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Article

Evaluation of Mechanically and Adhesively Fixed External Insulation Systems Using Vacuum Insulation Panels for High-Rise Apartment Buildings

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Abstract: Buildings account for a significant portion of a nation's total energy consumption. To meet the global demand for greater energy efficiency, many countries are drastically strengthening insulation regulations for buildings. Thus, dramatically thicker wall insulation may be required, which can adversely affect the value of a building by reducing its effective floor area. Hence, high-performance insulation materials, such as vacuum insulation panels (VIPs), are of interest in building design. In this study, external insulation systems using VIPs were examined to determine their effectiveness in high-performance insulation systems for high-rise apartment buildings. A variety of mechanically and adhesively fixed external insulation systems with various insulation layer compositions have been 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 the ease of installation of the various systems 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.

Keywords: vacuum insulation panel; external insulation system; apartment building; insulation performance; construction

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1. Introduction

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 [1].

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 [2], are required to facilitate the construction of energy-efficient apartment buildings with high levels of insulation performance.

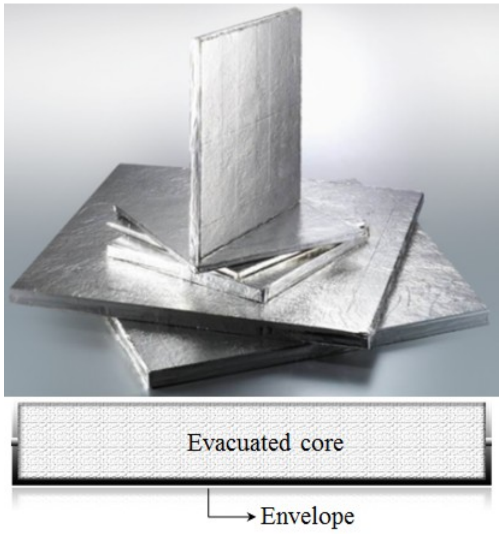
In this study, external insulation systems using a new type of highly insulating material [3], vacuum insulation panels (VIPs) were evaluated to determine their effectiveness in high-performance insulation systems. A variety of mechanically and adhesively fixed external insulation systems with various 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.

2. Overview, Previous Research, and Applications of Vacuum Insulation Panels

2.1. Overview of Vacuum Insulation Panels and Existing Research

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 [2,4]. 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 1, 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. 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 [5–7].

Figure 1. Vacuum Insulation Panels (VIPs) samples and construction.



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. Nussbaumer *et al*. [2] 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 [7] 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 [7,8]. These effects must all be considered for building applications because they may diminish the overall usability and thermal performance [9].

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) [4–6]. 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.* [11] 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.* [12] 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 [8] 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 [8,13] 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*. [14] 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.

2.2. Application of Vacuum Insulation Panels in Building Construction

Table 1 lists notable applications of VIPs in building construction in Korea. 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 [15].

Table 1. Applications of VIPs in buildings in Korea.

Building type (city)	**Insulation system**	**Insulation layers and thicknesses**	**Outer wall *U*-value (W/m^2·K)**	**Pictures**
L apartment building (Seoul)	Internal insulation	VIP, 40 mm	0.10	 
D apartment building (Bucheon)	Internal insulation	VIP, 15 mm	0.30	 

Table 1. *Cont.*

Building type (city)	**Insulation system**	**Insulation layers and thicknesses**	**Outer wall *U*-value (W/m²·K)**	**Pictures**
K detached house (Ganghwa)	Internal insulation	VIP, 15 mm	0.30	 
M nursery (Uiwang, renovation project)	External insulation	VIP, 30 mm + EPS, 50 mm	0.13	 
H bank (Jeju)	External insulation	VIP, 30 mm	0.15	 
I office (Iksan)	External insulation	VIP, 15 mm + EPS, 45 mm	0.26	 
N office (Iksan)	Internal insulation	VIP, 20 mm	0.23	 

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 [4,5].

3. Evaluation Methods for Mechanically and Adhesively Fixed External Insulation Systems with Vacuum Insulation Panels

3.1. Overview

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.

3.2. Configurations and Parameters of the Insulation Unit Alternatives

3.2.1. Configurations of the Insulation Unit Alternatives

The cost of a VIP increases substantially with the thickness, and it is important to minimize the thermal bridging between VIPs [7,8] and to prevent damage during handling and installation. According to Tenpierik and Cauberg [16], 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.

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. Table 2 lists the alternatives for mechanically fixed external insulation systems with VIPs. Steel fasteners, the details of which are given in Figure 2, are used for the attachment of external insulation systems in Korea. 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 VIPs from being damaged, dowels are placed between bobbins installed at the joints of the insulation units, as shown in Figure 3. Table 3 lists the alternatives for adhesively fixed external insulation systems with VIPs. Figure 3 illustrates the use of bobbins and dowels for mounting an insulation unit.

Figure 2. Steel fasteners for mechanically fixed external insulation systems with VIPs.

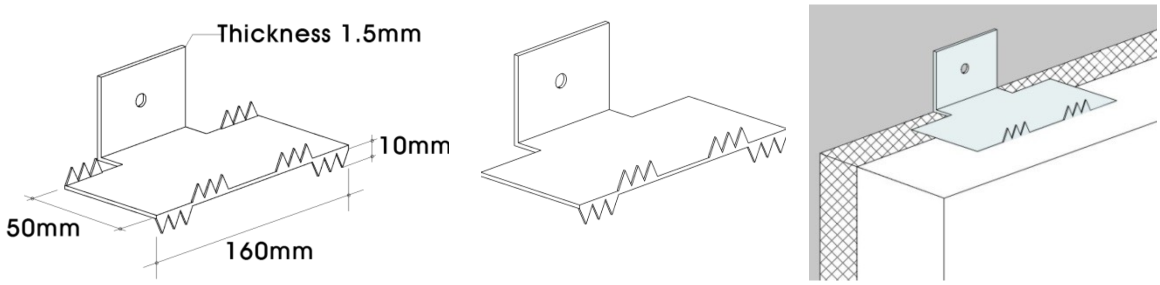


Table 2. Alternatives for mechanically fixed external insulation systems with VIPs.

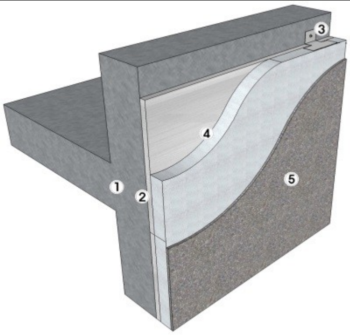
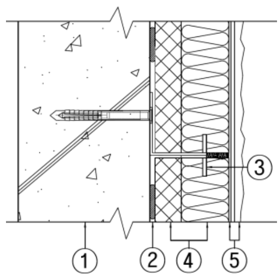
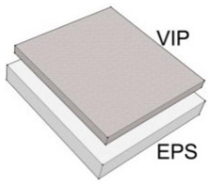
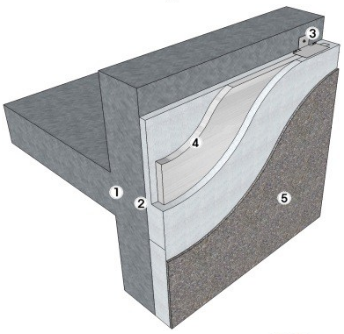
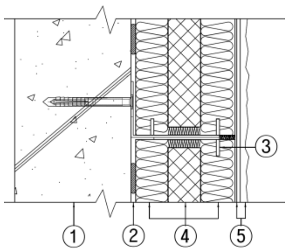
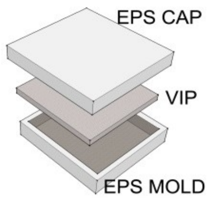
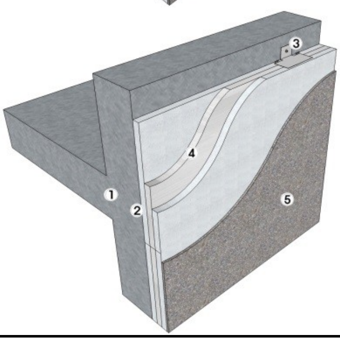
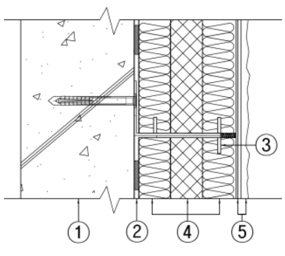
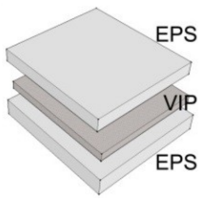
No.	Perspective	Vertical section	Outer wall components	Insulation unit
MF-C2			① Reinforced concrete ② Adhesive ③ Steel fastener ④ Covered-type two-layer insulation unit (VIP + EPS) ⑤ Reinforcing mesh and coat, finish plaster	
MF-E3			① Reinforced concrete ② Adhesive ③ Steel fastener ④ Encapsulated-type three-layer insulation unit (EPS + VIP + EPS) ⑤ Reinforcing mesh and coat, finish plaster	
MF-C3			① Reinforced concrete ② Adhesive ③ Steel fastener ④ Covered-type three-layer insulation unit (EPS + VIP + EPS) ⑤ Reinforcing mesh and coat, finish plaster	

Figure 3. Use of bobbins and dowels for mounting adhesively fixed external insulation systems with VIPs.

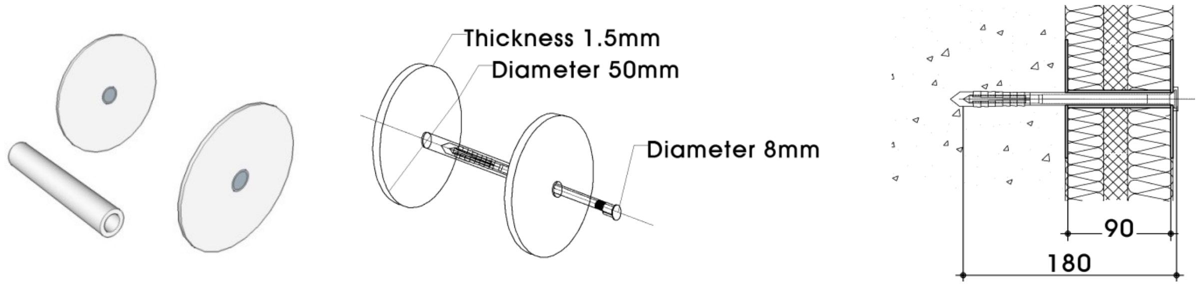
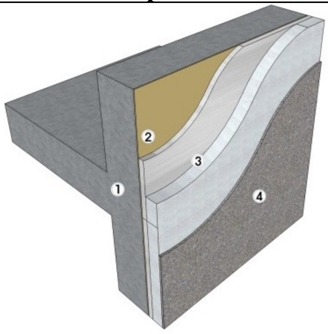
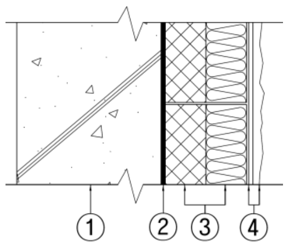
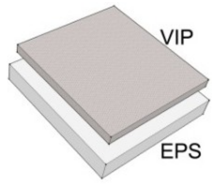
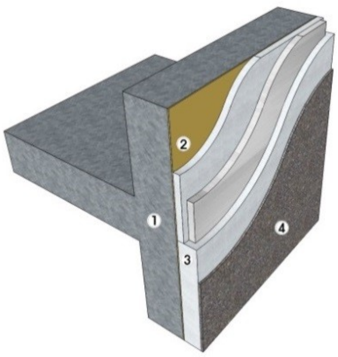
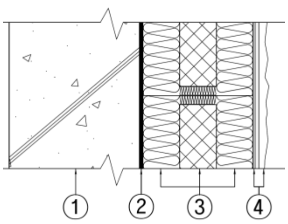
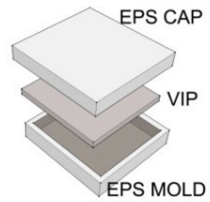
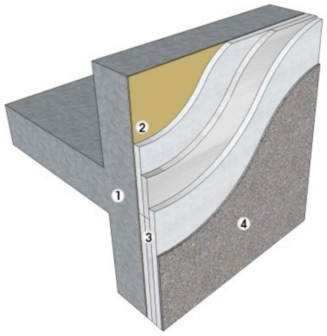
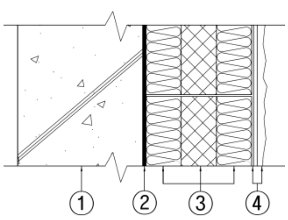
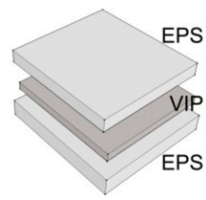


Table 3. Alternatives for adhesively fixed external insulation systems with VIPs.

No.	Perspective	Vertical section	Outer wall components	Insulation unit
AF-C2			① Reinforced concrete ② Adhesive ③ Covered-type two-layer insulation unit (VIP + EPS) ④ Reinforcing mesh and coat, finish plaster	
AF-E3			① Reinforced concrete ② Adhesive ③ Encapsulated-type three-layer insulation unit (EPS + VIP + EPS) ④ Reinforcing mesh and coat, finish plaster	
AF-C3			① Reinforced concrete ② Adhesive ③ Covered-type three-layer insulation unit (EPS + VIP + EPS) ④ Reinforcing mesh and coat, finish plaster	

3.2.2. Parameters of the Insulation Unit Alternatives

The Korean government announced that it seeks to reduce the energy consumption of residential buildings by 60% compared to 2009 levels by 2017 and will require that the energy performance of such buildings matches that of the European Passive House. In this study, the *U*-value used to evaluate the insulation performance of an outer wall was 0.15 $W/m^2 \cdot K$ [17], as required by the Passive House standards. The required thickness of the insulation was calculated to satisfy the U-value requirement of the outer wall for each alternative. Table 4 lists the surface heat transfer coefficients used in the calculations. Table 5 lists the thermal conductivity of each material. The center-of-panel thermal conductivity of VIP was given by the ENERVAC (VIP product name, manufactured by OCI Ltd., Seoul, Korea) properties listed in Table 6, which lists the product specifications of the VIPs. All other material thermal conductivities were from the Code for Energy-efficient Building Design of Korea [18].

Table 4. Boundary conditions.

Location	Temperature (°C)	Surface heat transfer coefficient ($W/m^2 \cdot K$)
Interior	20.0	9.09
Exterior	−11.3	23.25

Table 5. Material properties.

Material	Thermal conductivity (W/m·K)	Material			Thermal conductivity (W/m·K)
Concrete	1.600	Adhesive			0.353
Lightweight concrete	0.130	Reinforcing coat			0.181
Cement mortar	1.400	Finish plaster			0.196
Gypsum board	0.180	Polyvinyl chloride (bobbin)			0.170
Graphite-enhanced expanded polystyrene (EPS)	0.034	VIP	λ_{cop}		0.0045
Expanded polystyrene extruded (XPS)	0.029		λ_{eff}	Thickness 20 mm	5.419×10^{-3}
Wood	0.170			Thickness 25 mm	5.648×10^{-3}
Steel	45.3	–			–

Table 6. VIP specifications (ENERVAC by OCI).

Classification	Content	Classification	Content
Core	Fumed silica	Applied temperature	−200–100 °C
Envelope	Metallized film with aluminum	Maximum size	940 mm × 1650 mm
Thermal conductivity at center of panel	≤0.0045 W/m·K	Thickness	5–40 mm
Degree of vacuum	<5 mbar	Length tolerance	<1,000 mm, ±6 mm ≥1,000 mm, ±10 mm
Density	210 ± 30 kg/m^3	Thickness tolerance	<20 mm, ±1.5 mm ≥20 mm, ±2.0 mm
Fire resistance	Semi-non-combustible	Compression strength	>8 N/cm^2 at thickness of 30 mm

Table 7 lists the insulation unit parameters for both the existing system (conventional internal insulation system) and the alternatives that have the required outer wall *U*-value. The *U*-value for each alternative may not be an exact match because the thicknesses of commercially available insulation products were used. For the covered-type two-layer alternatives (MF-C2 and AF-C2), two configurations (MF-C2-①, ②, AF-C2-①, ②) with different thicknesses for the VIP and EPS layers were tested.

Table 7. Parameters of insulation unit alternatives.

Classification	Components of insulation unit (thickness, mm)	Total insulation thickness (mm)	U-value [(a)] ($W/m^2 \cdot K$)
Existing system	EPS (230)	230	0.141
MF-C2, AF-C2	① VIP (25) + EPS (40)	65	0.141
	② VIP (20) + EPS (70)	90	0.144
MF-E3, AF-E3	EPS (30) + VIP (20) + EPS (40)	90	0.144
MF-C3, AF-C3	EPS (30) + VIP (20) + EPS (40)	90	0.144

Note: [(a)] Thermal bridges are not considered.

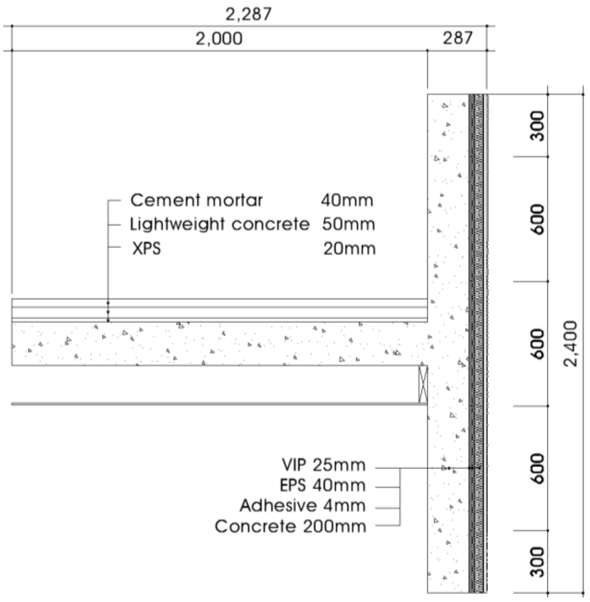
3.3. Performance Evaluation Method

3.3.1. Insulation Performance

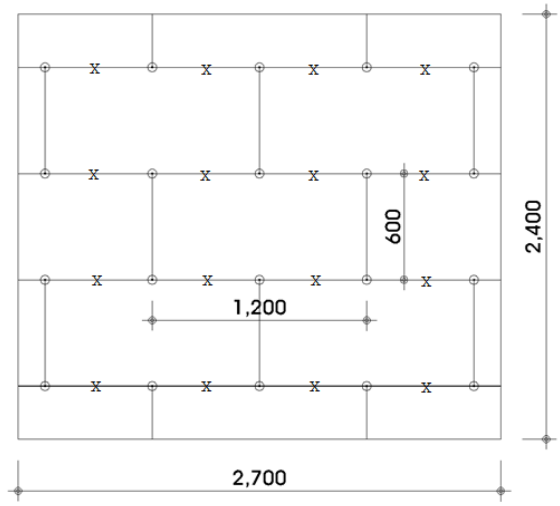
The software TRISCO v. 12.0 (Physibel, Maldegem, Belgium) was used for the three-dimensional, steady-state heat transfer simulations. TRISCO is an analysis program that solves heat balance equations using a finite difference method, and yields highly accurate solutions for problems with complex geometries [19]. The joint between the outer wall and floor structure was modeled in the heat transfer simulation. An insulation unit consisting of a VIP and EPS was assumed to have a width of 1200 mm and a height of 600 mm. As shown in Figures 4 and 5, the area modeled in the heat transfer simulations of the existing system and alternatives had a width (parallel to the x-axis in Figure 5) of 2700 mm, a height (parallel to the y-axis in Figure 5) of 2400 mm, and a depth (parallel to the z-axis in Figure 5) of 2000 mm from the interior side of the outer wall. Both the external and internal surface areas of the heat transfer simulation models were equal for the existing insulation system and alternatives.

The floor structure in the heat transfer simulation model consisted of 40 mm of cement mortar, 50 mm of lightweight concrete, 20 mm of expanded polystyrene extruded (XPS), 210 mm of reinforced concrete slab, and 9.5 mm of gypsum board. The plenum space between the reinforced concrete slab and the gypsum board was considered as an air cavity, which is modeled as an equivalent material with the automatically calculated thermal conductivity in accordance to standards approved by the Commission for European Norms (CEN) [20]. All these materials are widely used in building construction. Figure 4b,c present the locations of the steel fasteners for the mechanically fixed insulation units and the bobbins and dowels for the adhesively fixed insulation units. Figure 5 presents the heat transfer simulation model of the existing system.

Figure 4. Simulated region and boundary: X symbols indicate installation locations of steel fasteners for the mechanically fixed systems, and O symbols indicate installation locations of bobbins and dowels for the adhesively fixed systems. (**a**) Vertical section (AF-C2-①); (**b**) Elevation of the insulation unit installation; (**c**) Simulation model of AF-C2-① (left) and MF-C2-① (right).



(**a**)



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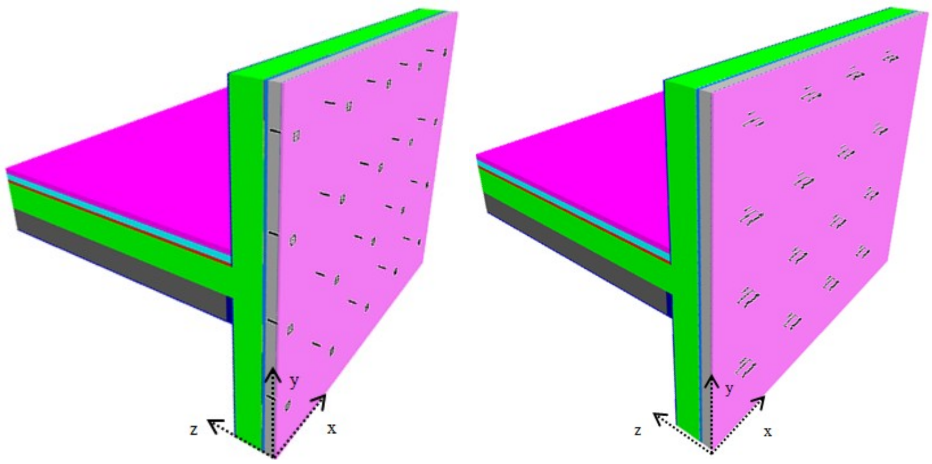
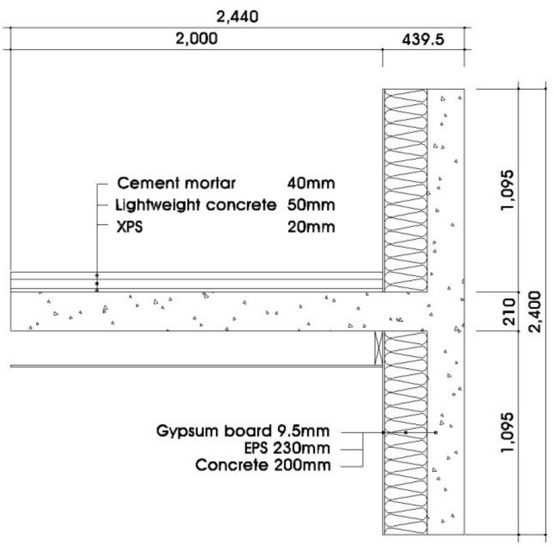


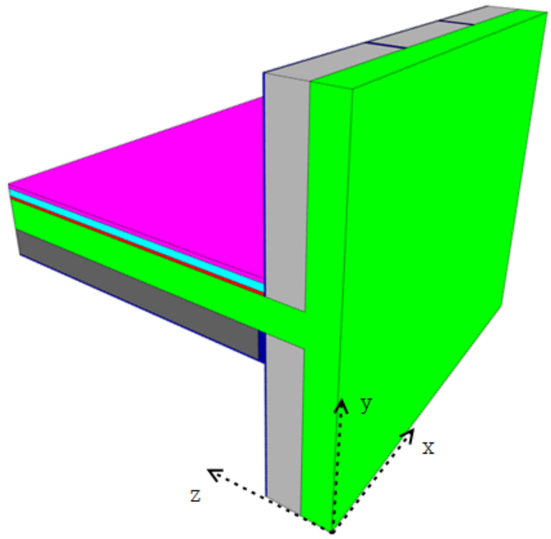
(**c**)

The boundary conditions for the heat transfer simulations were based on the Code for Energy-efficient Building Design of Korea [18] and are listed in Table 6. Table 7 lists the material properties and Table 8 lists the simulation parameters. The effective thermal conductivity was used as the thermal conductivity of the VIP in the heat transfer simulations to reflect the thermal bridging effects at the VIP edges.

Figure 5. Vertical section and simulation model of the existing system. (**a**) Vertical section; (**b**) Simulation model.



(**a**)



(**b**)

Table 8. Simulation parameters.

Parameter	Assigned value
Maximum number of iteration cycles	5
Maximum number of iterations within each iteration cycle	10,000
Maximum temperature difference within each iteration cycle	0.0001 °C
Maximum temperature difference between iteration cycles	0.001 °C
Maximum heat flow divergence for total object	0.001%
Maximum heat flow divergence for any node	1%

The effective thermal conductivity was computed using Equation (1) [4]. The linear thermal transmittance value of 9.19×10^{-3} W/m·K for a metalized barrier with 300 nm of aluminum and small seams folded at the panel edges was obtained from [4], which describes a case that closely matches the envelope of the ENERVAC product. The center-of-panel thermal conductivity of VIP (λcop), 0.0045 W/mK was given by ENERVAC manufacturer (refer to Table 6) and the perimeter (*p*) and area (*A*) were also based on the VIP size of 600 mm × 1200 mm. Two different thicknesses of VIP, 20 mm and 25 mm were applied to calculate the effective thermal conductivity of VIP:

$$\lambda_{eff} = \lambda_{cop} + \psi_{vip} \cdot d \cdot p/A \quad (1)$$

where λ_{eff} is the effective thermal conductivity (W/m·K), λ_{cop} is the thermal conductivity at the center of the panel (W/m·K), ψ_{vip} is the linear thermal transmittance (W/m·K), *d* is the thickness of the VIP in the heat flow direction (m), p is the perimeter of the panel surface (m), and *A* is the surface area of the VIP perpendicular to the heat flow direction (m^2).

3.3.2. Construction Costs and Ease of Installation

For the existing system and all the alternatives, the construction costs per unit area of the outer wall were estimated by determining the material and labor costs of constructing a 10 m × 10 m wall structure. The assumptions for the estimate of the construction costs are the following:

- Costs related to insulation and finish work are estimated;
- Material costs are based on retail prices. Costs of general materials are based on the price information provided in [20]. Costs of special materials are based on the current market prices;
- The labor cost of each job is estimated based on the standards of construction estimates and the square-meter costs for workers [21];
- The taxes and miscellaneous administrative costs are not included. Costs of temporary structures (scaffolding and stepping plates) are not included.

Because each alternative differs in the amount of exposure of the VIPs, the number of construction steps, and the constructability, the ease of installation of each alternative was evaluated based on the productivity and handling of the insulation units, the construction process, and the constructability.

4. Evaluation Results

4.1. Insulation Performance

Tables 9 and 10 present the simulated temperature distributions and list the insulation performance evaluation results of the existing system and the mechanically and adhesively fixed external insulation systems with VIPs. The elliptical patterns in the temperature distributions for the mechanically fixed alternatives correspond to the locations of the steel fasteners (refer to Figures 2, 4b,c and 6a) and the circular patterns in the temperature distributions correspond to the locations of the bobbins and the dowels for the adhesively fixed alternatives (refer to Figures 3, 4b,c and 6b).

Table 9. Evaluation results for mechanically fixed external insulation systems with VIPs.

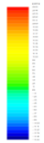
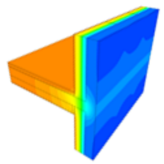
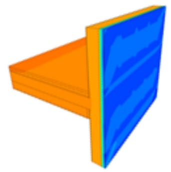
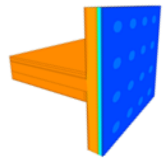
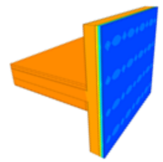
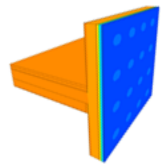
Specifications			**Existing system**	**MF-C2-①**	**MF-C2-②**	**MF-E3**	**MF-C3**
Temperature distribution	20 °C  −11.3 °C						
Insulation performance	U-value [(a)] (W/m²·K)		0.141	0.141	0.144	0.144	0.144
	Components of insulation unit (mm)		EPS (230)	VIP (25) EPS (40)	VIP (20) EPS (70)	EPS (30) VIP (20) EPS (40)	EPS (30) VIP (20) EPS (40)
	Heat loss (W)		80.3	39.5	36.0	40.9	36.7
	Decrease rate (%)		0	−51	−55	−49	−54
	Performance ranking [(b)]		–	★★	★★★★	★★	★★★★
Construction costs	Material (KRW/m²)	Insulation	25,600	90,975	80,475	92,445	83,445
		Finish	9,976	21,470	21,470	21,470	21,470
		Sum	35,576	112,445	101,945	113,915	104,915
	Labor (KRW/m²)	Insulation	4,877	14,371	15,127	10,590	12,102
		Finish	8,953	10,673	10,673	10,673	10,673
		Sum	13,830	25,044	25,800	21,264	22,776
	Total costs (KRW/m²)		49,406	137,489	127,745	135,178	127,691
	Increase rate (%)		0	+178	+159	+174	+158
	Performance ranking [(b)]		–	★	★★★★	★★	★★★★

Table 9. *Cont.*

Specifications		Existing system	MF-C2-①	MF-C2-②	MF-E3	MF-C3
Ease of installation	Productivity and handling of the insulation unit	• Handling of the insulation material is difficult due to the EPS thickness of 230 mm	• Thick VIP, higher cost • Must minimize size discrepancies between the VIP and EPS • Risk of damaging the front side and edges of the VIP during handling	• Must minimize size discrepancies between the VIP and EPS • Risk of damaging the front side and edges of the VIP during handling • Poor handling compared to MF-C2-① due to the increased EPS thickness	• EPS mold encapsulating entire VIP is costly • Low risk of damaging the VIP because of the encapsulation by EPS	• Must minimize size discrepancies between the VIP and EPS • Risk of damaging the edges of the VIP during handling
		–	★★	★	★★★★	★★★
	Construction process	1. Attach insulation material 2. Install gypsum board 3. Finish	1. Surface treatment 2. Attach insulation unit 3. Install fastener 4. Finish	1. Surface treatment 2. Attach insulation unit 3. Install fastener 4. Finish	1. Attach insulation unit 2. Install fastener 3. Finish	1. Attach insulation unit 2. Install fastener 3. Finish
		–	★★	★★	★★★★	★★★★
	Constructability	• Conventional construction method • Simple installation	• Surface treatment is necessary because the VIP is directly attached to the concrete wall • Caution required when installing fasteners because the front side and edges of the VIP are exposed • Insulation unit fixed using adhesive for the VIP	• Surface treatment is necessary because the VIP is directly attached to the concrete wall • Caution required when installing fasteners because the front side and edges of the VIP are exposed • Insulation unit fixed using adhesive for the VIP	• Same installation method as the conventional external insulation system • Simple installation • Low risk of damaging the VIP because the VIP is not exposed • Insulation unit fixed using adhesive for the EPS	• Caution required when installing fasteners because VIP edges are exposed • Insulation unit fixed using adhesive for the EPS
		–	★★	★★	★★★★	★★★
	Performance ranking	–	★★	★	★★★★	★★★

Notes: [(a)] Thermal bridges are not considered; [(b)] Considering uncertainties in the simulations and estimations, the same number of stars was given to the alternatives when the differences were not large. ★★★★ = first, ★★★ = second, ★★ = third, ★ = fourth, 1050 KRW = 1 USD.

Table 10. Evaluation results for adhesively fixed external insulation systems with VIPs.

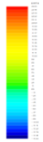
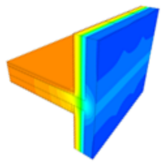
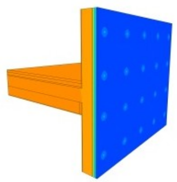
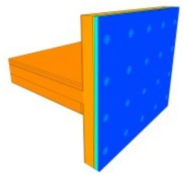
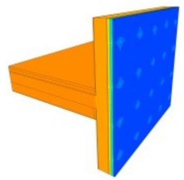
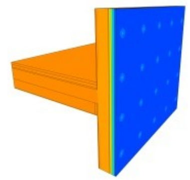
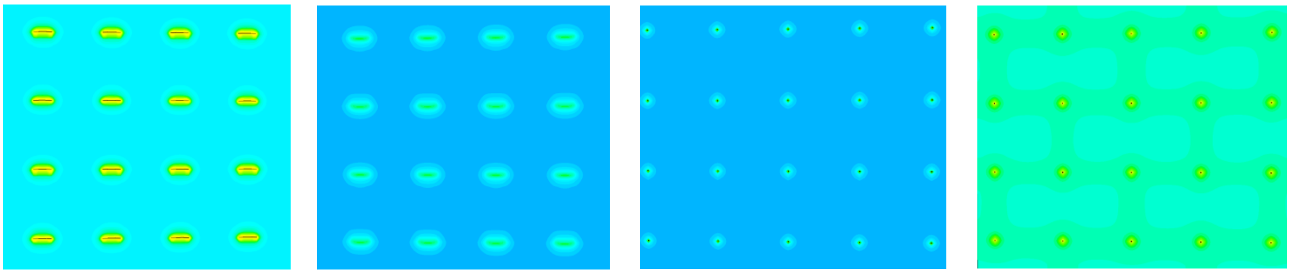
Specifications			**Existing system**	**AF-C2-①**	**AF-C2-②**	**AF-E3**	**AF-C3**
Temperature distribution	20 °C  −11.3°C						
Insulation performance	U-value [(a)] (W/m²·K)		0.141	0.141	0.144	0.144	0.144
	Components of insulation unit (mm)		EPS (230)	VIP (25) EPS (40)	VIP (20) EPS (70)	EPS (30) VIP (20) EPS (40)	EPS (30) VIP (20) EPS (40)
	Heat loss (W)		80.3	36.7	35.7	38.0	34.0
	Decrease rate (%)		0	−54	−56	−53	−58
	Performance ranking [(b)]		–	★★	★★★★	★★	★★★★
Construction costs	Material (KRW/m²)	Insulation	25,600	93,105	82,605	88,834	85,534
		Finish	9,976	21,470	21,470	21,470	21,470
		Sum	35,576	114,575	104,075	110,305	107,005
	Labor (KRW/m²)	Insulation	4,877	13,615	14,371	9,834	11,346
		Finish	8,953	10,673	10,673	10,673	10,673
		Sum	13,830	24,288	25,044	20,508	22,020
	Total costs (KRW/m²)		49,406	138,863	129,119	130,812	129,024
	Increase rate (%)		0	+181	+161	+165	+161
	Performance ranking [(b)]		–	★	★★★★	★★	★★★★

Table 10. *Cont.*

Specifications		Existing system	AF-C2-①	AF-C2-②	AF-E3	AF-C3
Ease of installation	Productivity and handling of the insulation unit	• Refer to Table 9	• Refer to Table 9 • Pre-cutting for bobbin installation required	• Refer to Table 9 • Pre-cutting for bobbin installation required	• Refer to Table 9	• Refer to Table 9 • Pre-cutting for bobbin installation required
		–	★★	★	★★★★	★★★
	Construction process	• Refer to Table 9	• Refer to Table 9 and install bobbin and dowel instead of fastener	• Refer to Table 9 and install bobbin and dowel instead of fastener	• Refer to Table 9 and install bobbin and dowel instead of fastener	• Refer to Table 9 and install bobbin and dowel instead of fastener
		–	★★	★★	★★★★	★★★
	Constructability	• Refer to Table 9	• Refer to Table 9 and install dowels instead of fasteners	• Refer to Table 9 and install dowels instead of fasteners	• Refer to Table 9 and install dowels instead of fasteners • No need for bobbins	• Refer to Table 9 and install dowels instead of fasteners
		–	★★	★★	★★★★	★★★
	Performance ranking	–	★★	★	★★★★	★★★

Notes: (a) Thermal bridges are not considered; (b) Considering uncertainties in the simulations and estimations, the same number of stars was given to the alternatives when the differences were not large. ★★★★ = first, ★★★ = second, ★★ = third, ★ = fourth, 1050 KRW = 1 USD.

Figure 6. The temperature distributions of MF-C2-① and AF-C2-①. (**a**) Around steel fasteners of MF-C2-①; (**b**) Around bobbins and dowels of AF-C2-①.



(**a**) (**b**)

If assuming that there is no thermal bridge at all, heat loss of existing system was 28.6 W calculated with *U*-value (0.141 W/m^2·K), wall surface area perpendicular to the heat flow direction (2700 mm × 2400 mm), and temperature difference between interior and exterior (31.3 °C). Simulated heat loss of existing system was 80.3 W. Linear thermal transmittance of existing system was 0.58 W/m·K, based on additional two-dimensional heat transfer simulation in accordance with ISO 10211: 2007 [22]. This result indicates that the heat loss due to the thermal bridge at the joint between the outer wall and the floor structure in the existing system was very large when the insulation performance of the outer wall was very high, which confirms that external insulation is essential.

Although the U-values were similar, the mechanically fixed alternatives reduced the heat loss by 49%–55% (39.4–44.3 W) compared with the existing system, and the adhesively fixed alternatives reduced the heat loss by 53%–58% (42.3–46.3 W). The explanation for these improvements is that the thermal bridge at the joint between the outer wall and the floor structure that was present in the existing system was eliminated, reducing the heat loss.

The heat losses of the mechanically fixed alternatives can be ranked as follows: MF-C2-② < MF-C3 < MF-C2-① < MF-E3. Alternative MF-C2-② had the best insulation performance. Similarly, the heat losses of the adhesively fixed alternatives can be ranked as follows: AF-C3 < AF-C2-② < AF-C2-① < AF-E3. Alternative AF-C3 had the best insulation performance. For C2-① and C2-②, the two-layer insulation units with different thickness of the VIP and EPS layers, C2-② with a thin VIP and a thick layer of EPS showed better performance for both the mechanically and adhesively fixed alternatives. Therefore, increasing the heat-flow path by increasing the total insulation thickness is advantageous when a VIP and conventional insulation are applied as an insulation unit.

For E3 and C3, which had three-layer insulation units consisting of EPS-VIP-EPS layers and differed in the way that EPS surrounds the VIP, C3 (VIP covered by EPS on the front and back sides) performed better than E3 (VIP encapsulated by EPS) for both the mechanically and adhesively fixed alternatives. The discontinuity of the VIP at the joint of the encapsulated-type insulation unit resulted in a localized reduction of the thermal resistance, which led to E3 performing worse than C3. Among the mechanically fixed alternatives consisting of VIP and EPS with the same insulation unit thicknesses, MF-C2-② performed better than MF-E3 and MF-C3. All of these alternatives used steel fasteners to fix the insulation unit in place. This was performed by driving wedges through the center of the EPS. Because the EPS thickness for MF-C2-② on the exterior side was the thickest among the alternatives, the length of the steel fastener in the z-axis (refer to Figure 5b) was the shortest. This reduced length led to lower heat transfer through the steel fastener, which is a strong thermal conductor, and improved its insulation performance.

The mechanically fixed alternatives exhibited heat losses that were 1%–8% greater than those of the adhesively fixed alternatives of the same type. This result indicates that the adhesively fixed method of attachment can provide slightly better insulation performance.

4.2. Construction Costs and Ease of Installation

Tables 9 and 10 list the evaluation results of the existing system and the alternatives with regard to the construction costs and ease of installation. Compared to the existing system, the construction costs of the mechanically fixed alternatives were 158%–178% higher and those of the adhesively fixed alternatives were 161%–181% higher. The high cost of VIPs was the main cause for these higher values. The construction costs of the mechanically fixed alternatives were in the following order: MF-C3 < MF-C2-② < MF-E3 < MF-C2-①. Alternative MF-C3 had the lowest construction costs. The construction costs of the adhesively fixed alternatives were in the following order: AF-C3 < AF-C2-② < AF-E3 < AF-C2-①. Alternative AF-C3 had the lowest construction costs. The material costs depend heavily on the thickness of the VIPs. The following factors also affect the material costs: the requirement for an EPS mold to encapsulate the VIP, the amount of adhesive between the VIPs and EPS, the necessity for pre-cutting to install bobbins when fabricating insulation units, the type of adhesive used to attach the insulation units, and whether bobbins are used when installing the insulation units. The labor costs are typically affected by the number of construction processes and the constructability, and the labor costs are considerably lower than the material costs. Alternatives MF-C3 and AF-C3 had the lowest construction costs for the following reasons: the VIP is thinner, no EPS mold is necessary, a conventional adhesive for EPS can be used to attach the insulation units, and no additional surface treatment process is required because EPS attaches directly to the concrete wall.

The material costs of the mechanically fixed alternatives were 2% lower than those of the adhesively fixed alternatives of the same type because the latter required pre-cutting of the insulation units and the installation of bobbins. The material costs of MF-E3 were only higher (by 3%) than those of AF-E3 for the E3 types because AF-E3 does not require bobbins even though it is adhesively fixed. Because all mechanically fixed alternatives require the installation of steel fasteners, which is labor intensive, the labor costs of the mechanically fixed alternatives were 3%–4% higher than those of the adhesively fixed alternatives of the same type. All mechanically fixed alternatives except MF-E3 had slightly lower total construction costs than the adhesively fixed alternatives of the same type; MF-E3 had slightly higher total construction costs, but the difference was insignificant.

In terms of the ease of installation, MF-E3 and AF-E3, in which the VIP is completely surrounded with EPS and thus protected, had the best performance for the following reasons: there is a low risk of damage to the VIPs during handling and installation, there is no requirement for surface treatment prior to installation, and the same installation method as with conventional external insulation systems can be used. In addition, AF-E3 had the advantage of not requiring bobbins. The ease of installation of MF-C2-①, MF-C2-②, AF-C2-①, and AF-C2-② were lower than those of the other alternatives because the front side and edges of the VIPs are exposed, and thus, they required special care during handling and installation to prevent damage; in addition, surface treatment prior to installation is required. Compared with MF-C2-①, MF-C2-②, AF-C2-①, and AF-C2-②, MF-C3 and AF-C3 have a lower risk of damage because only the edges of the VIPs are exposed; however, they still require care during handling and installation. Alternatives MF-C3 and AF-C3 do not require surface treatment prior to installation. Because drilling is required to install the dowels in the adhesively fixed alternatives, care must be taken during installation to prevent damage to the VIPs.

4.3. Case Study of the Alternatives' Effectiveness Based on the Authors-Defined Points and Weights

Each alternative was given a ranking point (number of stars) based on three performance measures: insulation performance, construction costs, and ease of installation. The ranking points were then weighted to calculate the overall performance score of each alternative. Overall performance score A used the same weight of 33.3% on all three performance measures. Overall performance score B emphasized the insulation performance by placing a 50% weight on the insulation performance ranking point and a 25% weight on the construction cost and ease of installation points. Overall performance score C emphasized the construction costs by placing a 50% weight on the construction cost ranking point and a 25% weight on the insulation performance and ease of installation points. Overall performance score D emphasized the ease of installation by placing a 50% weight on the ease of installation ranking point and a 25% weight on the insulation performance and construction cost points. Table 11 presents the results. The mechanically and adhesively fixed alternatives with a covered-type three-layer insulation unit (MF-C3 and AF-C3) were determined to be the most effective alternatives according to overall performance scores A–D. Table 11 lists the overall performance scores based on the points and weights defined by the authors as a case study. We did not intend to optimize the points and weights of each performance. The points and weights of each performance can be freely modified according to the needs of the readers.

Table 11. Overall performance score according to the importance of each performance.

Specifications		Mechanically fixed				Adhesively fixed			
		MF-C2-①	MF-C2-②	MF-E3	MF-C3	AF-C2-①	AF-C2-②	AF-E3	AF-C3
Point of each performance measure	Insulation performance	2	4	2	4	2	4	2	4
	Construction costs	1	4	2	4	1	4	2	4
	Ease of installation	2	1	4	3	2	1	4	3
Overall performance score	A	1.7	3.0	2.7	3.7	1.7	3.0	2.7	3.7
	B	1.8	3.3	2.5	3.8	1.8	3.3	2.5	3.8
	C	1.5	3.3	2.5	3.8	1.5	3.3	2.5	3.8
	D	1.8	2.5	3.0	3.5	1.8	2.5	3.0	3.5

5. Conclusions

This study investigated the thermal performance of mechanically and adhesively fixed external insulation systems using VIPs, which can drastically reduce the insulation thickness and eliminate thermal bridges in structural joints for high-rise apartment buildings. Each alternative was evaluated in terms of the insulation performance, construction costs, and ease of installation, and the overall performance was determined using a weighted sum of the three performance scores. The conclusions may be summarized as follows:

(1) Although the U-values of the outer walls were similar, the mechanically fixed alternatives reduced the heat loss by 49%–55% (39.4–44.3 W) compared with the existing system, and the adhesively fixed alternatives reduced the heat loss by 53%–58% (42.3–46.3 W). These results indicate that the heat loss due to the thermal bridge at the joint between the outer wall and floor structure in the existing system was large when the insulation performance of the outer wall was high, which confirms that the application of external insulation is essential.

(2) For the mechanically fixed alternatives, MF-C2-②, which was the covered-type two-layer insulation unit consisting of a thin VIP and a thick layer of EPS, had the best insulation performance. For the adhesively fixed alternatives, AF-C3, which was the covered-type three-layer insulation unit (EPS-VIP-EPS), exhibited the best insulation performance. For the alternatives with the covered-type two-layer insulation units, increasing the heat flow path by increasing the total insulation thickness provided better insulation performance. Because the mechanically fixed alternatives exhibited greater heat loss (1%–8%) than the adhesively fixed alternatives of the same type, the latter is advantageous in terms of achieving better insulation performance.

(3) Compared to the existing system, the construction costs of the mechanically and adhesively fixed alternatives were 158%–178% higher and 161%–181% higher, respectively. The high cost of VIPs was the main cause of these higher values. Alternatives MF-C3 and AF-C3 with the covered-type three-layer insulation units had the lowest construction costs. Most of the mechanically fixed alternatives had slightly lower construction costs than the adhesively fixed alternatives of the same type, but the differences were insignificant.

(4) Alternatives MF-E3 and AF-E3, which encapsulated the entire VIP with EPS to protect the VIP, had the greatest ease of installation. These units had a lower risk of damage to the VIPs during handling and installation, they did not require surface treatment prior to installation, and the installation method was the same as that used for conventional external insulation systems. In addition, AF-E3 had the advantage of not requiring bobbins to prevent damage to the VIPs.

(5) Each alternative was ranked based on its insulation performance, construction costs, and ease of installation. The overall performance of each alternative was evaluated with various weights placed on the three performance ranking points. Based on the authors-defined points and weights, the results indicated that MF-C3 and AF-C3, which were the covered-type three-layer insulation units, were the most effective.

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Author Contributions

Sihyun Park and Seung-Yeong Song performed the simulation and wrote the manuscript. Bo-Hye Choi and Jae-Han Lim researched the construction methodology. All authors read and approved the final manuscript for the publication and edited.

Conflicts of Interest

The authors declare no conflict of interest.

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