onto substrate and provides additional mechanical resistance, minimizing the risk of perforation of the VIPs. The 20 mm of EPS at the edges of the panels also allow for the use of auxiliary mechanical fixing (plastic anchors), as can be observed in Fig. 1, and to allow for small size adjustments. The remain ETICS components (adhesives, base coat mortar, fibre-glass mesh and finishing coat products) are commercial products commonly used in EPS based ETICS solutions.

2.2 Thermal performance

Thermal transmittance measurements were performed on a guarded hot plate apparatus (GHP), λ-Meter EP500e, following ISO 8302 [4] and EN 12667 [5]. The tests were carried



1. Support wall
2. Adhesive
3. Encapsulated VIP
4. Plastic anchor
5. Base coat (first layer)
6. Reinforcement (glass fibre mesh)
7. Base coat (second layer)
8. Finishing coat (primer and decorative coating)

Figure 1: VIP based ETICS scheme.

out in a controlled laboratory environment with (23 ± 2)°C air temperature and (50 ± 5)% air relative humidity. First, the thermal conductivity at the centre of panel (λ_{CoP}) was determined for each specimen. Next, the linear thermal transmittance between panel joints was measured. For this purpose, two VIPs were assembled within the GHP apparatus so that their joint was within the measuring area. The linear thermal transmittance, ψ, was determined by using the equation C.20 of EN 17140 [6]. Next, the equivalent thermal conductivity of the panel was determined according to equation C.23 of EN 17140 [6].

Besides the edge thermal bridging effects, the point thermal transmittances caused by mechanical fixation also need to be included in the effective thermal transmittance. For this reason, the methods described in EOTA TR 025 [7] and ISO 10211 [8] were followed and TRISCO software version v14.0w by Physibel [9] was used to determine the point thermal transmittance.

Then, the effective thermal transmittance of VIP based ETICS walls, including linear and point thermal transmittance was calculated and compared with a conventional ETICS solution. More details about the methodology used to evaluate the edge thermal bridging effect of VIPs can be found in Gonçalves et al. [10].

2.3 Onsite monitoring

To evaluate the VIP based ETICS performance under service conditions, two case studies were built and monitored. The first case focused on the hygrothermal behaviour of VIP based ETICS. The second one, aimed to evaluate and compare the condensation risk of VIP based ETICS and to compare with other conventional ETICS solutions. Both cases were monitored for more than 24 months. Next, the case studies are briefly described.

2.3.1 Case study 1

This case study consists in an existing façade retrofitted with ETICS solution with VIP. The retrofitted building is the Herpetarium of the Warsaw Zoo, Poland. The façade was divided in two areas: a reference wall side, corresponding to a traditional ETICS with EPS, and a VIP based ETICS wall with 42 m^2. Both walls are adjacent and face NE. Temperature, humidity and heat flux sensors were applied in two areas of the external wall under renovation. Sensors were placed behind the insulation and over the insulation (behind the rendering layer). Additionally, two sensors are located inside the building to measure indoor air temperature and humidity, and one sensor was placed outside the building to measure outdoor air temperature and humidity. More details about this case study are provided in Gonçalves et al. [11].

2.3.2 Case study 2

In case study 2, two free-standing walls with 5 m × 2 m (width × height) were built in Coimbra, Portugal. Each wall faces north and south. The walls are sectioned into areas that include different thermal insulation materials with 8 cm thickness, namely, expanded polystyrene, thermal insulation mortar (TIM), expanded cork (ICB) and encapsulated VIPs with 4 cm thickness. Two different finishing colours (white and black) were used for the finishing coat. Each area was instrumented with thermocouples that register temperature over time. Sensors were placed along the following interfaces: behind the insulation; over the insulation; and at the wall's external surface layer. Also, a weather station was placed near to the walls. Additional details about this case study are given in Gonçalves et al. [12].

2.4 Hygrothermal cycles resistance

With the goal of evaluating the hygrothermal performance of the VIP based ETICS, as well as evaluating its durability and identifying potential anomalies, accelerated ageing tests were carried out under controlled conditions. For this purpose, a real scale test-specimen with 2.8 m × 2.8 m was built. The hygrothermal cycles resistance was carried out according to section 2.2.6 of EAD 040083-00-0404 [15]. Furthermore, a new test procedure was proposed and implemented, that includes solar radiation simulation. This test method, further detailed in Simões et al. [16], allows for evaluate the impact of the optical properties of the rendering system on the ETICS performance. For this reason, two finishing coat colours were considered, namely black and white.

2.5 Life cycle costing

Since the high cost of VIPs is one of the main obstacles to the widely use of these materials in buildings, this research also focuses on their economic viability. The main goal was to identify the conditions under which the panels become cost-effective when compared with conventional ETICS. The study uses a comparative methodology based on the European cost-optimal methodology framework published in the Delegated Regulation no. 244/2012 [13], [14], with the added benefits of the rental income taken into account, as made possible by whole-life costing approach of ISO 15686-5 [15].

This study looks to quantify the economic benefit the additional space savings, due to their thinner nature of VIP when compared with EPS (considering the same thermal resistance). Thus, considering an office full-service leasing perspective, this investigation included the additional rental income expected due to the space savings resulting from the lower thickness of the VIP installation. The analysis was carried out with climatic and economic data from the city of Berlin, because in Germany the vacuum technology is most developed and whose climate is favourable to the use of high levels of thermal insulation. Further details are given in Simões et al. [16].

3 RESULTS

3.1 Thermal performance

The average VIP thermal conductivity measured at 10°C at the centre of panels is 4.20 mW/(m·K). While the average thermal conductivity measured at 25°C and 40°C, increased 4.40 mW/(m·K) and 4.67 mW/(m·K), respectively. Additional measurements were performed on intentionally perforated panels (panels without vacuum), resulting in a thermal conductivity of 21.6 mW/(m·K), which was still lower than conventional insulation materials.

Regarding the encapsulated VIP (panel encapsulated in EPS), the average thermal conductivity of centre of panels is 7.5 mW/(m·K). The linear thermal transmittance resulting from the joints between two encapsulated panels is 19.77 mW/(m·K), 20.95 mW/(m·K) and 22.25 mW/(m·K), considering the temperatures at 10°C, 25°C and 40°C, respectively.

In order to evaluate the influence of the panel's size, the increment of the equivalent thermal conductivity of the VIPs due to the inclusion of edge thermal bridging effects is presented in Table 1 (as a function of the size of the panel). These values are based on the assumption that the vertical rims of the panels have seamless joints (ψ_{10} = 9.89 mW/(m·K)), while the horizontal rims are assembled with overlapping foils (ψ_{10} = 11.20 W/(m·K)).

Table 1: Percentage increment of the equivalent thermal conductivity of encapsulated VIPs due to the edge effect.

		Horizontal rims						
	(mm)	**200**	**300**	**400**	**600**	**800**	**1000**	**1200**
Vertical rims	**200**	114%	96%	87%	78%	74%	71%	69%
	300	94%	76%	67%	58%	54%	51%	49%
	400	84%	66%	57%	48%	44%	41%	39%
	600	74%	56%	47%	38%	33%	31%	29%
	800	68%	51%	42%	33%	28%	26%	24%
	1000	65%	48%	39%	30%	25%	23%	21%
	1200	63%	46%	37%	28%	23%	21%	19%

As expected, using larger panels will reduce the influence of the edge thermal bridging. Also, the shape of the panels is relevant as the ratio between CoP area and VIP joints length may change.

Table 2 shows the U-value of a ceramic brick wall with VIP based ETICS considering the thermal conductivity of VIP at CoP (including 25 year ageing) with and without the edge thermal bridging effects. Also, the effective U-value, that includes the linear and point thermal transmittance is presented. The point thermal transmittance influence was calculated considering a number of mechanical fixings for each panel of five per square meter for smaller panels and three per square meter for larger panels. Additionally, the values considering an EPS with 40 mm thickness (same as VIP solution) instead the VIP solution are presented in brackets for use as reference. Internal and external surface thermal resistances of 0.13 (m^2·K)/W and 0.04 (m^2·K)/W were considered.

3.2 Onsite monitoring

3.2.1 Case study 1

Temperature and heat flux measurements allowed to prove the higher thermal performance of VIP, comparing with EPS ETICS solution. Fig. 2 shows the heat fluxes measured behind the VIP insulation (at the CoP and the joint area) in the VIP wall, as well as in the EPS wall, for a representative week during cold period.

Table 2: Effective U-value of the VIP based ETICS walls and EPS ETICS wall (in brackets), expressed in W/(m²·K).

	Ceramic brick wall	
Panel size	440 mm × 440 mm	640 mm × 640 mm
U-value without edge thermal bridging effect	0.235 (0.568)	0.206 (0.568)
U-value with edge thermal bridging effect	0.286 (0.574)	0.244 (0.572)
Effective U-value	**0.311** (0.576)	**0.259** (0.573)

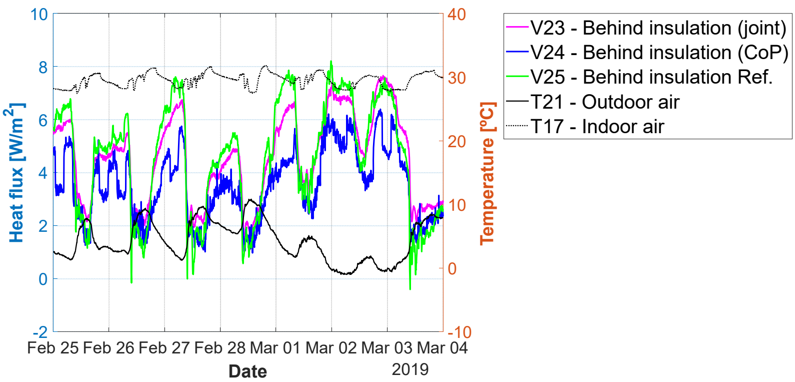


Figure 2: Heat fluxes and ambient temperatures curves during a winter period.

After 24 months of monitoring, regarding the appearance of ETICS rendering, no cracking, blistering, or aesthetic anomalies were found. Furthermore, infrared inspections were taken were taken periodically and from these thermograms, it is clear that the VIPs have not lost their vacuum during this period. In terms of humidity levels, the experimental measurements indicates that, when compared to the EPS wall, the VIP solution will not present additional problems regarding internal humidity levels.

3.2.2 Case study 2

Surface condensation issues contribute to microbiological growth, which is a common anomaly associated with ETICS. Condensation risk occurs when the superficial temperature is lower than the dew point. Thus, for one year, the time period in each month with surface temperature lower than the dew point temperature was determined. The annual condensation risk is presented in Fig. 3 for white and black walls (south orientation). The results suggest that walls with a higher level of insulation, that were finished with a white coloured surface are more likely to develop surface condensations that represents a higher biological growth risk in VIP ETICS walls.

Similar findings were found for the north-facing walls. However, in this case, the percentage of time in which there is risk of condensation increases around 18%, when compared with the south-facing walls.

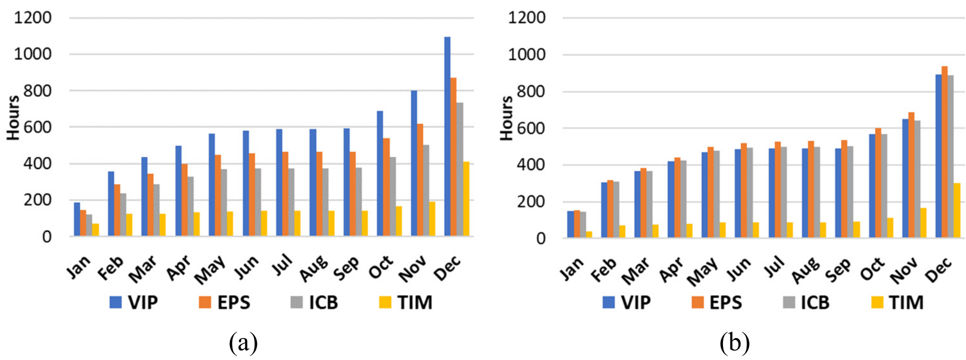


Figure 3: Accumulated hours in 2019 with surface condensation risk for different ETICS solutions. (a) White wall; and (b) Black wall.

3.3 Hygrothermal cycles resistance

Heat–rain and freeze–thaw standardized cycles were performed to assess the solution as resistant to hygrothermal cycle. After these hygrothermal cycles, no anomalies were found. Thus, according to the EAD for ETICS [17] this VIP based ETICS solution is assessed as resistant to hygrothermal cycles.

However, the new test that includes solar radiation cycles caused defects which were not found after the standard procedures, namely anomalies such as loss of flatness and finishing coat microcracking. This reveals the importance of studying the radiation effect on ETICS systems. Fig. 4 shows in detail the location of the microcracking on the finishing coat layer. Most of these cracks are located vertically and horizontally along the VIP joints. The cracking occurred only at within the solar radiation exposure area and its surrounding area.

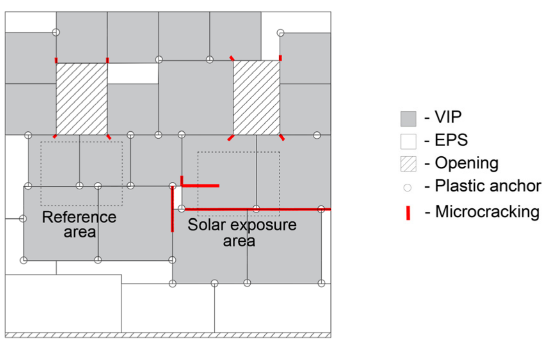


Figure 4: Layout pattern scheme of VIPs and location of the microcracking (in red) on the finishing coat layer.

Furthermore, during ageing cycles a loss of VIP thermal performance was verified. That is, the heat flux measurements carried out before and after the tests revealed a performance loss of about 70% compared to the initially estimated thermal transmission coefficient.

3.4 Life cycle costing

The cost-effectiveness of VIP solutions is strongly dependent on initial investment costs. Fig. 5 shows the results for the calculations performed considering an air conditioner system, a rental price area of 150, 250 and 350 €/(m^2.y) and a range in VIP prices between 1,500 €/m^3 and 3,000 €/m^3 (current price).

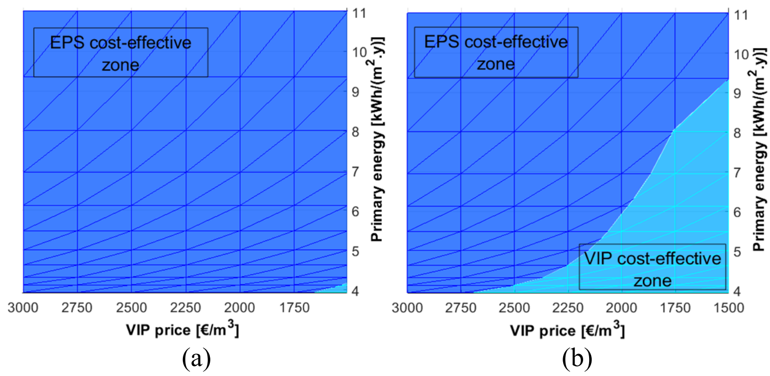


Figure 5: VIP price analysis for Berlin for financial perspective. (a) Fixed rental cost of 150 €/(m^2.y); and (b) Fixed rental cost of 250 €/(m^2.y).

Considering a low rental price area (150 €/(m^2.y) (Fig. 5(a))) it can be observed that the VIP is not profitable even when the VIP price is lower than 1,750 €/m^3. For a fixed value of rental cost of 250 €/(m^2.y) (Fig. 5(b)), if the cost of VIPs is reduced to less than 2,600 €/m^3, it may become a competitive solution against EPS, depending on the insulation level required.

4 CONCLUSIONS AND FUTURE WORKS

This paper presented a summary of results for an ETICS solution that incorporates vacuum insulation panels instead a conventional insulation material. The investigation focused on the study of the edge thermal bridges, on the analysis of VIP based ETICS performance under service conditions, on the implementation of accelerated ageing tests that simulates real conditions of exposure, as well as on the study of the economic competitiveness of the novel solution.

The results demonstrating that the thermal bridging effect between panel joints have a significant impact on the overall thermal performance of the walls. The installation (existence of air gaps), the size of the panel and the edge material design are determinant factors for reducing linear thermal transmittance values, and consequently, for promoting better overall thermal performance.

The higher thermal performance of VIP, compared to conventional insulations, was confirmed through temperatures and heat fluxes measurements, even when measuring at the joint area where the thermal bridging edge effect occurs. However, in comparison with other insulation materials, higher surface temperature amplitudes were found in the VIP solutions, increasing the risk of the rendering system cracking. Also, the condensation risk was found to be slightly higher when compared with an EPS ETICS solution, leading to higher biological growth risk on VIP based ETICS façades. After more than 24 months of onsite monitoring, the VIP based ETICS solution did not revealed remarkable anomalies. However, continue the long-term onsite monitoring campaign to evaluate the degradation of the thermal performance of the VIPs over time is suggested.

The proposed ageing cycles campaign revealed the importance of studying the solar radiation effect on ETICS systems. VIP joints could be considered the critical issue of the VIP based ETICS solution, since in addition to higher heat flux measurements verified at the joints, most of finishing coat microcracking occurred over joints. From the durability point of view, an increase of the VIP thermal conductivity was found. A deeper knowledge for the solar radiation impact on ETICS, even on innovative or conventional solutions, will be relevant to optimize solutions and assure a better long-term performance.

The use of VIPs in ETICS places greater demands for the rendering products, such as the need to resist to higher temperature amplitudes and slightly higher condensation risk, when compared to conventional ETICS solutions (as previously stated). So, there is a challenge to manufactures to develop rendering products able to mitigate these risks.

Replacing a conventional insulation by a vacuum panel allows a significant reduction in wall thickness and, consequently, an increase in the useful area. This space-saving economic benefit contributes to balance the high costs of the solution, from a perspective of long-term economic profitability analysis. This work shown the cost-effectiveness of VIPs, identifying the limits under which the panels become cost-effective against the use of expanded polystyrene.

Since the use of VIPs in ETICS are still few and recent, it is important to contribute to the experimental validation of this innovative solution, identifying the main limitations, promoting the optimization of products, and consequently increasing their competitiveness against current solutions. In this sense, this work contributes to increase knowledge in this field.

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