Journal of Architecture and Construction
Volume 2, Issue 1, 2019, PP 53-63
ISSN 2637-5796

Vacuum Insulation Panels Applications as Building Insulators

Amin Saboktakin[1], **Mohammadreza Saboktakin**[2]

[1] *Architecture department, Hochschule Wismar, Germany*
[2] *Nanotechnology departments, Phillips University of Marburg, Germany*

Corresponding Author: *Amin Saboktakin Architecture department, Hochschule Wismar, Germany*

ABSTRACT

Vacuum insulation panels (VIP) were developed to be used in refrigerators, freezers and cold shipping boxes where the space for insulation is limited. The product was introduced in the middle 1980s following the search for materials that could replace insulation materials which contained CFCs, harmful to the ozone layer. The potential of using VIP in buildings is large but VIP cannot be integrated in buildings without considering the ageing of the material. The technical life time of a refrigerator is around 10-20 years, which is much shorter than what can be expected from a building.

Keywords: *Vacuum insulation panels, building, insulation, polymers.*

INTRODUCTION

Buildings should typically last for 80-100 years without too much maintenance while VIP available today typically has a service life of around 25-40 years. The first VIP originates from 1930 when a German patent on a rubber enclosed porous body was filed. Around 20 years later a patent on a glass wool core welded to a steel foil was filed in the US. In 1963, the first patent of a panel with a core of a nanostructure material was filed. The development of VIP continued with experiments of different core material and envelope techniques. The increasing demands from food, pharmaceutical and electronic industries boosted the development of thin films with low permeability. Nanostructure materials that could be used in the core were available already in the 1930s following Kistlers experiments with aero gels. However, the commercial production of aero gels was suspended in the 1970s which lead to development of alternative core materials [1].

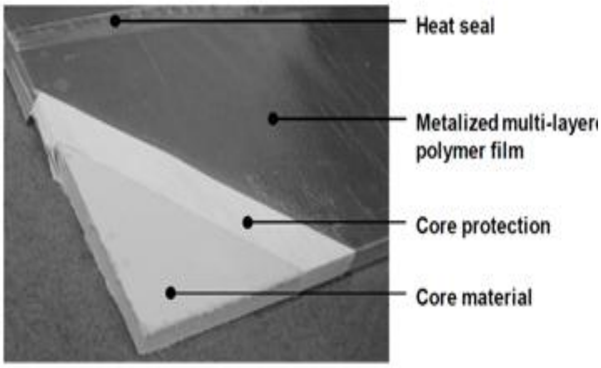

Fig 1. *VIP sample*

The results show a VIP of the type that is common today which was first introduced in the early 1990s. The core material was at that time precipitated silica which was enclosed by a plastic envelope with a 12 µm tick aluminum film. Another product that was introduced at the same time was a VIP with a fiber core and an envelope of 75 µm thin welded sheet steel. The product was intended for the refrigerator industry and the thermal conductivity of the products ranged around 2-7 mW/(m·K). VIP with a diatomite filling and a 100 µm sheet steel casing were also tested for application in district heating pipes. The core material of VIP is a fine powder or fiber from which the air has been removed to a gas pressure of 0.2-3 mbar. The core has to be able to resist the atmospheric pressure on the envelope, i.e. 1 000 mbar. The most common core material in Europe is fumed silica while also glass fiber and open cell polyurethane are common in Asia.

The glass wool is a porous material with large cavities where the heat transfer by convection and gas conduction are dominant at atmospheric pressure. Polystyrene, polyurethane and precipitated silica have smaller pores compared to glass wool which means the gas conduction and convection are smaller in these materials. The pore size of fumed silica is around 10-100 nm which is the same order of magnitude as the mean free path of air molecules, around 70 nm, in normal temperature and atmospheric pressure. When the pressure decreases towards vacuum, the heat transfer by gas conduction and convection decreases and heat transfer by radiation and conduction through the solid are left. They are constant as long as the temperature and density of the material are left unchanged. Fumed silica is used in semiconductor industry and in the production of photovoltaic cells. It is produced by pyrolysis of silicon tetrachloride, $SiCl_4$, which is vaporized and reacts with oxygen to form silicon dioxide, SiO_2. To reduce the heat transfer by radiation silicon carbide, SiC, is added to the silica and a fiber material is used to increase the stability of the mixture.

Around the core material, a metalized multilayered polymer films with thin aluminum layers, 30-100 nm, are typically used as envelope. The film is not perfectly gas tight which makes it possible for gas molecules to diffuse through the envelope. An irreversible pressure increase takes place which increases the thermal conductivity of the VIP. The center of panel thermal conductivity of a new VIP is around 4.5 mW/ (m·K) which can be expected to increase with 2.9 mW (m·K) after 25 years. Thus, the recommended design value of the thermal conductivity of a VIP with fumed silica is 7-8 mW/ (m·K) depending on the moisture conditions in the construction. If the panel is punctured, the thermal conductivity increases to 20 mW/ (m·K) which is still lower than e.g. mineral wool which has a thermal conductivity around 40 mW/ (m·K).

A thermal bridge is defined as the linear thermal transmittance, ψ (W/ (m·K)), which is multiplied with the length of the thermal bridge, i.e. the perimeter of the VIP. The magnitude of the thermal bridge is dependent on the center of panel thermal conductivity and the equivalent thermal conductivity of the film.

Also the thickness of the panel and film influences the thermal bridge together with the thermal conductivity of the surrounding materials. Studies of the thermal bridges created by the VIP envelope have been performed by a number of researchers. Schwab et al. used a numerical method to calculate the influence by air gaps between the VIP and also investigated the influence by encapsulating the VIP in polystyrene [2]. The simulations showed that the effective Uvalue increased with up to 360% for the laminated aluminum film with a 5 mm air gap, while the effective U-value for the VIP with metalized multi-layered polymer film only increased with 44%.

Ghazi Wakili et al. compared numerical simulations with measurements of the thermal bridge effect of the film on 20 mm thick VIP of sizes 500x500 and 500x250 mm. Two different films were tested, one film with a total aluminum thickness of 90 nm and another film with 300 nm. The linear thermal transmittance was 7 mW/ (m·K) for the 90 nm aluminum and 9 mW/ (m·K) for the 300 nm aluminum. The increased heat flow through the film leads to a higher effective thermal conductivity of the VIP; 14% higher for the film with 90 nm aluminum and 19% higher for the film with 300 nm aluminum compared to the center of panel thermal conductivity [10].

In a follow-up study by Ghazi Wakili et al., the effect of the film in constructions with double layered VIP was investigated. Different arrangements of 15-40 mm thick, 500x500 and 500x250 mm panels were measured in guarded hot plate apparatus. The panels were encapsulated in a multi-layered polymer film with a total aluminum thickness of 300 nm. The panels had an average center of panel thermal conductivity of 4.1 mW/ (m·K). Adding the effect of the thermal bridge created between the two small panels on top of an unbroken layer of VIP, the average effective thermal conductivity increased by around 2.5 mW/(m·K)[11]. The VIP is prone to damages and has to be handled with great care during the construction process. To increase the durability of VIP, different approaches have been suggested and tested. A more robust version of the panels is the vacuum insulated sandwiches (VIS) which are covered by a stainless steel casing. The sandwich can be part of the load-bearing system and take loads without any additional protection [3]. Gudmundsson [13] calculated the thermal bridges created by the robust protective casing around the VIS and found that the thermal bridge could be reduced by using insulation materials adjacent to the VIS.

Also, the length of the edge could be elongated to decrease the influence of the casing. Thorsell investigated a serpentine edge of the casing which showed that the thermal bridges decreased with this design. With 11 slots of 20 mm depth the influence could be minimized to a linear thermal transmittance of 11 mW/(m·K) which is comparable to the metalized multi-layered polymer film. The linear thermal transmittance of the casing was 28 mW/ (m·K) without any slots. Since the film around the VIP is vapor tight, the vapor permeability of the panels is virtually zero. This may cause problems around the panels if the connection between them is insufficiently sealed and allows for air and vapor transport through the layer. In some cases sealing tape has been used to increase the air tightness of the connections.

Another option is to use an additional layer of vapor retarder to ensure a vapor tight layer. It might also be worth to investigate if a dynamic vapor barrier could be used, i.e. a material that let the vapor through when it is in moist environment and stop the vapor when it is dry. Especially this solution could be worthwhile if there is a risk of condensation in the construction.

The moisture and heat flow through the construction where the VIP is integrated will change substantially. The risk of damages to the construction in case of a punctured VIP has to be investigated with hydrothermal simulations. In Johansson (2012), a theoretical study of a wall retrofitted with VIP is presented. The study showed that the risk for moisture damages was decreased when VIP was added to the exterior of an old exterior wall. If the VIP was punctured, only a small change in the moisture performance of the wall could be found.

If a VIP is damaged in the construction, the heat flow through the construction will increase. In the design process this have to be treated and if it has an unacceptable consequence for the energy use for heating of the building, the construction should be prepared for easy exchange of the damaged panel. In that case the construction has to be flexible and designed in a way that the VIP is easily accessible and possible to remove. It should also be possible to detect the damaged VIP with e.g. infrared thermograph, which means that the VIP should not be covered on both sides with high conductive materials or be placed behind a ventilated air space[3].

A way to avoid unnecessary risks on the construction site is to integrate the VIP in prefabricated constructions. Industrial treatment of the VIP means they will be in a controlled environment where the staff involved in the handling of the panels can gain experience and be trained to treat the VIP with care. Also the surroundings of the site of assembly can be equipped with the right protective equipment such as protective mats and felt shoes [3]. All attachments and joint details need to be carefully designed since brackets, window attachments and such components may harm the envelope of the VIP. A good design can ensure this which means the designers and builders have to be aware of the special requirements of the VIP early in the design process. If the design and construction are performed following the recommendations from producers VIP can be feasible and an important means for building energy efficient buildings.

Fumed silica is nonflammable and is therefore classified A1 according to DIN ISO EN 13501-1 (Porextherm, 2010). On the other hand, the silica is encapsulated by a multi-layered polymer film which is highly flammable. The multi-layered polymer will start decomposing at around 150°C causing production of carbon monoxide, formaldehyde and possibly other aldehydes. The film auto ignites at around 350°C with a fast fire development, see Figure 2.5. Newly developed VIP has a 6 µm thick flame-retardant brominated acrylic copolymer coating on the outside of the film.

An investigation in 1999-2002 commenced by the US Department of Housing and Urban Development evaluated the market potentials for VIP in residential buildings in the US. 27 different constructions were evaluated during a brainstorming process based on a number of evaluation criteria (NAHB Research Center, 2002)

The brainstorming process and evaluation resulted in ten alternatives of which five alternatives were chosen as most promising based on their respective annual market potentials (NAHB Research Center, 2002):

- Manufactured housing floor panels (45.4 km^2)
- Exterior doors (9.3 km^2)
- Garage doors (3.1 km^2)
- Manufactured housing ceiling panels (45.4 km^2)
- Attic access panels/stairway insulation (approx. 1 million access panels)
- The five other applications were (NAHB Research Center, 2002):
- Precast concrete panels, foundation/wall (0.1 km2, could expand)
- Insulated metal roofing panels (0.4 km2)
- Rectangular duct insulation (3.7 km2)
- Retrofit exterior insulation (6 km2, could expand)
- Acoustical ceiling panels (potentially large commercial building market)

The recommendation from the first part of the study was to investigate insulated attic hatches and insulated attic stairs further. Together with the two VIP producers, designs were evaluated and contacts taken with attic hatch and stair producers. The study was based on American building traditions for detached single family houses which mean that the conclusions cannot be directly applied on the European building market where other applications might be more interesting. After the report was produced, the development in the durability and thermal resistance of the VIP has continued and the number of possible applications increased.

During 2002-2005, an international research team investigated the possibilities to use VIP in buildings. Researchers from Switzerland, Germany, France, the Netherlands, Sweden and Canada worked in the IEA/ECBCS Annex 39 High Performance Thermal Insulation (HiPTI). The research was divided in two subtasks where the first part was regarding the VIP properties and durability while the second part concerned the use of VIP in building applications. In total 20 constructions were built or retrofitted and the consequences on energy use, thermal bridges and moisture performance were analyzed. The research team concluded that VIP has become a feasible and important mean for designing energy efficient buildings. There are obstacles to overcome, mainly cost and issues with durability and quality assurance of VIP in buildings, before VIP can be introduced on a wide scale.

Willems and Schild discussed different construction where VIP could be used. Examples of how loggias and roof terraces, curtain walls, flat roofs, pitched roofs, floors and external walls could be designed with VIP integrated in the construction are presented. Examples of how the more load resistant VIS, covered by a stainless steel casing, can be a part of the load-bearing system were also presented. A Norwegian investigation by Grynning et al. concluded that the building traditions in the Nordic countries are different from the traditions in central Europe [12]. Many of the constructions with VIP are located in Switzerland and Germany where the use of timber constructions is less common. Norwegian single family houses are almost exclusively built using timber frame constru ctions with a ventilated roof. This means that the conclusions from the Swiss and German studies cannot be applied directly to the Nordic buildings without more evaluations. A number of constructions where it could be possible to use VIP in the Nordic countries were identified:

- Prefabricated sandwich elements
  - Continuous insulation layer in non-load bearing walls
  - Thin timber frame walls
  - Floors and compact roofs
  - Retrofitting of buildings with limited available space
  - New buildings in areas with high ground costs
  - Doors and windows
  - Insulation of terrace floors where even connections are important

The use of VIP in these constructions is limited by the higher cost in relation to the commonly used insulation materials. Grynning presented a simplified economical calculation where a 6 cm thick VIP was used in an exterior wall. At a market value of 17 500 NOK/m^2 (approx. EUR 2 300 per m^2) there was no additional costs for the VIP compared to using mineral wool. In this example, the thermal resistance of the VIP was five times higher than for the mineral wool and the cost of the 6 cm thick VIP was 1 600 NOK/m^2 (approx. EUR 200 per m^2). The costs for increased design and construction times were not included in the study.

A study of the economic consequences of using VIP in Swedish multi-family buildings was performed by Pramsten and Hedlund [27]. A wall with VIP was compared to a wall with the same thermal transmittance using EPS. With the assumptions in the study, VIP is not an economical alternative compared to EPS. Either the price of the VIP has to decrease or the energy price has to increase to make VIP an economical alternative for buildings. For a market value of 22 450 SEK/m^2 (approx. EUR 2 500 per m^2) the price of EPS and VIP are equal. The prize of the 20 mm thick VIP was 1 800 SEK/m^2 (approx. EUR 200 per m^2).Alam et al. calculated the payback period (PBP) using VIP in four different retrofitting scenarios where the thickness of the VIP was varied [1]. The PBP using VIP was compared to a wall with the same thermal resistance using EPS. The scenarios were based on commercial buildings in the UK where the available space for the construction is limited. The PBP was 15.3 years for the case with 10 mm VIP and decreased to 9.6 years with

25 mm VIP. For the wall with an U-value of 0.27 W/(m^2K), the PBP was 10 times higher for the VIP compared to the EPS. In the fourth scenario the PBP was 6 years longer using VIP compared to EPS? However, the EPS required 256 mm insulation thickness compared to only 60 mm VIP for the same thermal resistance. The PBP was reduced significantly when the additional income from the rentable space gained by using VIP was taken into consideration. The value of the gained space was £40/ft^2 which is approximately EUR 500 per m^2, corresponding to the average yearly rent of commercial buildings in London, UK. With this increased income the payback period was less using VIP compared to EPS, 0.8 compared to 0.9 years, for the wall with a U-value of 0.24 W/m2K. A new generation of highly insulating materials [31, 32] called vacuum insulation panels (VIP) has been developed since the beginning of this millennium. These comprise a core material of fumed silica encased in a multi-component barrier film containing at least 90 nm of aluminum (Figure 1; Type A). The core material is vacuum-packed to minimize heat transfer by convection [33], with a pacifier powder added to reduce heat transfer by radiation. The range of VIP products (Figure 2) provided by different manufacturers employ various barrier envelope and sealing solutions.

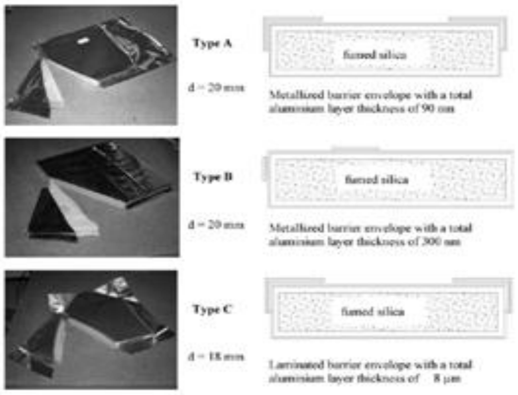

Fig 2. *Cross-section through corner of different VIP types with associated schematic sketch.*

Given the vulnerability of these thin barrier envelopes, which are subjected to a pressure difference of about one atmosphere, VIPs require special protection during construction and over the entire building lifespan. Ideally, therefore, VIP units should be covered by a protective layer, as is the case for door systems with VIPs sandwiched between door facings. The present investigation set out to determine the impact of VIPs on the overall thermal behavior of a door system for both intact and damaged cases. For this, hot box measurements and steady-state 3D calculations have been carried out and their results compared. Research conducted by the National Association of Home Builders (NAHB) in collaboration with the US industry [34] and aimed at accelerating the adoption of vacuum insulation technology in home construction, renovation and re-modeling, reported on a number of VIP applications in residential schemes—specifically floor panels, exterior doors, garage doors, ceiling panels and attic access panels or insulated attic stairs. In the case of exterior doors, it was mentioned that the reduction of thermal bridges through the lock block area and metal fittings could be a requirement to be considered. This aspect was therefore specially examined in the present study. The fact that wooden door systems with integrated VIPs are already available on the Swiss market, chiefly for incorporation in low-energy houses, provided an additional incentive for this study. Further investigations dealing with the service life of VIPs have been published elsewhere [35].

Vacuum insulation panels (VIP) in general are flat elements consisting of an open porous (and therefore evacuation-capable) core material which has to withstand the external load caused by atmospheric pressure, as well as a sufficiently gas-tight envelope to maintain the required quality of the vacuum. Nano-structured materials have been found to require the least quality of vacuum, which has to be achieved and to be maintained.

In panels basically made of pressed fumed silica, the contribution of the gas to the total heat transfer is virtually eliminated even at an internal gas pressure of a few hundred Pascal. The densities are in the range of 160 kg/m^3 to 190 kg/m^3. The porosity is higher than 90%, the specific surface area is higher than 200 m^2/g. High sorption capability results from the huge specific surface area. Thus fumed silica may act as a desiccant. For high humidity, from 60 up to 95%, there is an exponential increase mainly due to the capillary condensation in the small pores. Indeed, according to the Kelvin-Laplace law, at 95%, all the pores with a size smaller than 20 nm are filled with water. In 2008, the energy consumption of the building sector accounted for 22.2% of the total energy consumption in Korea; 53% of the energy consumed in the building sector was from residential buildings. From 2000 to 2006, the annual energy consumption in residential buildings increased at a rate of 3.9%, which was considerably higher than that of other developed countries (Germany, 0.0%, Japan, −0.2%, and USA, −1.6%). Thus, reducing the energy consumption of residential buildings is essential to meet national goals of reducing greenhouse gas emissions.

To this end, the Korean government has implemented various policies to reduce the annual energy consumption of residential buildings by 60% compared to 2009 levels by 2017 and make zero energy consumption mandatory by 2025. The core of the policy is a drastic strengthening of building insulation regulations; similar measures have also been taken in many other countries [36]. In practice, ensuring a high level of insulation performance requires the elimination of thermal bridges in the building envelope that reduce the local thermal resistance. In European countries, the elimination of thermal bridges is strongly suggested or even mandated by building codes, which either specify the maximum linear thermal transmittances of linear thermal bridges or include the heat loss due to thermal bridges when calculating the heating energy demand for the Energy Performance Certificate. In Korea, apartment buildings are the most common type of residential building.

However, most apartment buildings in Korea have internal insulation systems that cannot avoid the numerous thermal bridges because the insulation layers must be discontinuous at structural joints. Thus, the Korean government is planning to mandate the elimination of thermal bridges in the building envelope.

The construction industry anticipates that external insulation systems will be the only suitable solution to the pending mandate. Most apartment buildings in Korea are high-rise buildings. Thus, high-performance external insulation systems, which are thinner than the 200–300 mm thicknesses typical of conventional insulation materials [37], are required to facilitate the construction of energy-efficient apartment buildings with high levels of insulation performance.

In this book, external insulation systems using a new type of highly insulating material [38], vacuum insulation panels (VIPs) were evaluated to determine their effectiveness in high-performance insulation systems. A variety of mechanically and adhesively fixed external insulation systems with various insulation layer compositions were proposed as alternatives to conventional internal insulation systems. The performance of conventional insulation systems and the proposed alternatives were compared through three-dimensional heat transfer simulations.

The construction costs and ease of installation of each system were also compared. The overall performance of each alternative in terms of the insulation performance, construction costs, and ease of installation was thus evaluated to determine the most effective alternative. VIPs have long been used in devices such as refrigerators and freezers, and they are now being used for building construction in walls, roofs, floors, and doors.

The thermal conductivity of a highly evacuated dry VIP with a fumed silica core is typically approximately 0.004 W/ (m·K) after production, as measured at the center of a large panel [37, 39]. The thermal resistance of VIPs is five to ten times greater than that of conventional insulation materials with the same thickness. As shown in Figure 3, VIPs are generally flat with an open porous core material that resists the external load caused by atmospheric pressure and a sufficiently gas-tight envelope to maintain the required level of the vacuum.

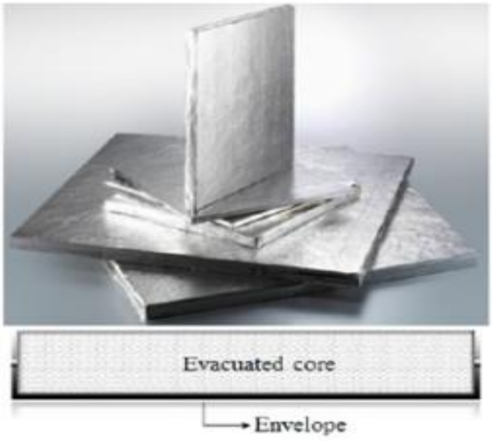

Fig3. *New Vacuum insulation Panels samples and construction.*

Common core materials include fumed and precipitated silica, open-cell polyurethane, and several types of fiberglass. Fumed silica is considered the best currently available core material because it exhibits low conductivity at pressures greater than 50 mbar and the conductivity at ambient pressure is half that of conventional insulation materials. The most common materials used for VIP envelopes are metalized-film and aluminum-foil laminates [40-42].

VIPs are regarded as one of the most promising high-performance insulation solutions on the market because of their great potential for reducing building energy consumption while allowing for slim construction. Nussbaum ret al. [37] described that VIP opened the field for slim and energy efficient building envelope design which allows to enlarge the useable inner room sizes for a given exterior construction volume without reducing the thermal comfort. Tenpierik and Cauberg [42] also stated that the reduction of thickness is among the most interesting features for large-scale application of VIPs in the building industry.

However, VIPs are more expensive than conventional insulation materials. Furthermore, VIPs cannot be cut on site, and the panels are fragile and easily damaged. Thus, caution must be taken to avoid damage due to impact during handling and installation. In addition, thermal bridging may occur at the panel edges with aluminized films, and the thermal performance may degrade over time [42, 43]. These effects must all be considered for building applications because they may diminish the overall usability and thermal performance [44].

For these reasons, various studies have examined the physical properties of VIPs and their application in building construction. Among these studies, the most noteworthy was the international research collaboration led by the Energy Conservation in Buildings and Community Systems (ECBCS) program of the International Energy Agency (IEA) from 2001 to 2005: Annex 39 High Performance Thermal Insulation Systems (HiPTI) [39–42].

This research addressed the basic concepts and materials of VIPs, building applications, system developments, and demonstrations. Glicksman [10] was the first to mathematically explain thermal bridge effects on vacuum and reflective insulation materials. Wakili et al. [45] researched VIPs with evacuated fumed silica as the core material and various barrier envelopes to determine their effective thermal conductivity, which reflects the thermal conductivity of a panel both at the center and at the edges. Schwab et al. [46] investigated the effect of thermal bridges on the joint areas of VIPs with laminated aluminum foils when installed on walls and the effect of attachment methods on the insulation performance. Researchers performed to find the way of reducing the thermal bridge effects caused by highly conductive materials like laminated aluminum foils. Thorsell and Källebrink investigated the possibility of reducing thermal shunting in VIPs covered with stainless steel foil based laminates earlier in their research in 2005. A year after, Thorsell [47] proposed serpentine edges to reduce thermal bridging at the edges of VIPs, evaluated their performance through computer simulations, and assessed the permeability of VIPs with double-coated films. In addition to the thermal bridge edge effect, VIP has been questioned about its durability. Simmler *et al.* [48] described the aging mechanisms of VIPs and reported experimental results for various temperature- and humidity-induced deteriorations.

The authors calculated the increase in internal pressure based on a dynamic thermal model and discussed end-of-life criteria and service life estimates. VIPs have been used as external or internal insulation in detached houses, apartment buildings, nurseries, and office buildings in both new construction and renovations. Various combinations of insulation layers were used: one-layer (VIP), two-layer (VIP and conventional insulation), and three-layer (conventional insulation, VIP, and conventional insulation).

For external insulation, the insulation layers were fixed to the substrate with adhesives, and plaster and stone were used as exterior finish materials [49]. European countries, such as Germany and Switzerland, have used VIPs for either external or internal insulation in outer walls, roofs, and floors. For external insulation, the insulation layers can be one-layer (VIP), two-layer (VIP and conventional insulation), and three-layer (conventional insulation, VIP, and conventional insulation). In some cases, metal panels with embedded VIPs were used.

The insulation layers were fixed to the substrate either mechanically (with fasteners and rails) or adhesively. Various exterior finish materials, such as plaster, stone, wood, metal sheets, wood fiberboard, and prism glass, were used. Although some outer walls of apartment buildings in Korea are built with curtain walls consisting of metal mullions, transoms, sheets, and glass, most are built from reinforced concrete with punched windows. Thus, this study focused on reinforced concrete outer walls and external insulation systems with a plaster finish because of their widespread use in the industry.

Two methods of fixing the external insulation systems to the concrete walls, mechanically and adhesively, were evaluated. The evaluation was then further divided by varying the composition of each type of insulation system. The conventional internal insulation systems and proposed alternatives were compared in terms of the insulation performance, construction cost, and ease of installation. The insulation performance was evaluated according to the heat loss, which was calculated through three-dimensional, steady-state heat transfer simulations.

The conventional and proposed systems were modeled so that the outer walls had similar thermal transmittances (U-values). The advantages and disadvantages of the proposed alternatives over the conventional systems in terms of the construction costs and ease of installation were evaluated, and the results were used to rank the alternatives. Each alternative was given a point according to its ranking in each performance category: insulation performance, construction costs, and ease of installation.

Each point was then weighted according to importance. The most effective alternative was determined by summing all of the weighted scores. The cost of a VIP increases substantially with the thickness, and it is important to minimize the thermal bridging between VIPs and to prevent damage during handling and installation. According to Tenpierik and Cauberg [50, 51], due to the fragile nature of their barrier envelopes, their large dimensional tolerances and their prefabricated character, VIPs are sometimes integrated into an expanded polystyrene (EPS) or polyurethane (PU) foam insulation board. Therefore, the insulation was configured with several layers consisting of a VIP layer and layers of conventional insulation. Graphite-enhanced expanded polystyrene insulation (EPS) was used for the conventional insulation. Three configurations were evaluated: covered-type two-layer insulation (EPS covering the back side of the VIP, denoted as MF-C2 and AF-C2 for mechanically fixed and adhesively fixed, respectively), encapsulated-type three-layer insulation (EPS encapsulating the entire VIP, denoted as MF-E3 and AF-E3 for mechanically fixed and adhesively fixed, respectively), and covered-type three-layer insulation (EPS covering the front and back sides of the VIP, denoted as MF-C3 and AF-C3 for mechanically fixed and adhesively fixed, respectively).

Each insulation unit consisting of a VIP and EPS was assumed to be fabricated at a factory in advance for convenient installation. Steel fasteners, the details of which are given in Figure 4, are used for the attachment of external insulation systems in Korea.

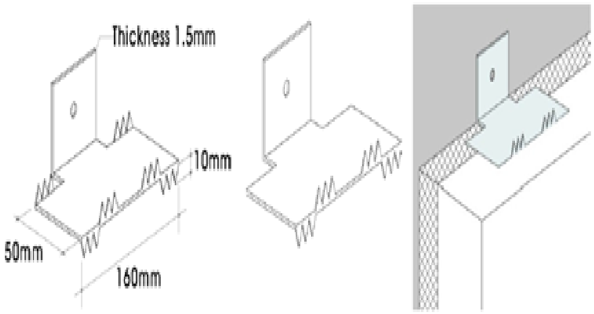

Fig 4. *Steel fasteners for mechanically fixed external insulation systems with VIPs.*

For adhesively fixed external insulation systems, the insulation units were assumed to be fixed to the concrete wall with adhesives. Although dowels are typically placed at the joints of the insulation units to support the attachment of conventional adhesively fixed external insulation systems, doing so with VIPs requires care because VIPs can be easily damaged. To prevent the VIP from being damaged, dowels are placed between bobbins installed at the joints of the insulation units

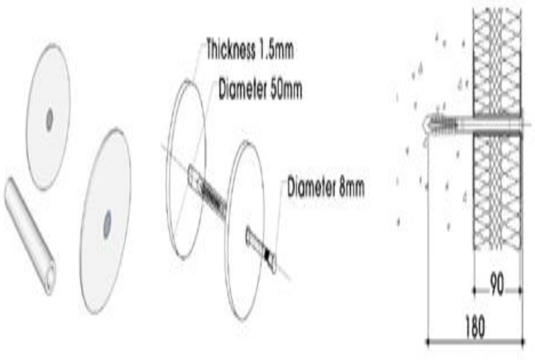

Fig 5. *Use of bobbins and dowels for mounting adhesively fixed external insulation systems with VIPs.*

CONCLUSION

For the mechanically fixed external insulation systems, the insulation units were assumed to be fixed to the concrete wall with steel fasteners; small amounts of adhesive were assumed to be used at a few locations between the insulation unit and concrete wall to improve the stability of the insulation unit.

REFERENCES

[1] Alam, M., Singh, H., and Limbachiya, M. C. (2011). Vacuum Insulation Panels (VIPs) for building construction industry - A review of the contemporary developments and future directions. *Applied Energy, 88*(11), 3592–3602.

[2] Bauphysik. (2011). Aktuell.*Bauphysik, 33*(1), 73.

[3] Binz, A., Moosmann, A., Steinke, G., Schonh ardt, U., Fregnan, F., Simmler, H., Brunner, S., Ghazi, K., Bundi, R., Heinemann, U., Schwab, H., Cauberg, J. J. M., Tenpierik, M. J., Jóhannesson, G. A., Thorsell, T. I., Erb, M., and Nussbaumer, B. (2005). *Vacuum Insulation in the Building Sector. Systems and Applications (Subtask B)*: IEA/ECBCS Annex 39 High Performance Thermal Insulation (HiPTI). BINE Information sdienst. (2007). Vacuum-insulated prefabricated elements in construction.*Projektinfo, 09*(07).

[4] Binz, A. and Steinke, G. (2006). Fassadend ämmung mit Vakuum. *applica, 113*(6), 22-30.

[5] Boverket. (2010). *Energi i bebyggelsen - tekniska egenskaper och beräkningar - resultat från projektet BETSI*. Karlskrona, Sweden: Boverket. Boverket. (2011). *Regelsamling för byggande, BBR 2012*. Karlskrona, Sweden: Boverket.

[6] Brunner, S. and Simmler, H. (2008). In situ performance assessment of vacuum insulation panels in a flat roof construction. *Vacuum, 82*(7), 700-707.

[7] European Commission. (2008). *Communication from the Commission to the European Parlia ment, the Council, the European Economic and Social Committee and the Committee of the Regions - 20 by 2020 Europe's climate change opportunity*. Retrieved from http://eur-lex.europa.eu/LexUriServ/LexUri Ser v .do?uri= CELEX:52008DC0030:EN:HTML:NOT.\ [8] Fricke, J., Heinemann, U., and Ebert, H. P. (2008). Vacuum insulation panels – From research to market. *Vacuum, 82*(7), 680-690.

[8] Ghazi Wakili, K., Bundi, R., and Binder, B. (2004). Effective thermal conductivity of vacuum insulation panels. *Building Research and Information, 32*(4), 293-299.

[9] Ghazi Wakili, K., Nussbaumer, T., and Bundi, R. (2005). Thermal performance of VIP assemblies in building constructions. *Proceedings of the 7th International Vacuum Insulation Symposium*, September 28-29, 2005, Duebendorf / Zurich, Switzerland. pp. 131-138.

[10] Ghazi Wakili, K., Stahl, T., and Brunner, S. (2011). Effective thermal conductivity of a staggered double layer of vacuum insulation panels. *Energy and Buildings, 43*(6), 1241-1246.

[11] Grynning, S., Baetens, R., Jelle, B., Gustavsen, A., Uvsløkk, S., and Meløysund, V. (2009). *Vakuumisol asjonspaneler for bruk i bygninger Egenskaper, kravogmu ligheter [Vacuum insulation panels for building applications: Properties, requirements and possibilities]* (Project number: B22479.18 Report ISSN1504-6958 ISBN 9788253610504). Oslo: SINTEF Byggforsk.

[12] Gudmundsson, K. (2009). A Parametric Study of a Metal Sandwich VIP. *Proceedings of the 9th International Vacuum Insulation Symposium*, September 18-19, 2009, London, UK.

[13] Haavi, T., Jelle, B., Gustavsen, A., Uvsløkk, S., and Baetens, R. (2010). Vacuum Insulation Panels in Wood Frame Wall Constructions - Hot Box Measurements and Numerical Simulations. *Proceedings of the 2nd Biennial International Conference on Building Enclosure Science and Technology*, April 12-14, 2010, Portland, USA.

[14] Heinemann, U. and Kastner, R. (2010). *VIP-PROVE Ergebnisse der wissenschaftlichen Begleitforschung. Project Final Report ZAE 2-1210-11.*

[15] Würzburg, Germany: Bayerisches Zentrum für Angewandte Energieforschung e.V. ZAE Bayern. Jasim, S. (2010).VIP i portgångar. Internal meeting, September 28, 2010.

[16] Gothenburg, Sweden: Göteborgs Egnahems AB. Johansson, P. (2012). *Retrofitting of old Exterior Wall with Vacuum Insulation Panels: Measurements of Thermal Properties, Moisture Performance and Practical Considerations (Lic. Thesis)*. Gothenburg, Sweden: Chalmers University of Technology, Department of Civil and Environmental Engineering.

[17] Korjenic, A. and Dreyer, J. (2003). Untersuchungen zurthermisch-hygrischen Eignung von Vakuum daemmplatten zur Sanierung von Gebaeuden der Wiener Gruenderzeit [Investigations thermal-hygral suitability of vacuum insulation panels for reinstatement of buildings from the 19th century in Vienna]. *Bauphysik, 25*(6), 344-349.

[18] Kubina, L. (2010). Etics with Integrated Vacuum Insulation Panels. *Proceedings of the*

International Conference Central Europe towards Sustainable Building CESB, June 30-July 2, 2010, Prague, Czech Republic.

[19] Kubina, L. (2011). Lock Plate System ETICS with Integrated VIP - Experience from Building Practice. *Proceedings of the 10th International Vacuum Insulation Symposium*, September 15-16, 2011, Ottawa, Canada.

[20] Künzel, H. (1998). Effect of interior and exterior insulation on the hydrothermal behavior of exposed walls. *Materials and Structures, 31*(2), 99-103.

[21] Microtherm. (2009). SlimVac Safety Data Sheet. Sint-Niklaas, Belgium: Micro herm N V.

[22] NAHB Research Center Inc. (2002). *Accelerating the Adoption of Vacuum Insulation Technology in Home Construction, Renovation, and Remodeling, Project Final Report*. Upper Marlboro, MD: Prepared for U.S. Department of Housing and Urban Development, Office of Policy Development and Research.

[23] Nussbaumer, T., Bundi, R., Tanner, C., and Muehlebach, H. (2005). Thermal analysis of a wooden door system with integrated vacuum insulation panels. *Energy and Buildings, 37*(11), 1107-1113.

[24] Pool, M. (2005). Neubau eines Wohn- und Geschaeftshauses mit Ultra-

[25] Niedrigenergiehaus-Standard unter Verwen dung von Vakuum isolation spaneelen [Constru ction of a new residential and business building in line with the ultra-low-energy house standard using vacuum insulation panels]. *Bauphysik, 27*(6), 363-368.

[26] Porextherm. (2010). Vacupor Safety Data Sheet (91/155/EEC). Kempten, Germany: Porextherm Dämmst off GmbH.

[27] Pramsten, E. and Hedlund, M. (2009). *Ekonomiskanalys avvakuumiso leringspaneler i ytterzväggar*. Stockholm: Skolanförarkite ktur ochsa mhälls byggnad, Kungliga Tekni skahö gskolan.

[28] Schonhardt, U., Binz, A., Wohler, M., and Dott, R. (2003). *Ökobilanz eines Vakuum- Isolations-Paneels (VIP)*. Muttenz, Switzerland: Institut für Energie, Fachhochschule beider Basel.

[29] Schwab, H., Stark, C., Wachtel, J., Ebert, H.-P., and Fricke, J. (2005). Thermal Bridges in Vacuum-insulated Building Façades. *Journal of Thermal Envelope & Building Science, 28*(4), 345-355.

[30] Schwab, H., Wachtel, J., Scheuerpflug, H., Stark, C., Heineman, U., Ebert, H.-P., and Fricke, J. (2004). *Entwicklung und Anwendung von evakuierten höchsteffizienten Dämmungen für Gebäude (Vakuumdämmung für Gebäude). Project Final Report ZAE 2-1203-21.* Würzburg, Germany: Bayerisches Zentrum für Angewandte Energieforschung e.V. ZAE Bayern.

[31] R. Caps, U. Heinemann, M. Ehrmanntraut, J. Fricke, Evacuated insulation panels filled with pyrogenic silica powders: properties and applications, High Temperatures High Pressures 33 (2001) 151–156.

[32] H.Simmler, Measurement of physical properties of VIP, in: M. Zimmermann, H. Bertschinger (Eds.), High Performance Thermal Insulation Systems, Vacuum Insulated Products (VIP). Proceeding of the International Conference and Workshop, Centre for Energy and Sustainability in Buildings, EMPA, Duebendorf Switzerland, 2001.

[33] J. Fricke, Physical aspects of heat transfer and development of thermal insulations, in: M. Zimmermann, H. Bertschinger (Eds.), High Performance Thermal Insulation Systems, Vacuum Insulated Products (VIP). Proceeding of the International Conference and Workshop, Centre for Energy and Sustainability in Buildings, EMPA, Duebendorf Switzerland, 2001.

[34] Accelerating the Adoption of Vacuum Insulation Technology in Home Construction, Renovation, and Remodeling, Project Final Report, prepared by NAHB Research Center Inc., Upper Marlboro, USA, 2002.

[35] S. Brunner, H. Simmler, Service life prediction for vacuum insulation panels, in: CISBAT 2003 Proceedings, Lausanne, 2003, pp. 341– 346.

[36] Korean Ministry of Construction and Trans portation. *Activation Plans for Green Cities and Buildings*; Korean Ministry of Construction and Transportation: Seoul, Korea, 2009. (In Korean)

[37] Nussbaumer, T.; Wakili, K.G.; Tanner, C. Experimental and numerical investigation of the thermal performance of a protected vacuum-insulation system applied to a concrete wall. *Appl. Energy* **2006**, *83*, 841–855.

[38] Caps, R.; Heinemann, U.; Ehrmanntraut, M.; Fricke, J. Evacuated insulation panels filled with pyrogenic silica powders: Properties and applications. *High Temp-High Press* **2001**, *33*, 151–156.

[39] Binz, A.; Moosmann, A.; Steinke, G.; Schonhardt, U.; Fregnan, F.; Simmer, H.; Brunner, S.; Ghazi, K.; Bundi, R.; Heinemann, U.; *et al*. Vacuum insulation in the building sector: Systems and applications. Available online: http://www.iea-ebc.org/fileadmin /user _upload/docs/ EBC_Annex_39_Report_Subtask-B.pdf (accessed on 29 August 2014).

[40] Erb, M.; Symons, W. *Vacuum Insulation Panel Properties and Building Applications*; IEA/E CBCS Annex 39 Project Summary Report; AECOM: Hertfordshire, UK, 2010.

[41] Simmler, H.; Brunner, S.; Heinemann, U.; Schwab, H.; Kumaran, K.; Mukhopadhyaya, P.; Quenard, D.; Sallee, H.; Noller, K.; Kuec uekpinar-Niarchos, E.; *et al*. Vacuum Insulation Panels Study on VIP Components and Panels for Service Life Prediction of VIP in Building Applications (Subrask A). Available online: http://www.ecbcs.org/docs/Annex_39_Report_ Subtask-A.pdf (accessed on 29 August 2014).

[42] Tenpierik, M.J.; Cauberg, J.J.M. Analytical models for calculating thermal bridge effects caused by thin high barrier envelopes around vacuum insulation panels. *J. Build. Phys.* **2007**, *30*, 185–215.

[43] Thorsell, T.I. Edge loss minimization in vacu um insulation panels. In *Research in Building Physics and Building Engineering*; Fazio, P., Ge, H., Rao, J., Desmarais, G., Eds.; Taylor and Francis Group: London, UK, 2006; pp. 251–256.

[44] Baetens, R.; Jelle, B.P.; Thue, J.V.; Tenpierik, M.J.; Grynning, S.; Uvsløkk, S.; Gustavsen, A. Vacuum insulation panels for building applications: A review and beyond. *Energy Build.* **2010**, *42*, 147–172.

[45] Glicksman, L.R. Two-dimensional heat transfer effects on vacuum and reflective insulations. *J. Therm. Insul.* **1991**, *14*, 281–294.

[46] Wakili, K.G.; Bundi, R.; Binder, B. Effective thermal conductivity of vacuum insulation panels. *Build. Res. Inf.* **2004**, *32*, 293–299.

[47] Schwab, H.; Stark, C.; Wachtel, J.; Ebert, H.; Fricke, J. Thermal bridges in vacuum-insulated building facades. *J. Therm. Envel. Build. Sci.* **2005**, *4*, 345–355.

[48] Thorsell, T. Vacuum insulation in buildings: Means to Prolong Service Life. Licentiate Thesis, KTH-The Royal Institute of Techn ology, Stockholm, Sweden, 2006.

[49] Simmler, H.; Brunner, S. Vacuum insulation panels for building application: Basic properties, aging mechanisms and service life. *Energy Build.* **2005**, *37*, 1122–1131.

[50] [50] *ENERVAC Introduction & Application System in Architecture*; OCI Ltd. Inc.: Seoul, Korea, 2012. (In Korean)

[51] Tenpierik, M.J.; Cauberg, J.J.M. Encapsulated vacuum insulation panels: Theoretical thermal optimization. *Build. Res. Inf.* **2010**, *38*, 660–669.

Citation: *Amin Saboktakin, "Vacuum Insulation Panels Applications as Building Insulators" Journal of Architecture and Construction, 2(1), 2019, pp. 53-63.*