Thermal Insulation of Buildings: A Synthesis of Approaches and Innovative Materials

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Preface

Thermal insulation has become a major concern in the sustainable design of buildings. As energy performance requirements grow increasingly stringent, it is essential for stakeholders in the construction sector including engineers, architects, educators, researchers, and students to master both the **scientific foundations** and the **technical solutions** related to insulation.

This book offers a **clear, structured, and accessible synthesis** of the essential concepts surrounding thermal insulation in buildings. It highlights classical approaches (such as internal insulation) while placing significant emphasis on **innovative materials** and **sustainable practices** emerging in the field.

Based on a **rigorous bibliographic study**, this work aims to provide a **solid knowledge base** for those seeking to **deepen their understanding of this technical and scientific domain**, which lies at the crossroads of energy efficiency, occupant comfort, and environmental sustainability.

It is primarily intended for **students**, **educators**, **building professionals**, and **researchers** who wish to gain a **synthetic, up-to-date, and critical overview** of thermal insulation techniques.

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General Introduction

In the face of growing challenges posed by **climate change** and the **progressive depletion of energy resources**, energy efficiency has become a global priority. The building sector alone accounts for a **significant share of global energy consumption**, primarily due to heating, cooling, and ventilation demands. In this context, improving the **thermal performance of buildings** has become an environmental, economic, and social imperative.

Thermal insulation stands out as one of the most effective strategies for **reducing energy loss, limiting greenhouse gas emissions**, and **ensuring long-lasting thermal comfort** regardless of external weather conditions. It is a key **pillar of bioclimatic architecture** and a central component of any sustainable construction strategy.

To design thermally efficient buildings, it is essential to **understand the mechanisms of heat transfer**, **master the various insulation methods**, and **evaluate the properties of insulating materials**, especially those emerging from recent technological advancements and eco-friendly approaches.

This book aims to provide a **comprehensive scientific and technical synthesis** on thermal insulation in buildings. It is intended to support:

- **Students**, by offering solid theoretical and practical foundations;
- **Researchers**, through a structured state-of-the-art overview;
- **Professionals**, by presenting high-performance and applicable solutions.

The content is organized in a **pedagogical sequence**: it begins with the **fundamental principles of heat transfer**, then explores **thermal insulation techniques** and **various types of insulating materials** (traditional, bio-based, and innovative). Special attention is given to **External Thermal Insulation (ETI)**, which is considered one of the most effective and durable approaches in building design.

Finally, the book concludes with a **synthesis of ETI techniques** specifically adapted for **reinforced concrete structures**, supported by real-world examples, with the goal of providing a **complete, current, and practical** understanding of the topic.

Chapter I: Fundamental Principles of Heat Transfer

1.1 General theory of heat exchange

Temperature indicates the speed rate of agitation of the elementary particles in matter. Between two bodies with different temperatures, heat flow inevitably occurs, with heat moving from the hot body to the cold one until temperature equilibrium is reached (Eyrolles, 1977, p. 11). There is no way to prevent the exchange of heat; only its intensity can be altered.

1.2 Modes of heat transfer

Heat is exchanged through three fundamental modes: conduction, convection and radiation.

1.2.1 Conduction

Heat transfer by **conduction** is an exchange of energy that occurs without the movement of matter, thus involving solids and immobilized fluids (Venkateshan, 2021, p. 9). This transfer can occur within a single body or through contact between two bodies. It involves the movement of free electrons within the crystalline lattice for solids (metals) and the transmission of kinetic energy through collisions between molecules for fluids.

The general equation for thermal conduction through a material is given by Fourier's law:

$$\vec{\Phi} = -\lambda \overrightarrow{\mathrm{grad}}\mathrm{T} = -\lambda S \frac{\mathrm{dT}}{\mathrm{dx}} \tag{I. 1}$$

Where:

- $\boldsymbol{\lambda}$ **:** Thermal conductivity of the material [W/m. K];
- $\boldsymbol{S}$: Surface through which the heat propagates [m²];
- $\boldsymbol{\Phi}$ **:** Heat flux through the surface [W];
- $\frac{\mathbf{dT}}{\mathbf{dx}}$ **:** Temperature gradient across the material [K/m].

1.2.2 Convection

Convection is a heat transfer that occurs in a material medium with the movement of matter (Mergui, 2024, pp. 3-4). This phenomenon occurs in fluid medium (liquids or gases) or between the interface of a solid wall and a moving fluid. Two types of convection are distinguished:

Natural Convection (free): movements are due to variations in density in a fluid subjected to the gravitational field. Density variations can be generated by temperature gradients (hot air is lighter than cold air).

Forced Convection: fluid movement is caused by external mechanical actions (pump, fan, etc.).

Mixed Convection combines both modes of convection mentioned above equally.

In the case of heat transfer between a fluid and a solid (Figure I.1), the thermal flux exchanged between the surface and the moving fluid is given by Newton's law:

$$\Phi = \mathrm{hS}(\mathrm{Tp} - \mathrm{Tf}) \qquad (\mathrm{I.2})$$

Where:

- **Tp** : Solid wall temperature [K];
- **S**: Surface area through which heat is transferred [m²];
- **Tf** : Temperature of the surrounding fluid [K];
- **Φ** : Heat flux through the wall [W];
- **h**: Convection heat transfer coefficient [W/m². K].

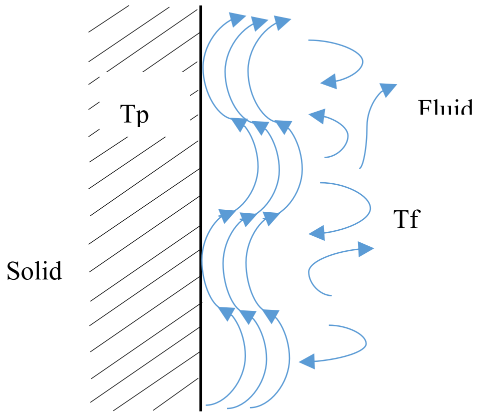


Figure I.1. *Convection between a solid and a fluid interface. Author source*

1.2.3 Radiation

Every solid and liquid object releases energy from its surfaces as electromagnetic waves. If **radiated energy** encounters a body absorbing these wavelengths, it is transformed into heat (Eyrolles, 1977, p. 11). This transfer requires no material support, and occurs even in a vacuum. (Example: the sun heats the earth by radiation).

The general equation for thermal radiation is Stefan-Boltzmann's law (Mergui, 2024, p. 7):

$$\Phi = S\varepsilon\sigma T^4 \tag{I.3}$$

Where:

- **S**: Emissive surface [m²];
- **ε**: body emissivity ($0 < \varepsilon \leq 1$) dimensionless;
- **Φ** : Radiant heat flux [W];
- **T** : Absolute temperature of the emissive surface [K];
- **σ**: Stefan-Boltzmann's constant (≈ $5{,}6703 \times 10^{-8}$ [W m^{-2} K^{-4}]).

The heat transfer modes referred above (conduction, convection and radiation) can be summarized in Figure I.2.

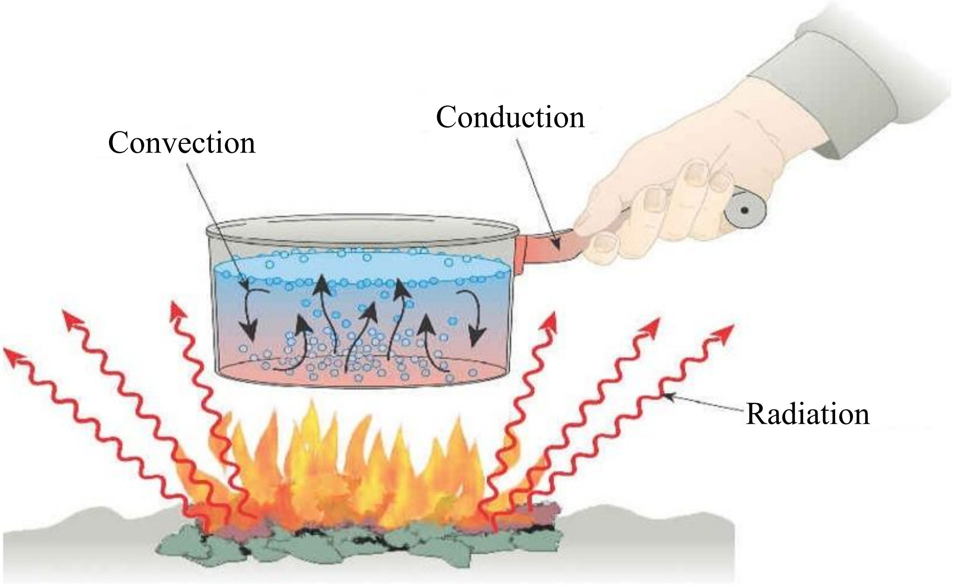


Figure I.2. *Main modes of heat transfer. Source : (Verschaere, 2016)*

1.3 Heat flux

Flux of heat (symbol Φ), represents the quantity of heat (Q) exchanged per unit of time [t], (Eyrolles, 1977, p. 12) :

$$\Phi = \frac{Q}{t} \tag{I.4}$$

It expresses an energy per unit of time, i.e. a power, and is measured in watts [W].

For calculating heat losses in buildings, it is convenient to relate the heat flux to unit area S. This ratio is called the flux density (symbol φ) :

$$\varphi = \frac{\Phi}{S} \tag{I.5}$$

The flux density is measured in watts per square meter: $[\mathrm{W} / \mathrm{m}^2]$.

1.4 Thermal conductivity coefficient

Thermal conductivity (noted λ) of a material (Eyrolles, 1977, p. 13) is defined as the amount of heat flux passing through it per meter of thickness for a temperature difference of 1°C between the two faces (Figure I.3).

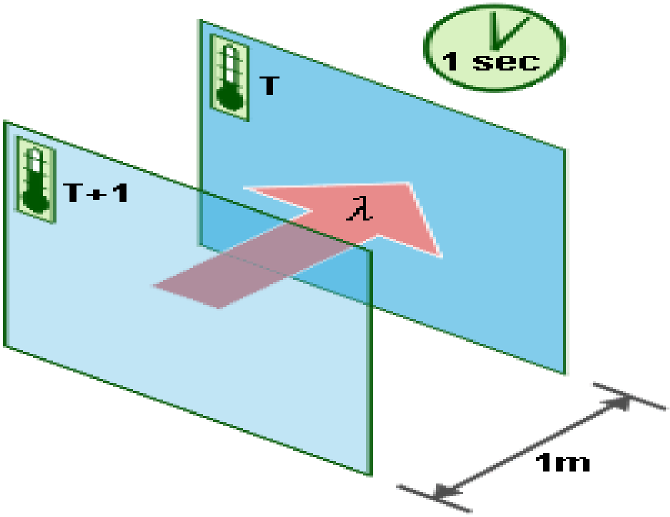


Figure I.3. *Thermal conductivity of a body. Source : (Apere asbl, 2021)*

1.5 Heat exchange between two environments separated by a wall

The phenomenon of heat exchange between two environments (indoor and outdoor) of different temperatures (Ti> Te), separated by a wall, takes place as follows (Eyrolles, 1977, p. 14):

Heat from the indoor environment is transferred to the wall through radiation and convection. Within the wall, it moves via conduction before being released back into the outside environment through radiation and convection (Figure I.4).

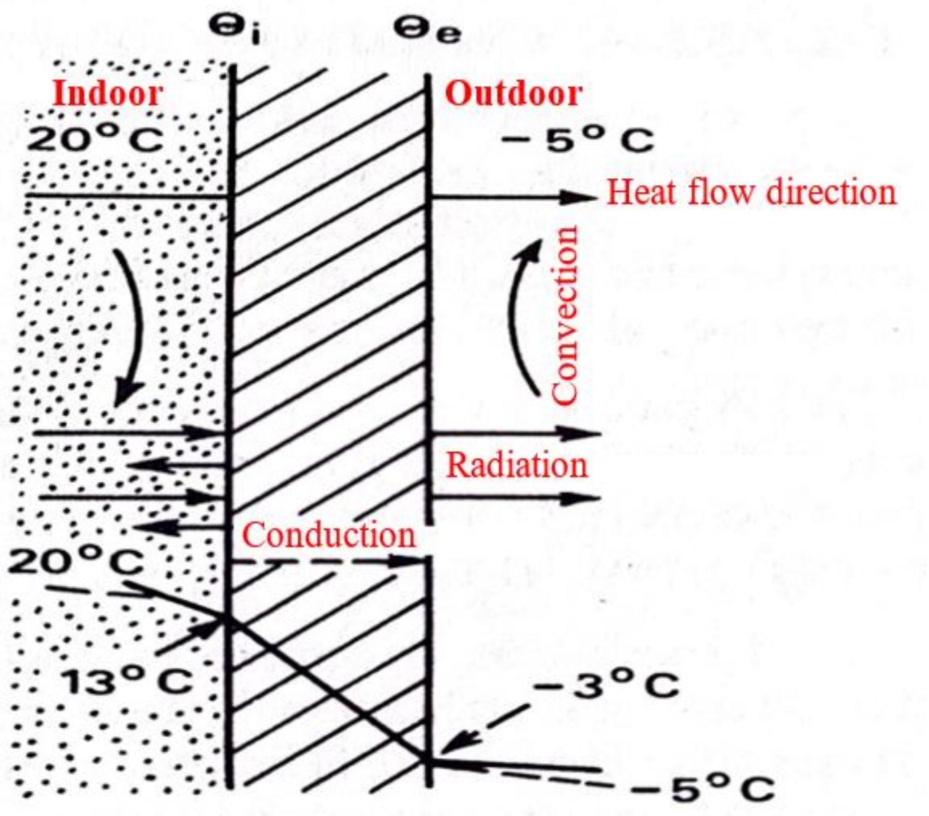


Figure I.4. *Heat exchange between two environments separated by a wall. (Eyrolles, 1977)*

Inside the wall, the temperature is **not uniform**.

In a homogeneous wall, it decreases steadily from the inner face to the outer face.

1.6 Heat flux density equation through a wall

1.6.1 Case of a single plate

Consider a portion of 1m² in the center of a very large wall made of a **homogeneous material**, both sides of the wall maintain surface temperatures (θ_i and θ_e) intermediate, that are between the ambient temperatures (Eyrolles, 1977, p. 15).

The temperature variance generates a heat flux directed from θ_i to θ_e ($\theta_i > \theta_e$). The density of this flux is directly proportional to the temperature difference and inversely proportional to the thermal resistance of the wall:

$$\varphi = \frac{\theta_i - \theta_e}{R_u} = \frac{\theta_i - \theta_e}{\frac{e}{\lambda}} \qquad (I.6)$$

Where:

- **e**: Thickness of material [m];
- $\mathbf{R_u}$: Thermal resistance of the wall [m². °C/W];
- $\boldsymbol{\theta_i}$ and $\boldsymbol{\theta_e}$: Internal and external surface temperatures of the wall [°C].

1.6.2 Case of juxtaposed plates

If the wall consists of parallel plates made of different materials, the thermal resistances of each plate add up to resist the passage of the heat flux:

$$\varphi = \frac{\theta_i - \theta_e}{R_{u1} + R_{u2} + R_{u3} + \cdots + R_{un}} = \frac{\theta_i - \theta_e}{\sum Ru} = \frac{\theta_i - \theta_e}{\sum \frac{e}{\lambda}} \qquad (I.7)$$

1.7 Thermal loss of an uninsulated dwelling

According to ADEME (Environment and Energy Management Agency), heat escapes from an uninsulated detached house (Figure I.5) 25 to 30% through the roof, 20 to 25% across the walls, 20 to 25% over ventilation, 10 to 15% along windows and exterior doors, 7 to 10% by floor (or ground) and 5 to 10% by thermal bridges (Virdi & Waters, 2017, pp. 87-88).

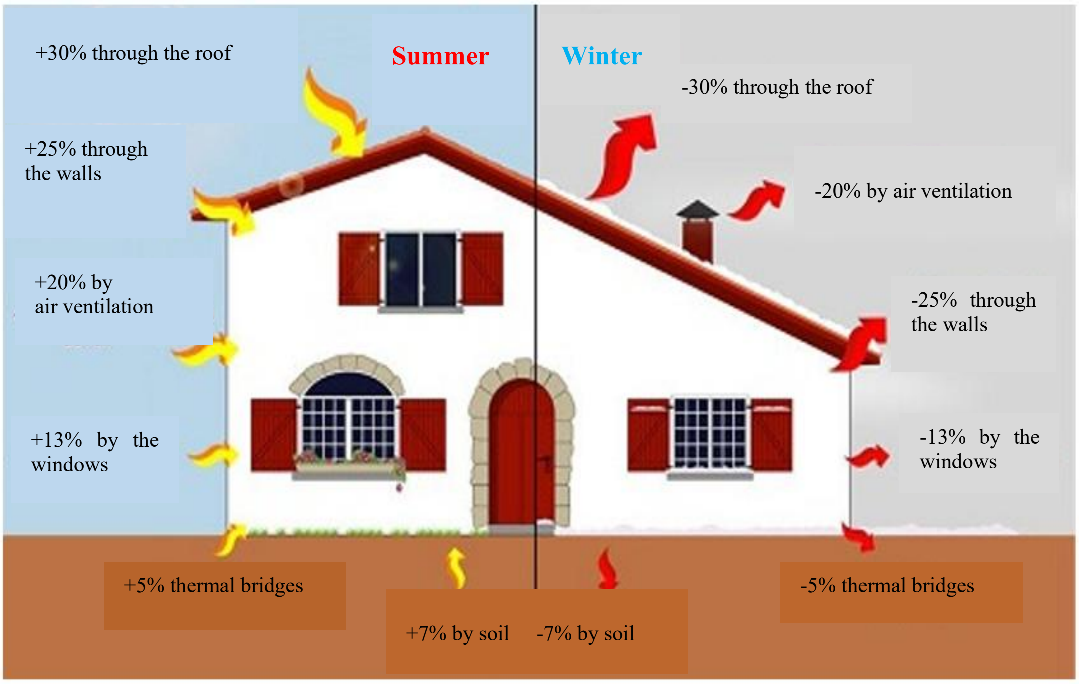


Figure I.5. *Thermal losses in winter and summer of an uninsulated dwelling. Source : (Francis , 2020)*

Chapter II: Fundamentals of Thermal Insulation in Buildings

2.1 Definition and principles

Thermal insulation (Beaumier & Janin, 2017) refers to all the techniques used to limit heat transfer between a hot and a cold environment. The term « **thermal insulation** » can be found in many fields. It is used in construction, industry, automotive industry, cold storage, kitchen and textiles (Matheswaran, Arjunan, & Selvaraj, 2023). In the case of buildings, thermal insulation can consist of a (single) insulating material or a combination of insulating materials (David W, Yarbrough, & Kośny, 2022). It mainly concerns the insulation of exterior walls, roofs and low floors. Thermal insulation enables to:

- Minimize heat exchange between the building interior and the external surroundings (thermal loss);
- Reduce energy consumption for heating and/or cooling (energy savings);
- Make the home more ecological by reducing pollution linked to the release of greenhouse gases into the atmosphere;
- Create a healthy living space (better living comfort) and a more comfortable building (thermal comfort).

When two elements in contact have different temperatures (the building and the outside environment), heat is exchanged between them until their temperatures become identical. The aim of thermal insulation is to retard this exchange, maintaining the walls at a temperature as similar as feasible to that of the indoor air (Gonzalez & Siano, 2021, p. 109). There exist three ways to insulate a building envelope, these includes: external insulation (ETI), distributed insulation (DTI), and internal insulation (ITI).

2.1.1 Internal Thermal Insulation (ITI)

This category of insulation (Figure II.1) consists of installing a thermal insulation inside the building, against the structural elements (walls and floors). ITI is widely used in France (Eyrolles, 1977), thanks to its ease of implementation and lower installation costs than other types of insulation, to improve a building's thermal insulation. It's especially preferable for apartment renovations, as it's difficult to intervene on the building's exterior. While, its disadvantages are more important: it reduces living space, eliminates the benefits of thermal inertia, causes wall condensation and creates thermal bridges (wall/floor and wall/roof junctions). In addition, the quality of interior insulation can decline over time (wool settling behind plasterboard, mouse holes in polystyrene, etc.).

Figure II.1. *Interior thermal insulation of walls. Source : (Isover France, 2019)*

2.1.2 External Thermal Insulation (ETI)

Also known as « **coat wall** » or « **ETI** » in its abbreviated form, this approach involves applying a thermal coat to the external envelope of the building, including walls and roofs (Barreira & De Freitas, 2015). It is more effective than the first type (ITI), since it preserves living space, eliminates most thermal bridges, protects structural elements (load-bearing walls, floors between storeys and roofs) against thermal stress and reduces the risk of condensation occurring within the masonry. This form of insulation is extensively utilized in Belgium and Luxembourg, and even more so in Germany, Switzerland, Austria and Poland (Eyrolles, 1977). On the other hand, ETI is difficult to install on some older buildings (protected facades) and almost always requires the intervention of qualified professionals, so it is often more expensive to install.

2.1.3 Distributed Thermal Insulation (DTI)

This technique combines building materials and thermal insulation to create a single material with a dual function (insulating and load-bearing) (Christian Lhomme, 2014, p. 35). These are known as « **monomers** » (Figure II.2). DTI uses materials that incorporate insulation in their structure, such as aerated concrete, hemp bricks, clay bricks with insulating cores and so on (Akin & Boztaş, 2024; Dlimi, Agounoun, Kadiri, Saadani, & Rahmoune, 2023). Monomers are generally assembled using glue (chosen for its low thermal conductivity) rather than cement mortar, with the main aim of minimizing thermal bridges and improving overall thermal insulation performance (Li Wang, Jiang Li, Kang Li, Kun Hui, & Wang, 2022). In addition, distributed insulation is generally used in new-build construction, at a slightly higher cost than other types of insulation (interior and exterior). As a result, this type of insulation offers good comfort in both winter and summer, is a high-performance, long-lasting solution, is quick to install, limits the risk of humidity and condensation, and requires no insulation on the walls. However, it's preferable to call in a professional to install this type of insulation.

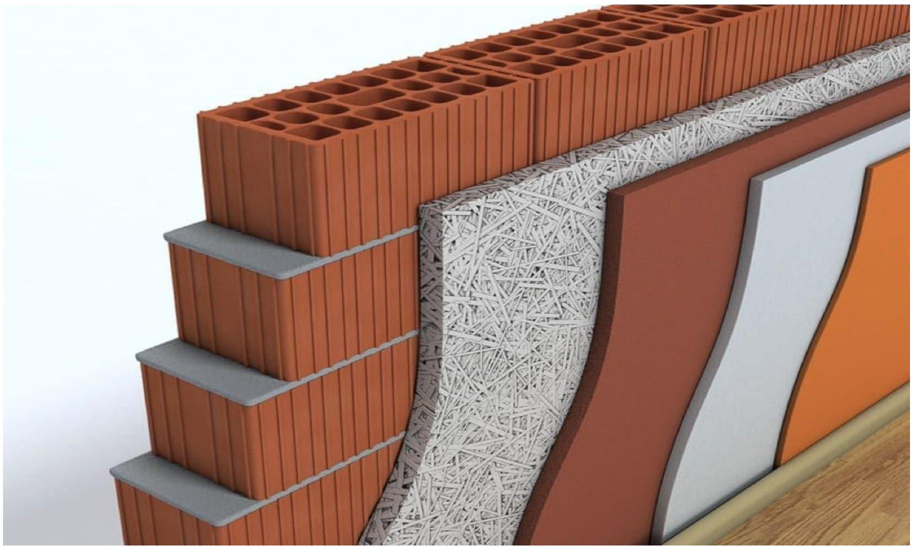


Figure II.2. *Illustration of distributed insulation. Source : (Gluzicki, 2020)*

2.2 Thermal insulation methods

Enhancing the thermal insulation of a dwelling involves several key strategic points: roof, walls, windows and floors (Gonzalez & Siano, 2021, pp. 109-110), However, it's essential to select the elements that have priority over others, in order to achieve efficient and long-lasting thermal insulation. Indeed, the priority of the element is established according to its high percentage of thermal losses.

2.2.1 Roof insulation

The roof is a structure covering the upper part of a building, representing a significant surface area that is highly exposed to external elements such as rain, wind, cold, and sun. The roof is responsible for the largest portion of thermal losses in a non-insulated dwelling, accounting for approximately 25 to 30% of the losses depending on the roof configuration: flat roofs (horizontal roofs) or sloped roofs (converted or unconverted attics). It is the primary area where heat escapes, making it a critical site for thermal insulation. Depending on the type of roof (flat or sloped), thermal insulation can be applied either from the inside or outside (Figure II.3). In the case of a flat roof, a rigid insulating material such as polystyrene, polyurethane, cork, wood fibers, or hemp is required to be placed on the roof with adequate protection. Properly insulating the roof with suitable materials helps extend the lifespan of the building by preventing moisture infiltration and the deterioration of roofing materials. However, the cost of the work varies depending on the technique used, roof slope, roof area, and chosen materials.

Figure II.3. *External insulation of a flat roof. Source : (Isolation-Toiture.fr, 2021)*

2.2.2 Exterior walls insulation (opaque vertical walls)

An exterior wall is any load-bearing construction element, made of stone, brick, breeze-block or other material, which separates two environments (a heated part of the building and the outside environment). Its role is purely mechanical (strength), however, it must also serve as a protective screen to safeguard the habitat and withstand various external stresses and aggressions (such as rainwater penetration, thermal shocks, etc.). Walls are the second most important source of heat loss, following closely following the roof, with 20 to 25% of wasted energy, requiring particular attention to these elements in thermal insulation works (priority number 2). On the other hand, two main techniques are possible: insulation from the inside or the outside (Figure II.4), mainly using rigid insulating panels (polystyrene, mineral fibers, expanded cork, compressed straw, etc.), which are glued directly to the load-bearing wall or screwed onto a support structure (metal or wood). Furthermore, the thermal insulation can be placed inside the wall into which it is integrated, thus the wall can be built using insulating materials (DTI). In fact, thermal insulation of walls allows to limit energy losses from the building, reduce noise nuisances by improving sound insulation, and consequently save money and enhance the comfort of the occupants.

Figure II.4. *External thermal insulation of a wall. Source : (DSD Renov, 2024)*

2.2.3 Windows insulation

The window is an architectural component of the building façade, representing an opening with glass in a wall or sloping roof. It provides several functions for the room concerned: sunlight, ventilation, view of the outside environment and sometimes verbal communication and evacuations safety. However, when they are in poor condition, poorly installed or too thinly glazed, they contribute significantly to thermal losses (10 to 15% of total building heat loss). Following the exterior walls, these elements are considered weak points in the building's overall thermal insulation and are thus ranked third in priority for thermal insulation and renovation plan. In order to achieve effective acoustic and thermal insulation, three solutions were proposed:

- Installation **double glazing**, which comprises two panes of glass separated by a layer of stationary air (air space), to reduce cold-wall effect, condensation and heat loss;
- Adopt **reinforced insulation double glazing (RIG)**, which has the same insulating properties as double glazing, but with solar control represented by a metal optical filter that reflects infrared radiation or heat radiation, while transmitting visible light. In addition, RIG prevents heat from escaping in winter and entering in summer;

- Use **triple glazing** (Figure II.5), which consists of three panes of glass separated by two layers of immobile air (air space) working as insulation. This technique offers the best thermal performance, but is relatively heavy and cannot be installed everywhere.

Figure II.5. *Triple-glazed window for thermal and acoustic insulation. Source : (SMOME, 2024)*

2.2.4 Low floor insulation

The low floor is the lowest soil of the building, below which there is no other level, and only the upper part of this floor opens onto a heated space. It is generally composed of (clean concrete, dry stone hedgehog, reinforced slab, etc.). This load-bearing component of the structure supports both fixed and variable loads and allows for the passage of ducts and piping networks. Among these types are the floor on ground or on unheated basement. On the other hand, it contributes to thermal losses (7 to 10% of total heat loss from an uninsulated building). Indeed, thermal insulation of low floors is not a priority compared to the other building elements mentioned above (roof, external walls and windows) and can therefore be classified as « fourth priority ». However, it is essential to insulate it thermally in order to minimize heat loss, offer long-term living comfort and make a very profitable investment. In this context, the thermal insulation of low floors can be achieved using two techniques: insulation from the **top** or insulation from the **bottom**:

- **Insulation from the bottom (under reinforced slab) :** this is the simplest technique. Insulation in this case is placed between the soil and the reinforced slab, and must be a low-compression, non-hydrophilic insulating material, or well protected against moisture (polyurethane foam, polystyrene foam, mineral fibers and cellular glass). In addition, the insulation boards should be laid with staggered joints to prevent any laitance from running off;

- **Insulation from the top (under reported or floating screed) :** this technique requires heavy work (total renovation of the floor, raising door thresholds, etc.), which can be difficult and costly to implement in renovation projects. Insulation must be placed on the raw floor slab (Figure II.6), with a waterproof film interposed to prevent rising humidity, before being covered with a coating and allowed to circulate in the rooms. Nonetheless, the insulation must be as low-compressible and resilient as possible (polyurethane foam, polystyrene foam, wood fibers and expanded cork). Thus, the Board insulation is laid with staggered joints, and with the edges against each other, to prevent any laitance from flowing between the boards.

Figure II.6. *Insulating a low floor from the top. Source : (SDLM Travaux, 2018)*

2.3 Thermal insulating materials

2.3.1 What is a thermal insulating material ?

A **thermal insulator** (Roulet, 2012, p. 27) is a **material** with **low thermal conductivity**, unlike a thermal conductor, which has high thermal conductivity. It acts by slowing the transmission of heat through it, which helps maintain a stable temperature inside a space while limiting heat loss to the outside or heat gains from the outside. Thermal insulators are widely used in many fields, including **building construction**, industrial applications, heating and air-conditioning systems. In the construction sector, insulation ensures good thermal insulation of the building by reducing heat leakage (heating) or heat entry (keeping cool) during winter and summer periods.

2.4 Types of thermal insulators

Moreover, there are different types of thermal insulators, which we can classify into families according to their origin; we distinguish the following families:

2.4.1 Synthetic insulators

Synthetic insulators materials (Pfundstein, Gellert, Spitzner, & Rudolphi, 2012) (Figure II.7) are rigid alveolar products (or foams), commonly called « insulating plastics », and are the fruits of modern chemistry. They are made from petrochemical materials. Their manufacturing process is based on non-renewable resources and energy-intensive processes. These main materials include expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane (PUR).

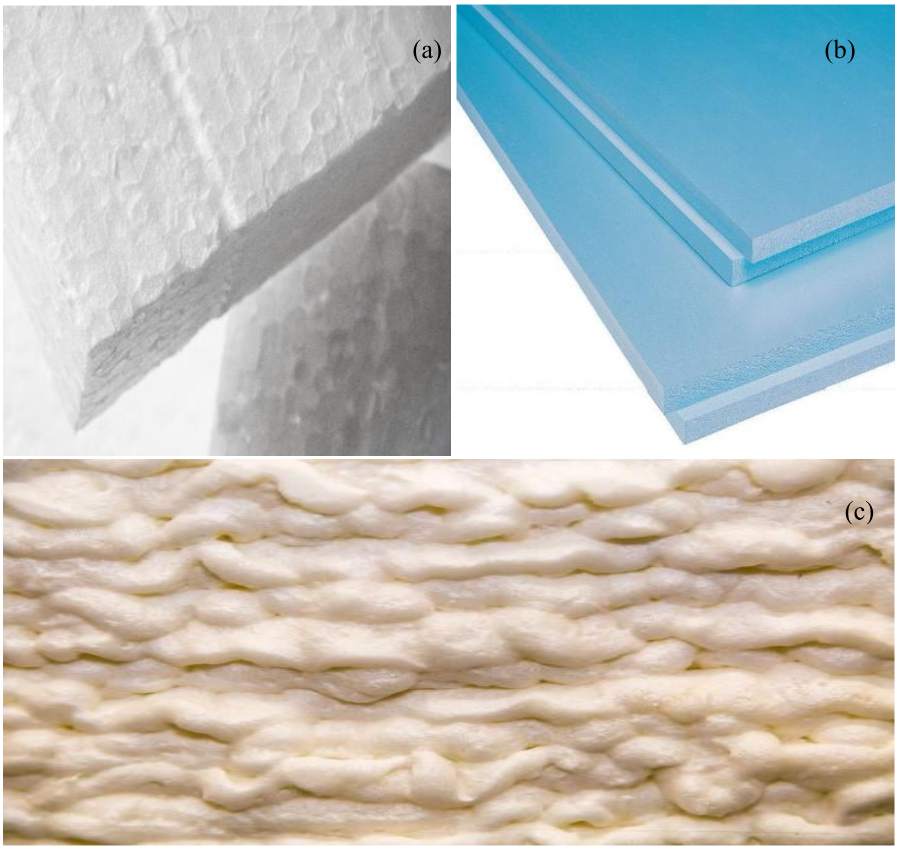


Figure II.7. *Synthetic insulators (a) : expanded polystyrene, (b) : extruded polystyrene, (c) : polyurethane foam. Source : (Futura Sciences, 2019; Batiproduits, 2017; Zherebtsov, 2019)*

2.4.2 Mineral-based insulators

These insulators are made from mineral raw materials (silica, clay, volcanic rock, etc.), which are generally transformed into fine fibers, rolls, panels or granules by incorporating additives (Roulet, 2012). The manufacturing method for this type of materials is based on high-temperature firing, which is energy-intensive and CO_2-producing. Mineral insulators are renowned for their fire resistance, durability, low thermal conductivity and ability to withstand high temperatures. They include rock wool, glass wool, expanded vermiculite and perlite (Figure II.8). The recycling of materials depends on the nature of the products and the additives used.

Figure II.8. *Mineral insulators (a) : glass wool, (b) : expanded perlite, (c) : rock wool, (d) : expanded vermiculite. Source : (Isolation et chauffage, 2024; Keji, 2023; Knauf Insulation Maghreb, 2024; Health Canada, 2009)*

2.4.3 Plant-based insulators

Plant insulators (Pfundstein, Gellert, Spitzner, & Rudolphi, 2012) are materials whose basic component is of renewable plant origin, such as cork, straw, hemp and wood (Figure II.9). They are most often in panel form, and are used both as insulation and as supports or facings in the construction of insulation complexes. This insulation type is the preferred choice for green building practices, thanks to its low environmental impact, energy efficiency and insulating properties.

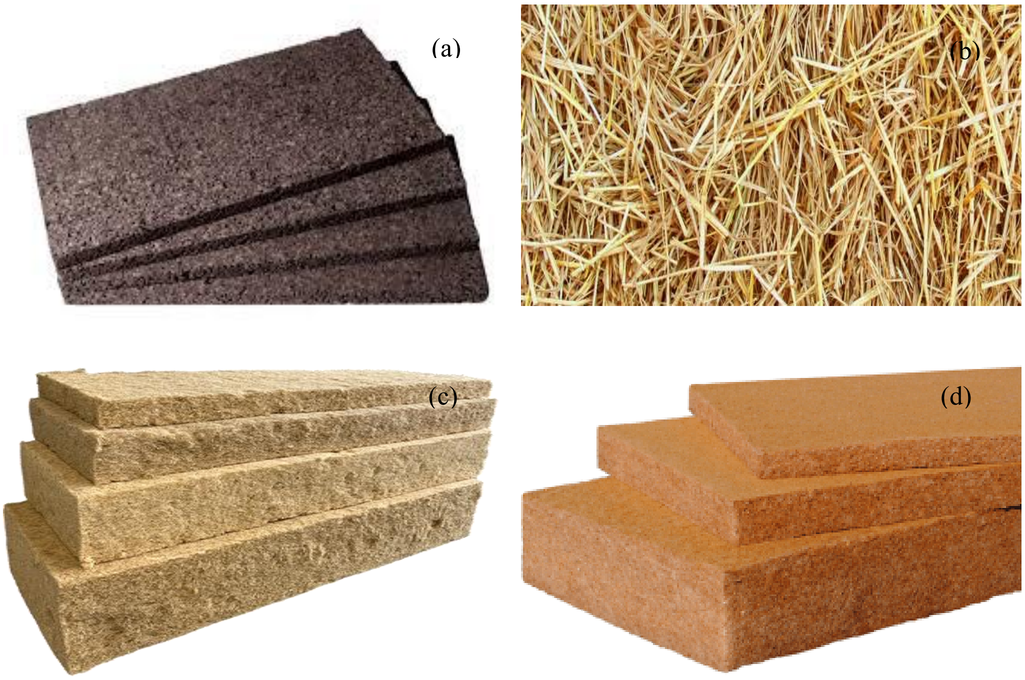


Figure II.9. *Plant insulators: (a): expanded cork, (b): straw, (c): hemp, (d): wood wool*
Source : (Alsabrico, 2020; Cluster Robin·s, 2024; Fauteux, 2024; Johan, 2024)

2.4.4 Recycled materials

Recycled insulators (Figure II.10) are insulation materials whose raw material is derived from the recycling of end-of-life products (paper, plastics, fabrics, etc.) (Trachte, 2012, p. 525).

Figure II.10. *Recycled insulators: (a): cellulose wadding, (b): recycled textile*
Source : (Guillois Isolation, 2024; Isolation-Thermique.org, 2024)

Introducing this type of material into the thermal insulation of buildings allows to preserve natural resources, to reduce the volume of waste generated and consequently the associated pollution. In addition, they offer insulation performance comparable to that of traditional insulation. The most common in this category are cellulose wadding and recycled textile.

2.4.5 Animal origin

Animal-based insulators (Pfundstein, Gellert, Spitzner, & Rudolphi, 2012) are materials made from animal resources (Figure II.11), such as sheep's wool and duck feathers (main insulators). They offer effective insulating properties and are appreciated for their durability and ability to regulate humidity. Animal-based insulation is often used as an ecological alternative to synthetic insulations, as it is renewable, helping to reduce the environmental footprint of buildings. In addition, theoretically all animal hair and feathers could be used as insulators.

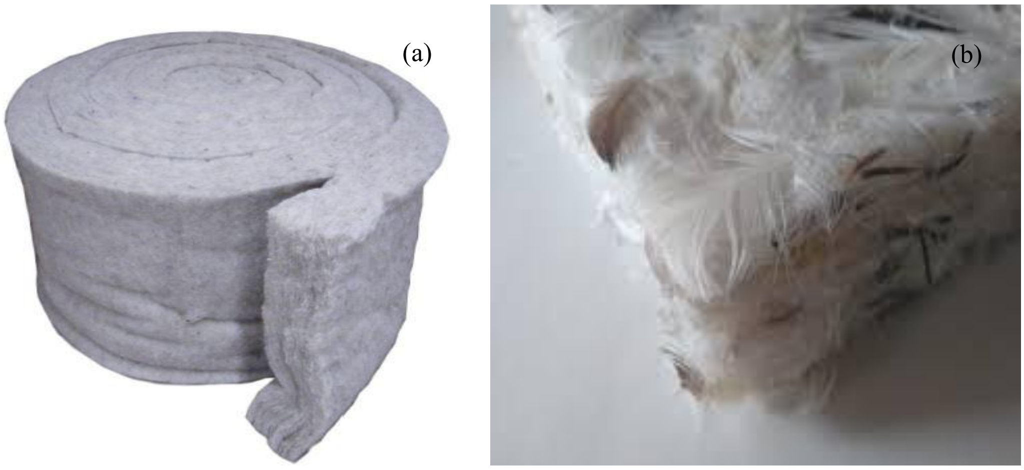


Figure II.11. *Insulation of animal origin: (a): sheep's wool, (b): duck feathers*
Source : (BZH Qualité, 2020)

2.4.6 Next-generation materials

New-generation thermal insulations (Figure II.12) are materials designed by researchers and manufacturers (Almusaed, 2012, pp. 65-69; Leventis, Aegerter, & Koebel, 2011, p. 585) to ensure better energy efficiency in construction and industrial applications, compared to traditional materials such as glass or rock wool, expanded polystyrene, etc. They are developed through innovative new technologies and advanced formulations. These include aerogels (AG) and vacuum insulation panels (VIP). While these insulators offer many advantages in terms of thermal insulation and durability, however they have disadvantages, notably high cost, installation and sensitivity to certain environments.

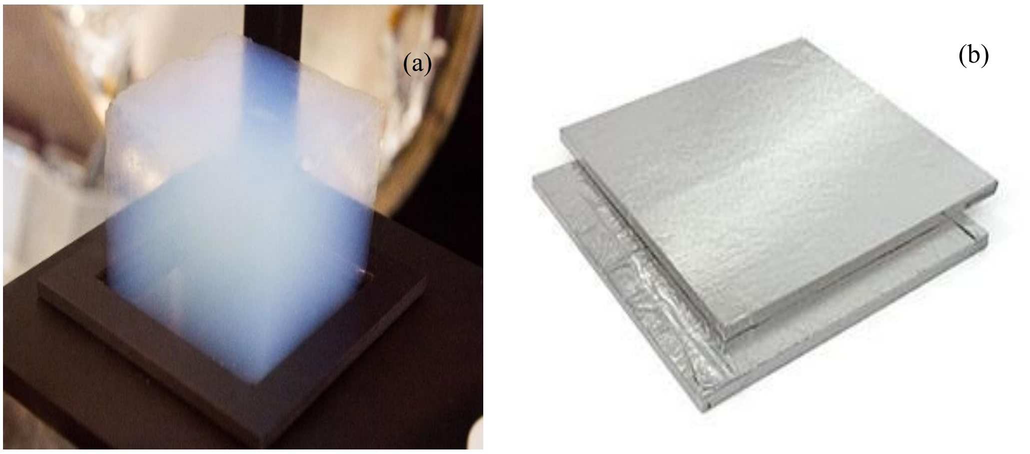


Figure II.12. *New-generation insulation :(a): aerogels, (b): vacuum insulation panels. Source : (Shanghai Tanchain, 2022; Recticel Insulation, 2024)*

2.5 Characteristics must have thermal insulator

In reality, the effectiveness of thermal insulation primarily hinges on the properties of the insulator itself. For this reason, the most important criteria (Roulet, 2012, p. 33) to obtain effective thermal insulator are:

- **Humidity resistance:** A good insulator must be resistant to or protected against humidity, as moisture can reduce the insulator's effectiveness;
- **High thermal resistance:** Thermal resistance indicates the insulator's ability to block the flow of heat. The higher the thermal resistance, the improved the insulation;
- **Adequate thickness:** The insulator must be sufficiently thick to ensure effective insulation. The greater the thickness, the more efficient the insulation;
- **Low thermal conductivity:** The insulator must have a minimal ability to conduct heat. The lower the thermal conductivity, the better the material insulates;
- **Non-flammability:** Preferably, the insulator should be non-flammable or possess very low flammability for safety reasons;
- **Thermal stability:** The insulator must be able to withstand temperature variations, swelling or dilatation without degrading;

- **Non-toxicity:** Insulation must be safe for human health and the environment, without harmful gas or particle emissions.

Chapter III:
External Thermal Insulation (ETI)

3.1 Overview of external thermal insulation

3.1.1 Definition

External Thermal Insulation of buildings (ETI) is a high-performance technique aimed to improve the energy efficiency and thermal comfort of structures by enveloping their exteriors with an insulating material (Simonnot & Lheureux, 2018, p. 124).

The explanation of the typical procedure of ETI for buildings is shown in Figure III.1.

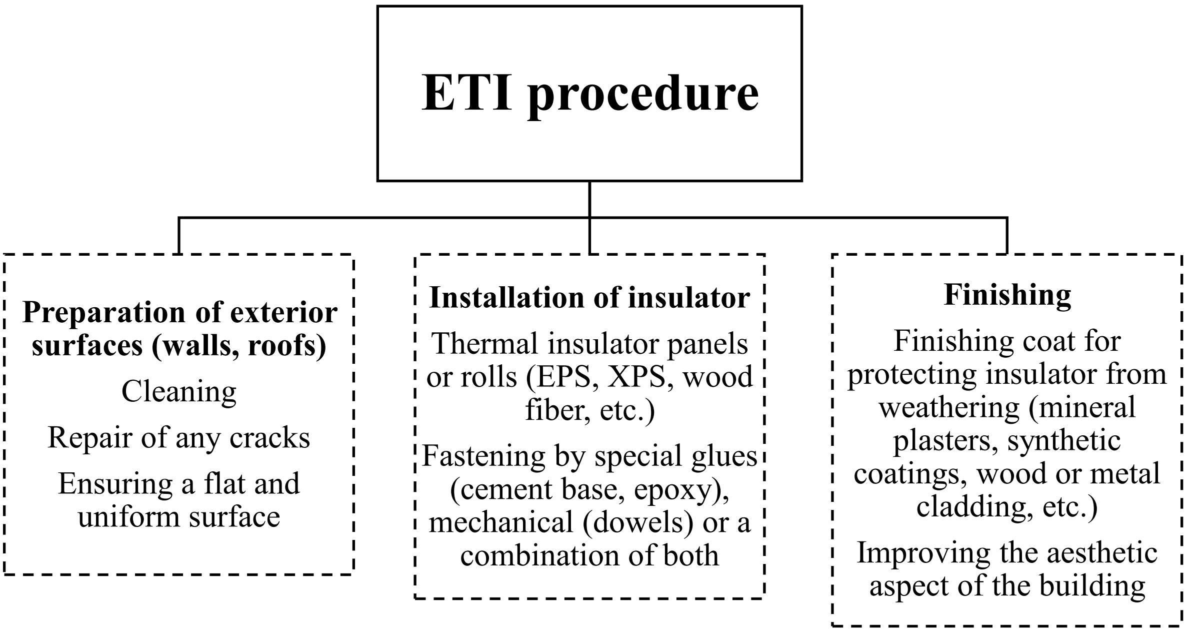


Figure III.1. *Illustrative flowchart of the typical procedure for the ETI of Buildings. Author source*

3.1.2 Benefits of external thermal insulation

This solution offers many benefits (Imbert & Mediouni, 2010, p. 5), including:

- Carrying out work without moving the inhabitants, on **occupied site**;
- **2-in-1 realization**, facade renovation and insulation;
- Preservation of living space and consequently the value of the building, compared to installing thermal insulation from the inside;

- Reduced **thermal losses** through walls and roof;
- Saving energy and thereby saving money;
- Diminution the risk of **condensation**, in contrast to internal thermal insulation and minimizing sources of **thermal bridging**, which are potential causes of building pathologies;
- Enhanced **thermal inertia** of the building envelope to improve comfort during both summer and winter seasons;
- Reduced **greenhouse gas** emissions (CO_2);
- Enhancing the architectural quality of the building and preserving its **heritage**;

3.1.3 Thermal performance of ETI

3.1.3.1 Summer and winter comfort

External insulation enhances thermal comfort (Fabbri, 2024; Humphreys, Nicol, Roaf, & Sykes, 2015) in both winter and summer by leveraging the thermal inertia of the wall (Imbert & Mediouni, 2010, p. 19). When insulation is installed on the exterior, it doesn't create a barrier between the interior of the building and the walls, allowing for the exchange of heat and contributing to regulating indoor temperature (Figure III.2).

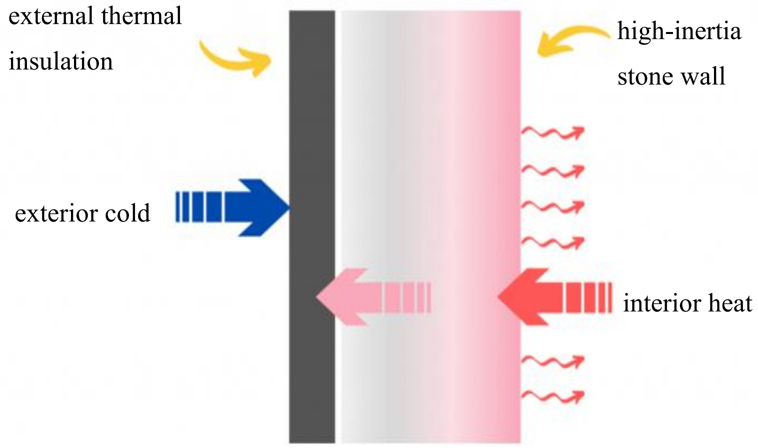


Figure III.2. *Thermal inertia phenomenon of a wall under ETI. Author source*

Additionally, it eliminates the sensation of cold walls. In winter, in a heated room, the walls store heat and release it if the indoor environment cools. In summer, by practicing night ventilation and using solar protection during the day, the walls can retain some of the coolness from the night, helping to decrease excessive heat during the day. This reduces the reliance on air conditioning.

3.1.3.2 Protection against climatic solicitations

External insulation protects the building structure against climatic stresses that can cause cracking and deterioration. The effects are twofold:

a) **Keep homogeneous temperatures in the building (main structural or load-bearing part):**

Figure III.3 below shows the temperature profile of a wall in summer and winter. This wall is initially composed of 20 [cm] breeze-block, on which is fixed, by glue pads sparing an air space of 2 [cm], a polystyrene plate of 2 [cm] is attached on the inside (Imbert & Mediouni, 2010, p. 20).

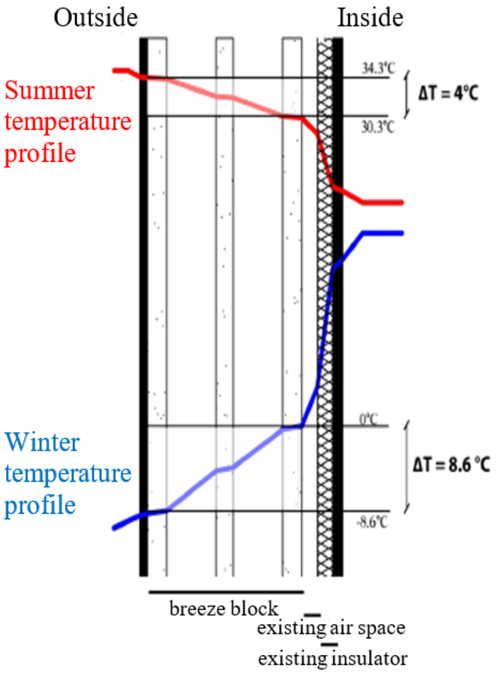


Figure III.3. *Temperature profile with a breeze-block wall. (Imbert & Mediouni, 2010)*

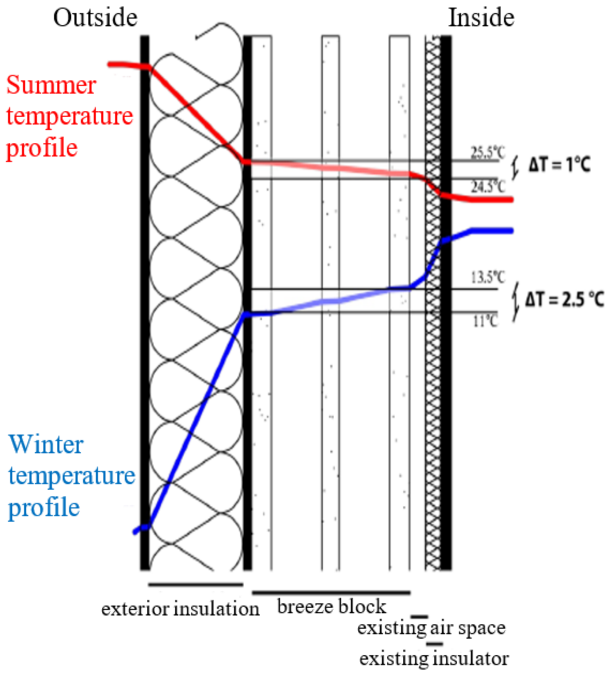


Figure III.4. *Temperature profile with external insulation. (Imbert & Mediouni, 2010)*

Note that the temperature contrast within the breeze-block, fluctuates, reaching 4 [°C] in during summer and 8.6 [°C] during winter. While once isolated on the outside by 12 [cm] of polystyrene (Figure III.4), the temperature difference is only 1 [°C] in summer and 2.5 [°C] in winter. These significant temperature variations within the structure are sources of differential expansion movement that can lead to cracking. At the level of thermal bridges, this phenomenon of differential expansion is accentuated. Moreover, external thermal insulation has the capability to address specific thermal bridges at floor and structural walls levels, thereby lowering the risk of cracking.

b) Reduce the temperature range swept between summer and winter

Figure III.5 below illustrates the thermal shock between summer and winter experienced by the structure, in this case the breeze block (Imbert & Mediouni, 2010, p. 21). Without external insulation, the temperature range swept between summer and winter is 43 [°C] at the breeze-block. With external insulation (Figure III.6), the temperature range is reduced to 15 [°C]. The structure receives less stress, so it moves less. Conversely, there is a significant temperature variance within the insulation and the coating, necessitating appropriately tailored technical attributes.

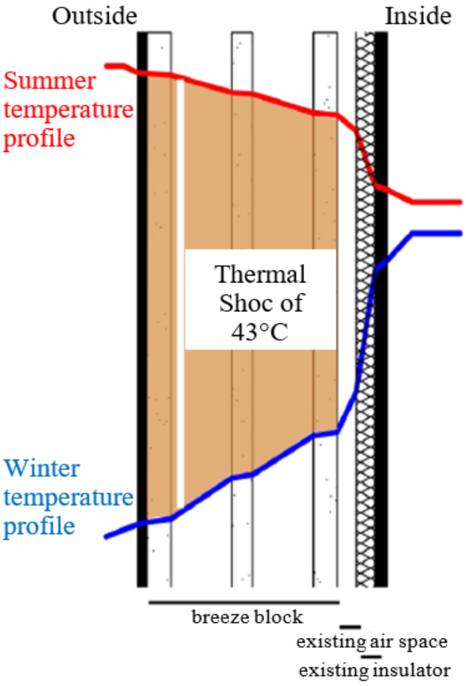


Figure III.5. *Thermal shock with a breeze-block wall. (Imbert & Mediouni, 2010)*

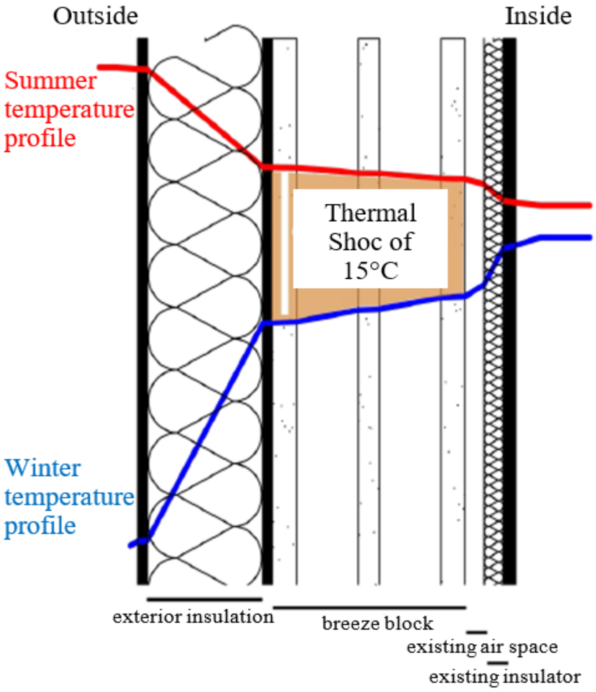


Figure III.6. *Thermal shock with external thermal insulation. (Imbert & Mediouni, 2010)*

3.1.4 Treatment of singular points in ETI

Singular points (Information Resources Management Association, 2021, p. 484) or discontinuity of an insulation (bay frames, balconies, stops and corners) create thermal bridges. These thermal bridges are cold points that lead to condensation and therefore moisture in the walls.

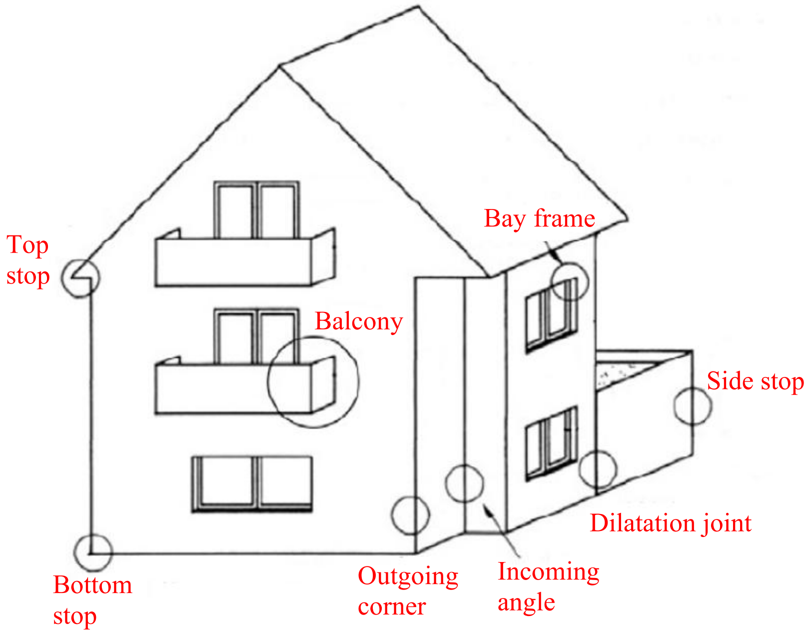


Figure III.7. *Singular points to be treated in external thermal insulation. (CSTB, 2000)*

Addressing singular points, as depicted in Figure III.7, is crucial. Frequently, the quality of their execution determines the maintenance of the works over time and the efficacy of the system. However, the most common thermal bridges and their corresponding solutions are summarized below:

a) **Bay and openings framing:** Doors and windows are sensitive points where thermal bridges occur. To deal with them, it is essential to use adapted profiles and to ensure a good connection between the joinery and the insulator. Solutions such as thermal bridge breakers or special frames can be used to minimize heat loss;
b) **Corners and stops:** Building corners and stops (bottom stop, top stop, side stop, outgoing and incoming corner stops) are areas where insulation can be interrupted or less effective. The treatment of these singular points, is made from the special profiles

(starting and finishing profiles, edge profiles and corner profiles) to ensure insulation continuity and avoid thermal bridges, thus guaranteeing homogeneous insulation;

c) **Junctions with salient elements:** Elements such as balconies, require special attention when installing ETI. To ensure waterproofing and continuity of insulation around these elements, there are flexible materials and special installation techniques such as (liquid waterproofing membranes, self-adhesive sealing strips, sealants, rubber profiles, etc.);

d) **Dilatation joints:** the treatment of dilatation joints in ETI involves the use of flexible materials (sealant), and an appropriate finish to ensure effective waterproofing and the structural stability of the building.

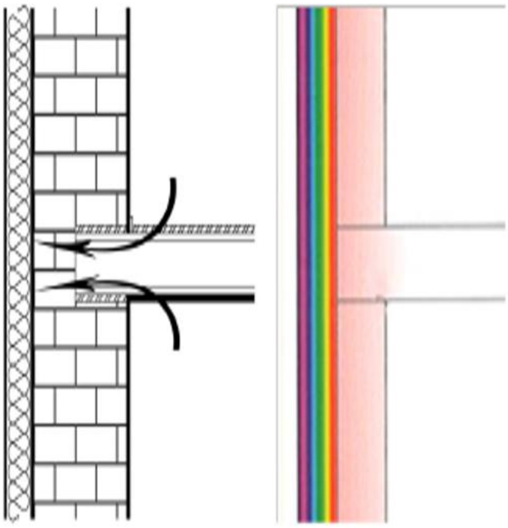
3.1.5 Impact of ETI on thermal bridges

A thermal bridge (David W, Yarbrough, & Kośny, 2022, p. 461) refers to a section of the building envelope where the typically consistent thermal resistance is significantly diminished due to the absence or localized degradation of insulation, resulting in significant heat leaks to the outside. On average, thermal bridges account for 10 % of the losses of an uninsulated collective building, increasing to 25 % in a building insulated internally. For an uninsulated dwelling, thermal bridges account for 5 to 10 %, rising to 18 % with internal insulation.

3.1.5.1 Junction thermal bridges

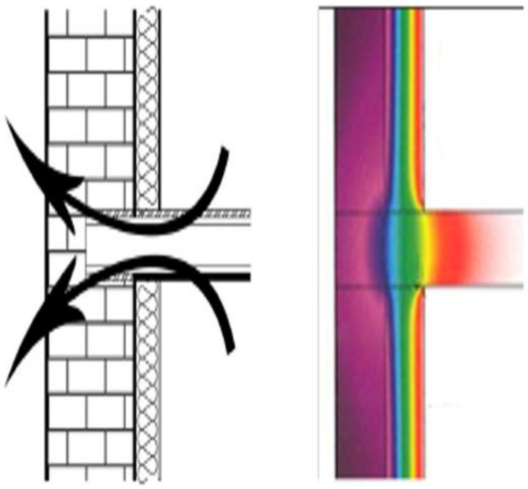
External insulation addresses the thermal bridge at the junctions between intermediate floors and the facade, as well as between load-bearing walls and the facade. With internal insulation (Figure III.8), the continuity of insulation is not guaranteed at intermediate floor level, which leads to a significant thermal leakage.

In contrast, in the case of external insulation (Figure III.9), insulation continuity is ensured, treating the thermal bridge and significantly limiting heat loss.



External Thermal Insulation

Figure III.9. *Internal temperature of an externally insulated wall. (Imbert & Mediouni, 2010)*



Internal Thermal Insulation

Figure III.8. *Internal temperature in a wall with internal thermal insulation. (Imbert & Mediouni, 2010)*

However, thermal bridges at connections (Guyer, P.E, & R.A, 2022) are not confined to intermediate floors and walls. They occur at the junction between two or more walls, at least one of which is exterior-facing. The optimal solution involves extending insulation into the buried section and insulating the lower floor. Similarly, the connection between the wall and the roof must be addressed by extending the insulation over the acroterion or eaves. The risk escalates if insulation is absent or discontinuous. In internal insulation, the discontinuity may arise if the insulation fails to reach the top plate in the attic, does not extend fully to the bottom of the wall, or is cut too short around joinery edges.

When insulating from the outside, it's essential to control the joint between the insulation panels. During renovations, rainwater downpipes must be dismantled before being repositioned in front of the insulation with longer fixing brackets, as the discontinuity created by stopping the insulation on either side of the downpipe creates a thermal bridge. Modenations, fascias and window supports also pose a problem.

These protrusions must imperatively be trimmed in order to pass the insulator in front without having to dig it in its thickness. Once dug in, the insulator is sometimes only one or two centimeters thick, which greatly reduces the thermal performance of the wall at these points and creates a thermal bridge.

3.1.5.2 Integrated thermal bridges

The realization of external insulation can be a source of integrated thermal bridges (Chateauneuf, Curt, Baroth, & Peyras, 2014), compromising the insulation within the wall itself. This differs from thermal bridges at connections, which occur at the junctions between the building's walls. These are very often caused by insulation fasteners or secondary frames (Figure III.10).

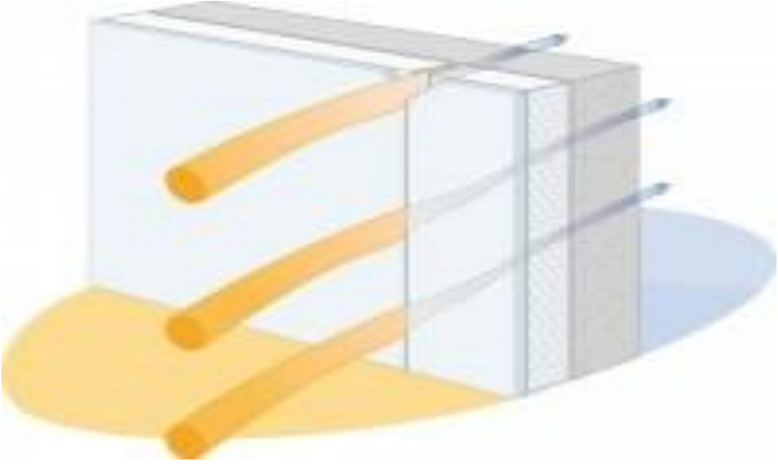


Figure III.10. *Integrated thermal bridges. Source : (Tout Sur l'Isolation, 2019)*

The effect of integrated thermal bridges in external thermal insulation varies depending on the chosen system (Imbert & Mediouni, 2010, pp. 52-53). For a coating system, the impact is minimal if the insulation is glued or mechanically fixed with plastic profiles. With metal profiles, however, the impact can be significant, i.e. it can reduce the wall's resistance by 15 to 30%. Most often, cladding systems also have a strong impact on wall insulation, due to the metal fasteners of the secondary framework. Positioning a plastic piece between the bracket and the wall can limit thermal bridge.

3.1.6 Impact of ETI on condensation and humidity

Air always contains a certain percentage of water vapor. The latter is generally higher inside dwellings than outside. Indeed, it is related to the presence of occupants, domestic activities (cooking, appliances, etc.), using the toilet (showers, etc.). But, the humidity always migrates towards either the driest or hottest environment, or both, in other words, from inside to outside (Louvigné, 2022). During this transfer through a more or less porous wall, water vapor can condense into liquid water at one level or another (Simmons, 2011, p. 427). It is this liquid water that generates pathologies, in particular: It can weaken the structure, by causing masonry to swell (Figure III.11) or encircling reinforcing steel, however it also compromises the physical properties of materials, particularly the thermal performance of the insulator, or peel off paint papers and being favorable to the development of mold (Figure III.12).

Figure III.11. *Swelling of the masonry. Source : (Mur Humide, 2024)*

Figure III.12. *Mold on a wall. Source : (Humidité-Expert, 2024)*

In addition, a hygrothermal study of a breeze-block wall (type of individual house) was carried out to assess its behavior in the face of natural agents such as heat and water (Imbert & Mediouni, 2010, pp. 56-58). This study consists in drawing **Glaser diagrams** for the different cases of wall and climatic conditions. First of all, a Glaser diagram includes a temperature curve, a water vapor saturation pressure curve and a partial pressure curve.

Note that, the study was conducted in summer and winter on a wall composed of 20 [cm] breeze-block, to which a 2 [cm] polystyrene panel is fixed by glue pads providing a 2 [cm] air space, then on the same wall after external insulation with 12 [cm] polystyrene. The climatic conditions selected for this study are shown in Table III.1 below:

Table III.1: *Climatic conditions of the study. (Imbert & Mediouni, 2010)*

	Outside		**Inside**	
	Temperature [°C]	Relative humidity %	Temperature [°C]	Relative humidity %
Winter	-10 [°C]	90 %	19 [°C]	60 %
Summer	35 [°C]	35 %	22 [°C]	40 %

In summer, the partial pressure curve (Pv) is largely lower than the saturation pressure curve, both in the initial state of the breeze-block wall (Figure III.13) and after external insulation (Figure III.14). Water vapor remains in the vapor state and doesn't condense.

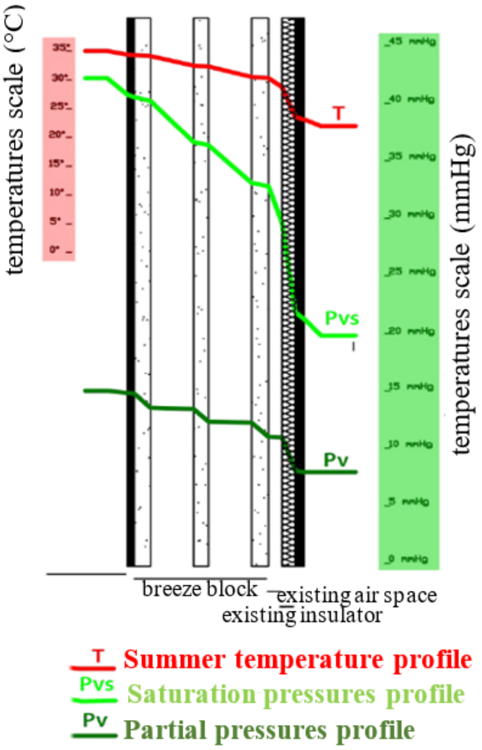


Figure III.13. *Glaser diagram of a breeze-block wall in summer. (Imbert & Mediouni, 2010)*

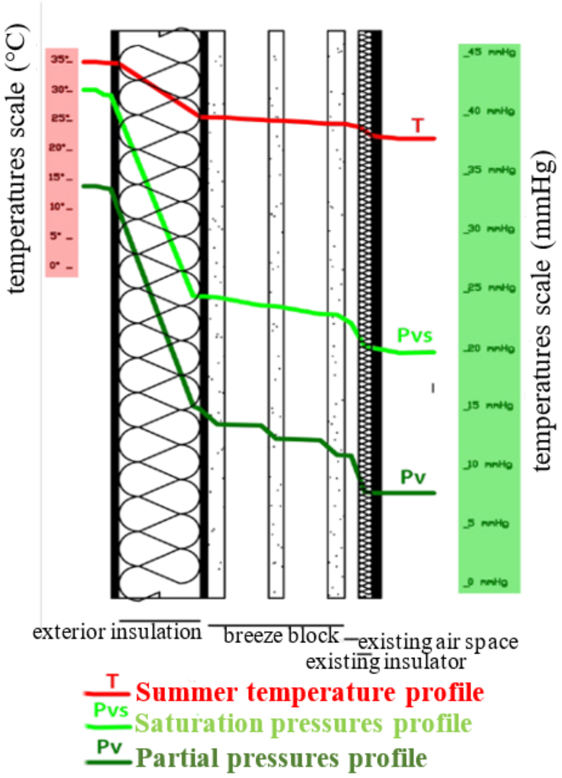


Figure III.14. *Glaser diagram of a breeze-block wall after external insulation in summer. (Imbert & Mediouni, 2010)*

In winter (Figure III.15), the partial pressure curve passes the saturation pressure curve at the interface between the thin inner insulation and the air space, and remains above it until the outer face of the breeze block. This indicates that total condensation occurs on the outer face (breeze-block side) of the insulator. Due to gravity, the water gathers at the base of the wall, and can cause damage to baseboards. Moreover, as condensation occurs at sub-zero temperatures, ice crystals are likely to settle on the walls of the breeze-block partitions.

Following the installation of external insulation (Figure III.16), the partial pressure curve consistently stays below the saturated pressure curve across the entire wall thickness. Consequently, the risks of condensation are reduced compared to the initial case.

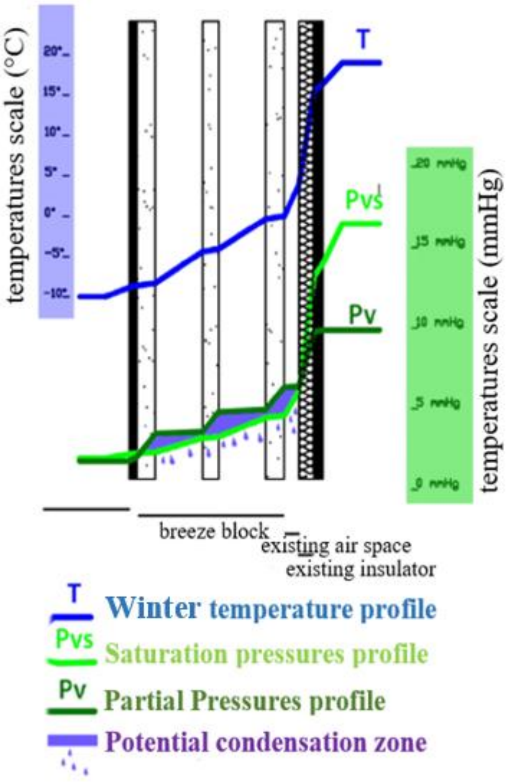


Figure III.15. *Glaser diagram of a breeze-block wall in winter. (Imbert & Mediouni, 2010)*

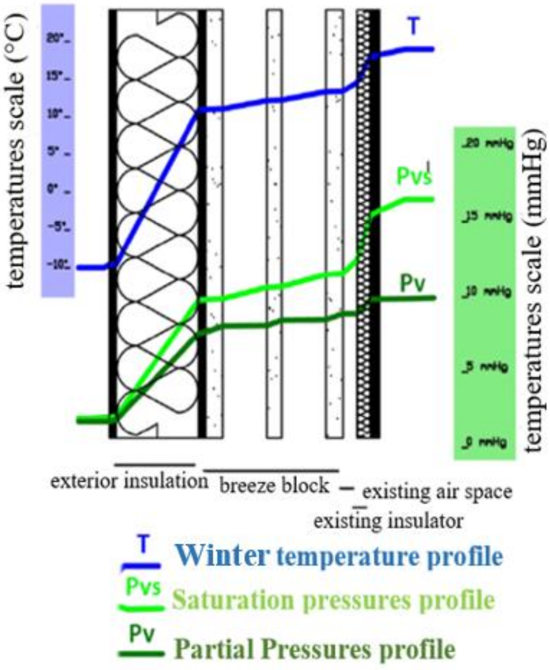


Figure III.16. *Glaser diagram of a breeze-block wall after external insulation in winter. (Imbert & Mediouni, 2010)*

External thermal insulation can protect moisture-sensitive building materials by keeping them at higher temperatures, reducing the risk of internal condensation and moisture damage.

3.2 Sustainable, naturally-derived materials for exterior insulation

In the case of exterior insulation, the insulator must satisfy several criteria, such as rigidity, which facilitates installation, or the insulator's behavior in an environment with high air humidity. Various insulator materials have evolved positively to meet the requirements of external thermal insulation. Among them, we can mention wood fiber, hemp and expanded cork.

3.2.1 Wood fiber

Wood fibers (sometimes derived from waste or untreated sawmill chips) can also be found in the form of flexible or semi-rigid insulation panels. When made from natural green wood, they are bound with polyolefin and ammonium phosphate, with no risk to health or the environment. These panels are recyclable, without chemical binders or carcinogenic short fibers. They have excellent thermal and acoustic insulation, inertia, moisture regulation and water vapor diffusion properties (Figure III.17), and are highly recommended for facade insulation (Horvathova, 2021).

Figure III.17. *ETI with wedge-laminated wood fiber panels.*
Source : (Dieumegard , 2016)

3.2.2 Hemp wool

Hemp is a very «ecological» material: its two main components are fiber and shives (Martínez, Mendizabal, Roncero, Maso, & Gil, 2024). The fiber is carded, shredded and mixed with polyester fibers, before being cooked and cut into rolls or panels. Additionally, the fiber yields wool that insulates well, regulates humidity and absorbs noise, resists pests without protective treatment, is non-toxic and rot-proof. In fact, impregnation with a fire-retardant substance (sodium carbon or ammonium phosphate) is essential for good fire behavior (Faiz Ahmed, Zahidul Islam, Sultan Mahmud, Sarker, & Reajul Islam, 2022).

In contrast, hemp blocks (Shewalul, Quiroz, Streicher, & Walls, 2023) (Figure III.18) are construction products made from hemp fibers mixed with natural binders such as lime or clay. These blocks are designed for external thermal insulation of walls, to offer additional benefits in terms of moisture regulation, environmental friendliness and breathability.

Figure III.18. *Realization of hemp blocks. Source : (Shewalul, Quiroz, Streicher, & Walls, 2023)*

3.2.3 Expanded cork

A natural material that is 100% plant-based, derived from the bark of the cork oak (Quercus suber). After harvesting, it rests for approximately three months to eliminate its moisture and sap. Then, the raw material is granulated and expanded by high-temperature steam (180 to 200 [°C]), allowing the residual sap to bind the granules together (Eyrolles, 1977). It can be packaged in a variety of forms: rigid panels, rolls, granules (or bulk), etc. Cork can be used in a wide range of thermal insulation applications, the main ones being: cold rooms, pipes (industrial insulation); vertical walls, floors, terraces, attics, etc. (in the building).

In the context of ETI, it is known for its insulating properties, notably its ability to reduce heat transmission, be moisture-resistant and offer good acoustic absorption (Lakreb, et al., 2023; Almeida, Simões, Tadeu, Palha, & Almeida, 2019). In addition, cork can withstand high temperatures, making it flame-retardant, rot-proof and compression-resistant. However, raw material resources are limited, making it an expensive insulator that should be reserved for uses for which other bio based insulants are technically unsuitable.

3.3 ETI techniques for reinforced concrete structures

3.3.1 Techniques for opaque walls

Exterior wall thermal insulation techniques (Eyrolles, 1977; Giebeler, Fisch, Krause, & Musso, 2012; Ziad, Benoudjafer, & Benoudjafer, 2024; Ziad, Benoudjafer, & Benoudjafer, 2024) can be divided into two main categories: the wet process, using coatings on insulators (thin or hydraulic), and the dry process, including the systems of cladding, veneer, clothing and brick counter-walls.

3.3.1.1 Coated systems

Thin coated systems (Figure III.19-a) consist of an insulator fixed to the outside of the wall and a specific coating reinforced with glass-fiber fabric and finishing coat. The thermal insulation layer in these systems is relatively thin and includes light materials, such as expanded polystyrene (EPS) board, polyurethane (PUR) board or glass fiber.

In the case of a hydraulic coating on insulation (Figure III.19-b), the thin coating is replaced by a hydraulic coating (cement mortar or lime), generally sprayed on. These systems involve the use of higher-density insulator materials, such as mineral wool panels or extruded polystyrene (XPS). Indeed, this system offers better thermal performance than thin coatings due to the greater thickness of the insulation.

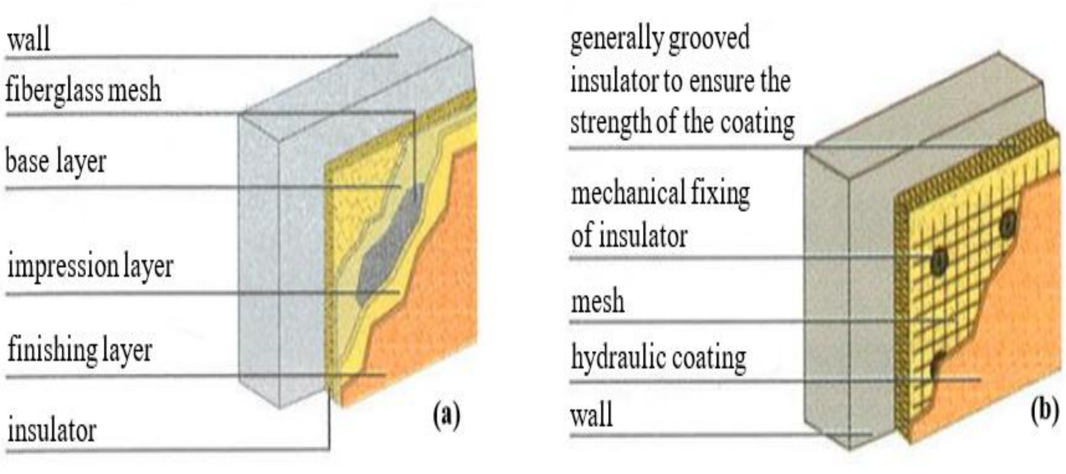


Figure III.19. *ETI techniques for walls under coating*
(a): System with thin coating, (b): System with hydraulic coating. Author source

3.3.1.2 Ventilated facade systems (Cladding)

The insulator in this case is protected from the weather and thermal shock by a sparing cladding (Figure III.20), between its internal face and the insulation there is a ventilated air space (Gonzalo & Habermann, 2008, p. 104). The latter avoids the insulator from thermal variations and eliminates any moisture that has migrated through the wall and its insulation. However, the presence of a vapor barrier on the hot side of the wall will sometimes be necessary, in order to limit the condensation that could occur on the cladding face. On the other hand, if the condensation was significant, in winter, there would be ice formation with risk of obturation of the air space (Imbert & Mediouni, 2010).

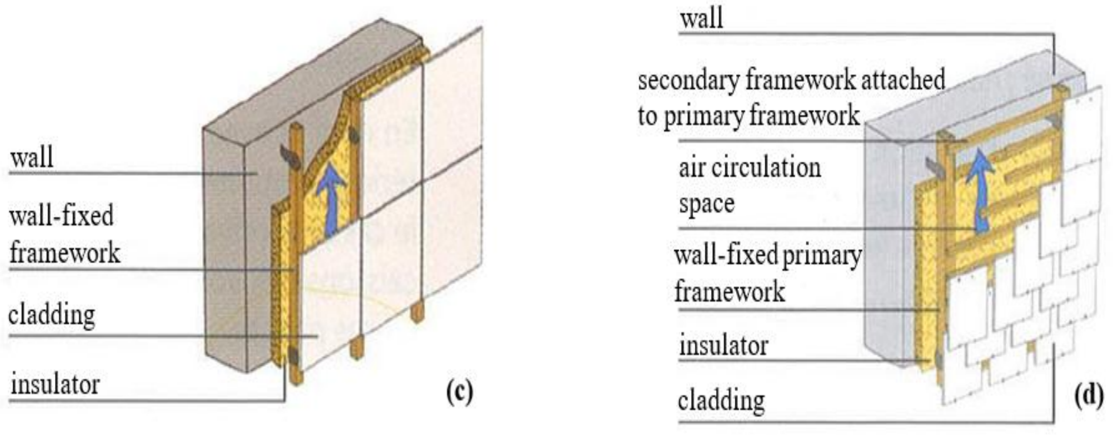


Figure III.20. *ETI techniques for walls under cladding*
(c): Single-frame cladding, (d): Double-frame cladding. Author source

3.3.1.3 Types of veneer and clothing systems

Veneers (Figure III.21-e) are manufactured insulation systems consisting of two products: thermal insulation factory-laminated to the back of a cladding sheet that forms the protective outer skin. The two elements (insulation and facing) are fitted together on the load-bearing wall, and are mechanically fastened to the wall with screws and plugs (Imbert & Mediouni, 2010; Matusiak, Rynska, Rucinska, Cieplik, & Kozminska, 2018). Unlike other ETI techniques, which require several passes over the substrate. In addition, there's no air gap between the cladding and the insulation, unlike in a cladding system.

Clothing (Figure III.21-f) are cladding elements without integrated insulation that are mechanically fastened to the supporting structure (wall). The facing, applied directly to the support with or without the air space, is fixed through the thermal insulator, with no intermediate framework implemented to the insulation as in the case of cladding. The insulator is temporarily attached to the wall, while the cladding guarantees its permanent stability.

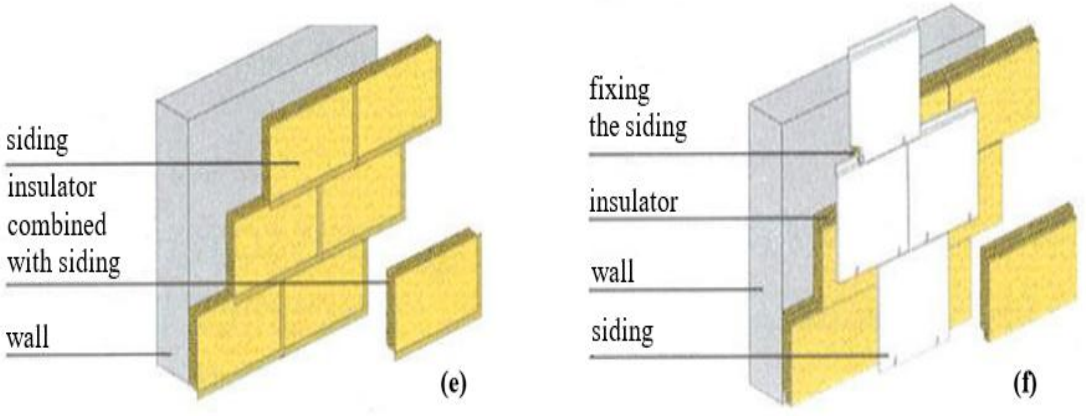


Figure III.21. *ETI techniques: veneer and clothing types (e): Veneer system, (f): Clothing system. Author source*

3.3.1.4 Thermal insulating coatings

What is a thermal insulating coating?

An insulating coating is a facade plaster composed of mortar, a binding ingredient (such as cement, clay, lime), and an insulating material (hemp microbeads, cork, expanded polystyrene). It enhances the insulation of a dwelling and serves as an aesthetic coating (Reichel, Hochberg, & Köpke, 2004).

When applied in combination with effective existing insulation, insulating coating improves the thermal resistance (R-value) of the facade. In fact, the higher the R-value, the better the wall is insulated.

Types of insulating coatings

There are several types of insulating coatings (Abu-Tair, Kinuthia, & Fırat, 2018), including the following:

- **Insulating paint:** this paint is typically white (Fig III.22-a), helping reflect sunlight and reduce indoor heat during summer. It also minimizes heat loss in winter and is resistant to weather conditions;
- **Polystyrene-based render:** a mortar mix containing polystyrene beads (Fig III.22-b). It is lightweight and effective but must be applied in several layers to achieve optimal performance;

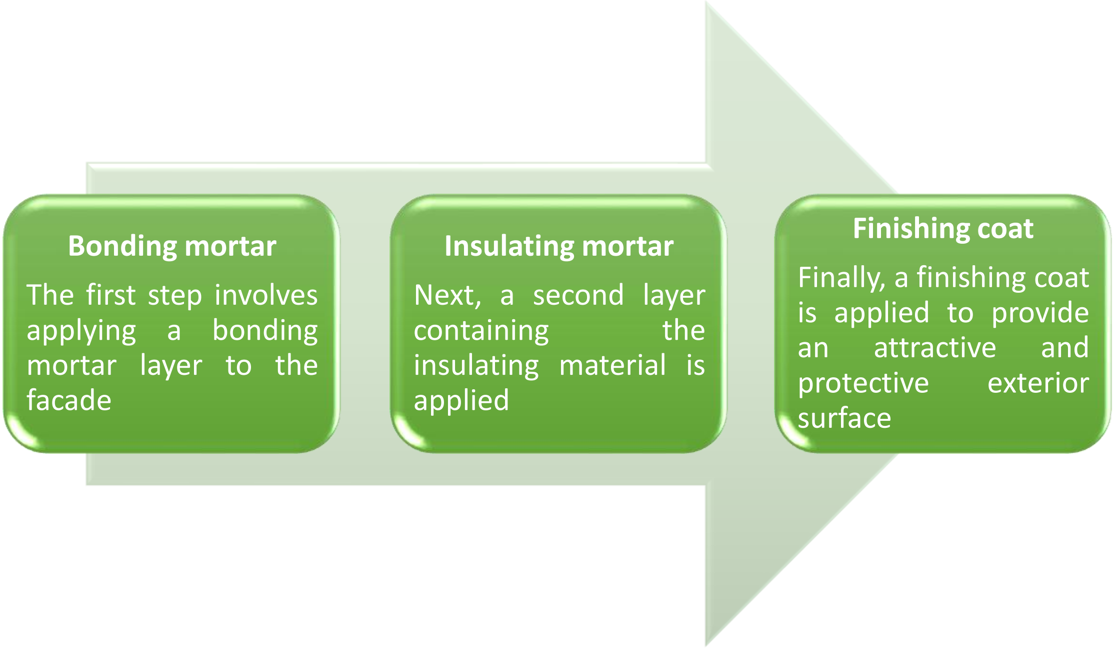
Figure III.22. *Types of insulating coatings. (a): Thermal insulating paint, (b): Polystyrene-based render. Source : (Rhea Habitat, 2024; Isolation-Thermique, 2025)*

- **Lime-hemp coating:** this type of coating helps regulates humidity and offers protection against electromagnetic waves and radiation. It is weather-resistant, pest-resistant, and durable. Making it especially suitable for old walls;
- **Wattle and daub (torchis):** an old but still effective insulation technique. It is an eco-friendly solution, made from a mixture of earth and straw, and also economical;

- **Lime-cork render:** provides both thermal and acoustic insulation for the building. Additionally, it is resistant to fire and adverse weather conditions;
- **Silica aerogel-based insulating coating:** silica aerogel remains relatively expensive due to its complex and costly manufacturing process, which limits its availability among craftsmen. However, its insulating performance is comparable to that of fiberglass.

Steps for applying insulating coating

Insulating coating can be applied to both new constructions and buildings undergoing renovation. Generally, the application process involves three simple steps:



Bonding mortar

The first step involves applying a bonding mortar layer to the facade

Insulating mortar

Next, a second layer containing the insulating material is applied

Finishing coat

Finally, a finishing coat is applied to provide an attractive and protective exterior surface

Figure III.23. *Application process of an insulating coating. Author source*

Advantages

Insulating coating combines practical thermal insulation with decorative appeal. In addition, it offers several other benefits:

- **Eco-friendly:** it can be used with natural insulating materials, such as hemp or cork, making it a viable solution for sustainable construction practices;

- **Thermal resistance:** insulating coating helps eliminate potential thermal bridges, which is ideal for improving thermal resistance. It is particularly suitable for renovation projects where existing insulation is insufficient;
- **Breathable material:** insulating coating made from lime, for example, regulates moisture and reduces the formation of mold on exterior walls;
- **Easy application:** the application process is straightforward and practical. Typically, three coats are enough to achieve an attractive facade finish.

3.3.2 ETI techniques for flat terrace roofs

Thermally insulating flat roofs is a primary focus in the field of thermal insulation for both new constructions and building renovations (Schwartz, 2021). Indeed, effective insulation of the roof terrace from the outside (ETI) contributes significantly to reducing energy consumption for cooling and heating, enhances indoor thermal comfort and may even prolong the lifespan of the roof itself, thereby ensuring the long-term durability of the structure.

There are three main techniques for insulating a flat roof from the outside: conventional insulation (or hot roof), inverted insulation and combined insulation (Benoudjafer, Ziad, & Benoudjafer, 2024).

3.3.2.1 Hot roof

This is the most common and recommended technique (Louvigné, 2022, p. 75). It consists of placing a layer of insulation between the waterproofing membrane and the vapor barrier, which is itself installed on the roof 's load-bearing structure (Figure III.24). The vapor barrier is an essential element for evacuating moisture from the hot part of the insulation. Conventional insulation also eliminates thermal bridges, providing effective protection against temperature variations and condensation, and thus reducing the risk of cracks.

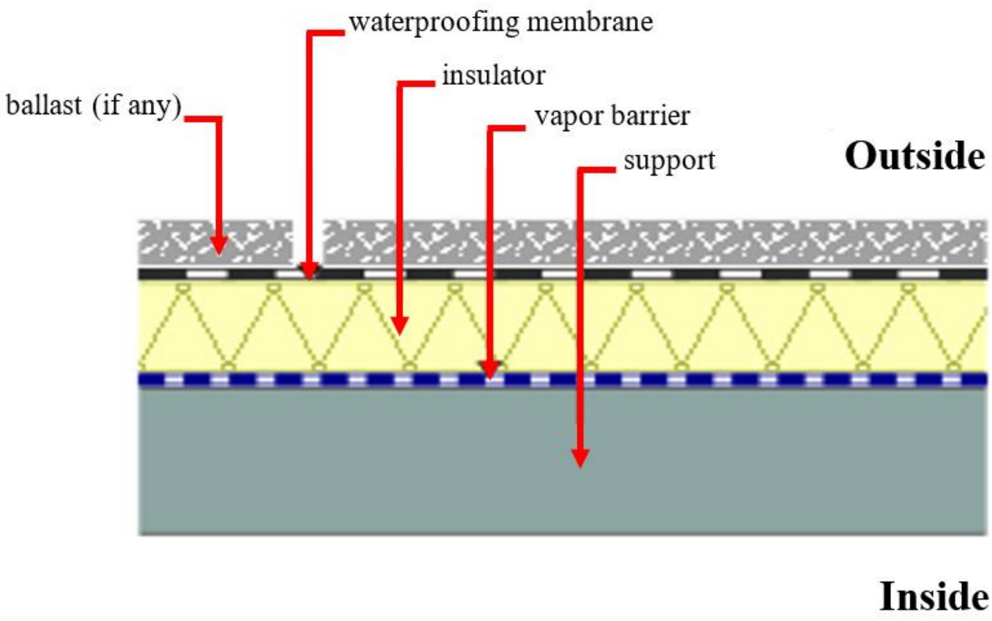


Figure III.24. *Hot roof system. Author source*

3.3.2.2 Inverted roof

Unlike the hot roof, inverted insulation involves placing the insulation on top of the waterproofing membrane (Figure III.25), which is then covered with slabs, tiles or gravel (Hegger, 2009, p. 125).

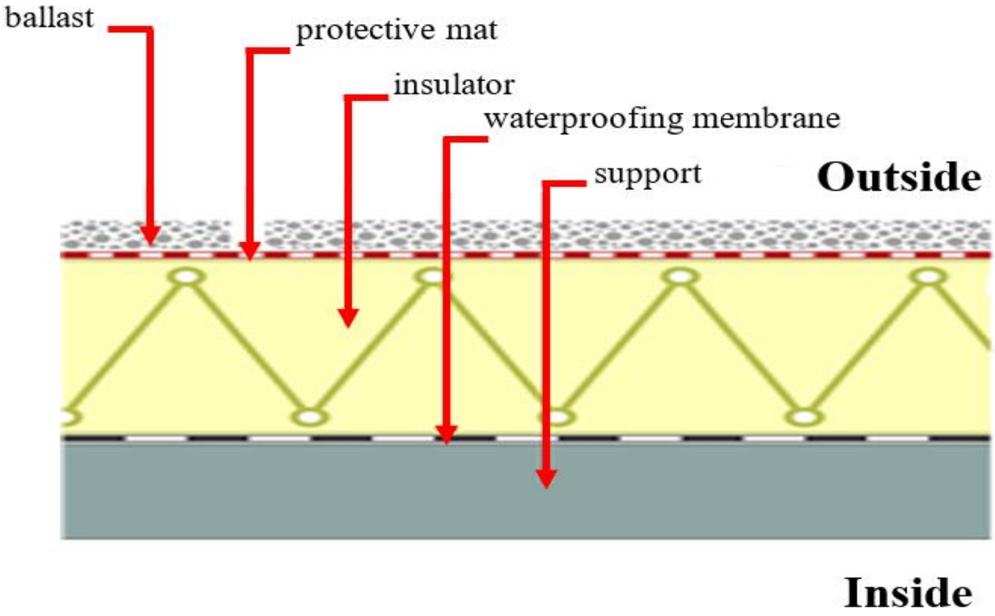


Figure III.25. *Inverted roof system. Author source*

This technique is less costly and quicker to install, as it does not require the addition of a vapor barrier. Moreover, it's ideal for renovation projects where the waterproofing membrane is in good condition. However, this process can have serious disadvantages over the long term, as the insulation is not protected from moisture and gradually loses its effectiveness.

3.3.2.3 Combined roof

The combined roof system (Hegger, 2009, p. 125) is a mixture of the two techniques hot roof and inverted roof, with the insulation mounted in two layers, as follows: the first layer of insulation is overlaid with the waterproofing membrane. While, the second layer of insulation is placed on top of the waterproofing membrane (Figure III.26). Then, a vapor barrier is interposed between the support and the lower insulation.

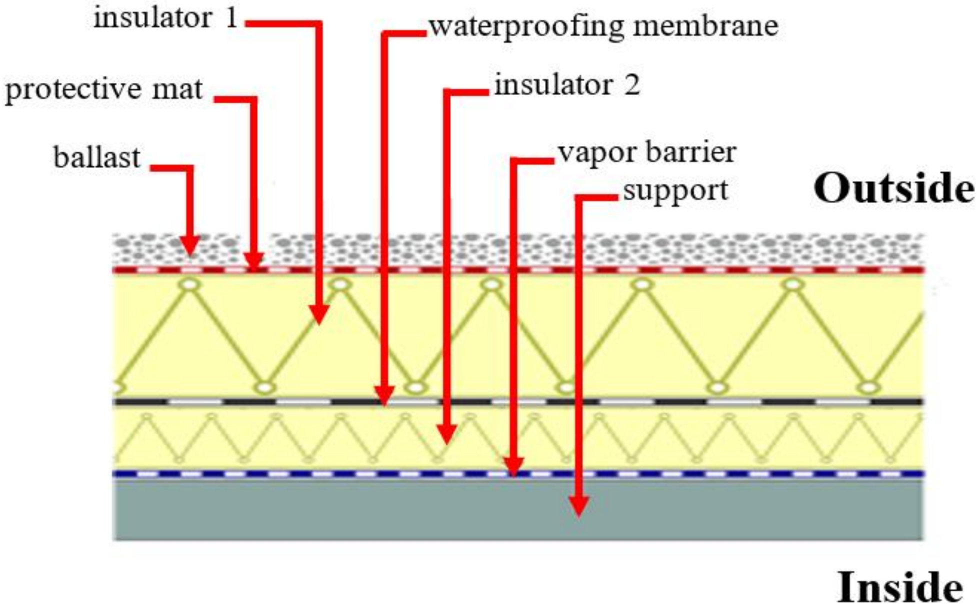


Figure III.26. *Combined roof system. Author source*

This insulation technique protects the waterproofing membrane from thermal shocks and ultraviolet radiation, and thus slows down its ageing.

General Conclusion

Thermal insulation in buildings is one of the most effective means to reduce energy demand in the construction sector, enhance occupant comfort, and address the environmental challenges associated with climate change.

This book has presented a **structured synthesis** of the theoretical foundations, insulation techniques, and materials used, with particular emphasis on **innovative and sustainable approaches**.

We first reviewed the **fundamental principles of heat transfer**, which are essential for understanding how insulation systems work. Three modes of heat transfer (conduction, convection, and radiation) are involved in thermal exchanges, and any insulation solution aims to **reduce their intensity**.

Next, we explored the **various thermal insulation methods** applied to building envelope components such as roofs, walls, windows, and floors, highlighting that **roofs** and **walls** are the **main sources of heat loss**. A classification of **insulating materials** was also presented, based on their nature (synthetic, mineral, bio-based, recycled), with emphasis on the importance of their **thermo-physical properties** to ensure the overall effectiveness of insulation.

Finally, special attention was given to **External Thermal Insulation (ETI)**, which provides both **high thermal performance** and **long-term protection of the building structure** against climatic stresses. ETI techniques were categorized into wet systems (coatings on insulator) and dry systems (cladding, veneers), for both vertical walls and flat roofs including (hot roofs, inverted roofs and combined roofs).

Future perspectives

In the context of the energy transition, thermal insulation is expected to evolve toward more **intelligent and adaptive** solutions. Some of the most promising avenues include:

- **Phase Change Materials (PCMs)**, which can store or release heat depending on thermal demand ;
- **Nano-based or aerogel insulation materials**, which deliver superior thermal performance with minimal thickness ;
- **Dynamic or active insulation systems**, integrating sensors, automated controls, and even features such as ventilation or energy recovery.

These innovations pave the way for **passive or net-positive energy buildings**, adapted to local climatic constraints and aligned with sustainable development goals.

Recommendations for research and practice

To address the technical, economic and environmental challenges, we offer the following recommendations:

- Strengthen **applied research** on bio-based, recyclable, and low-carbon insulating materials;
- Promote the **standardization** and **normalization** of ETI (External Thermal Insulation) techniques adapted to local contexts (climate, structural types, and available materials);
- Develop more accessible **thermal simulation tools** for professionals, incorporating real material performance data;
- Raise awareness among building stakeholders about the importance of a **holistic approach** (building + climate + usage), rather than focusing solely on materials;
- Integrate **smart insulation technologies** into public energy efficiency policies, in alignment with national and international goals.

In summary, this book aims to **equip readers** with a solid scientific foundation, up-to-date **technical knowledge**, and a forward-looking perspective, in order to contribute, each at their own level, to the design of buildings that are more sustainable, more energy-efficient, and better suited to the energy challenges of our century.

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Appendices

Appendix A — Thermal properties of common building insulation materials

Material	Thermal Conductivity (W/m·K)	Density (kg/m³)	Specific Heat Capacity (J/kg·K)
Polyurethane board	0.025	40	1400
Expanded polystyrene (EPS)	0.035	30	1450
Extruded polystyrene (XPS)	0.035	35	1450
Glass wool	0.035	60	1030
Rock wool	0.035	100	1030
Expanded cork	0.040	120	1700
Hemp fiber board	0.040	45	1550
Wood fiber boards	0.040	160	1470
Loose-fill cellulose	0.040	30	1600
Sheep wool	0.040	60	1500
Expanded perlite boards	0.057	145	900
Aerated concrete block	0.200	650	1000
Gypsum plaster	0.570	1200	1000
Lime plaster	0.730	1400	1000

Adapted from : (Ademe, Agence de l'Environnement et de la Maîtrise de l'Énergie, 2013)

Appendix B — Excerpts from thermal standards

1. International ISO standards (excerpts and main functions)

Standard	Full Title	Main Content
ISO 6946:2017	*Building components and building elements – Thermal resistance and thermal transmittance – Calculation method*	Calculation method for thermal resistance and U-value (thermal transmittance coefficient)
ISO 10456:2007	*Building materials and products – Thermal properties – Declared and design values*	Tables of thermal conductivity values for common materials (λ, R, etc.)
ISO 13789:2017	*Thermal performance of buildings – Transmission and ventilation heat transfer coefficients – Calculation method*	Calculation of heat losses through transmission and ventilation in buildings
ISO 10211:2017	*Thermal bridges in building construction – Heat flows and surface temperatures – Detailed calculations*	Treatment and calculation of thermal bridges using 2D/3D modeling

Reference: (ISO 6946, 2017; ISO 10456, 2007; ISO 13789, 2017; ISO 10211, 2017)

2. French and European thermal regulations

Regulation	Year	Scope	Key excerpts / Highlights
RT 2012	2012	French thermal regulation	Set a primary energy consumption limit of 50 kWh/m² per year
RE 2020	2020	Replaces RT2012	Incorporates carbon footprint and promotes bio-based materials
EN ISO 13370	2007	Insulation of floors in contact with the ground	Calculation methodology for heat flow beneath the floor
EN ISO 13790	2008 (replaced)	Calculation of heating energy demand	Quasi-static model for regulatory calculations

Reference: (Ministère de l'Écologie, du Développement durable, des Transports et du Logement, 2012; Ministère de la Transition Écologique, 2021; ISO 13370, 2017; EN ISO 13790, 2008)