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A Review of Insulation Materials for Enhanced Building Energy Performance

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Abstract. Insulation materials are essential for improving building energy efficiency. Both traditional and modern options offer distinct advantages and limitations. Traditional materials include rock wool, acrylic, and fiberglass. Rock wool provides high thermal resistance and acoustic performance but raises environmental concerns. Acrylic is lightweight and easy to install but has limited durability and a notable ecological footprint. Fiberglass is cost-effective, though installation can pose health risks. Modern alternatives include aerogel, rubber, wood, and cellulose. Aerogel offers excellent insulation at low density but is expensive. Rubber absorbs vibrations effectively, especially when recycled. Wood- and cellulose-based insulation have low carbon footprints, though their performance depends on installation conditions. Comparing these materials reveals the need to balance thermal efficiency, cost, durability, and environmental impact to optimize building comfort and sustainability. Selecting the appropriate insulation requires a careful assessment of these factors to achieve both energy savings and ecological responsibility.
Keywords: Thermal Insulation; Energy Efficiency; Sustainable Building Materials; Environmental Impact; Building Sustainability

1 Introduction

In Morocco, the construction sector is one of the three most energy-intensive sectors, reflecting the Kingdom's ambition to pursue green development by reducing its dependence on external energy sources. Despite reforms aimed at promoting energy efficiency in buildings, the problem persists for various reasons, including the poor performance of existing buildings, the limited diversification of materials, the lack of data on material properties, and a lack of understanding about the role of the hygrothermal properties of local materials in energy demand. Currently, biocomposite building materials can be utilized for various purposes in green buildings, whether for new construction or renovation. Indeed,

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biocomposite materials are very effective in promoting an optimal indoor environment in terms of thermal comfort [1].
The RTCM is, however, limited to the building component and does not take into account various other modes of electricity consumption, such as lighting, even though it is, for example, Article 3 of Law 47-09. The main objectives of this regulation are to reduce energy requirements for heating and air conditioning in buildings, improve thermal comfort, improve building envelope design, and conduct energy audits of existing buildings.
When it was drafted, Morocco's Thermal Building Regulations (RTCM) defined minimum energy performance requirements for the building envelope for different categories of buildings. These performance requirements include the thermal transmission coefficient U in W/(m2.K), which characterizes the rate of heat transfer in steady state, the overall glazing ratio TGBV (%) of heated and/or cooled spaces in buildings, and the solar factor Fs (%), which refers to the rate of light transmission through windows. An analysis of meteorological data between 1999 and 2008 has enabled Morocco to be subdivided into six climate zones (Agadir, Tangier, Fez, Ifrane, Marrakesh, and Er-Rachidia). These climate zones were defined based on the number of winter degree days and the number of summer degree days.
This paper endeavours to examine the different thermal insulation techniques and their efficient use in building energy conservation. Among the thermal insulation techniques, the following have been recognized, differing widely among themselves: rubbers, characterized by flexibility and water resistance, ensure the conservation of energy and prolong the life of buildings. Also, aerogels, known for their very low thermal conductivity, ensure the greatest level of insulation, even when the space is not very large, thus facilitating the maintenance of optimal building internal comfort, though it is expensive. Fibre-based materials, generally environment-friendly, ensure steady and controlled environmental temperatures, along with the facility for recycling, thus assuring the maintenance of a sustainable environment. Lastly, glass alfa, because of its lightness and fire resistance, insures building thermal properties and savings, along with the lowering of electricity bills.

2 Necessity of thermal insulation

Among the solutions for improving energy efficiency, a distinction should be made between "passive" and "active" solutions. The former improves the thermal comfort of building occupants while minimizing the energy required for heating/cooling, notably through thermal insulation, optimal orientation to take advantage of light energy, optimal window sizing, and natural ventilation. The latter aims to optimize the electrical loads of HVAC, ventilation, lighting, and household appliances.

Around the world, interest in thermal insulation for buildings continues to grow, as this technique is one of the most valuable tools for reducing energy consumption related to heating/cooling building envelopes. Reducing heat loss in winter saves on heating costs, while reducing heat gain in summer reduces cooling costs. In Morocco, thermal insulation was not common practice until it became a requirement in 2015 to meet the requirements of the thermal building regulations (RTCM).

3 Thermal insulation of the building envelope

Heat exchange in the building envelope occurs between its components and the indoor and outdoor environments. Thermal insulation is essential to minimize heat loss or gain, thereby maintaining temperatures close to those of the indoor air. A good insulating material must have low density to reduce thermal conduction and porous cells to limit thermal convection. Walls and roofs act as interfaces between the fluctuating exterior and interior comfort. Heat loss accounts for 25% for walls, 30% for roofs, 10-15% for doors and windows, 20% for air renewal, 7% for floors, and 5% for thermal bridges (Fig. 1). Thus, better insulation of walls and roofs can reduce the energy consumption of buildings by more than 60%.

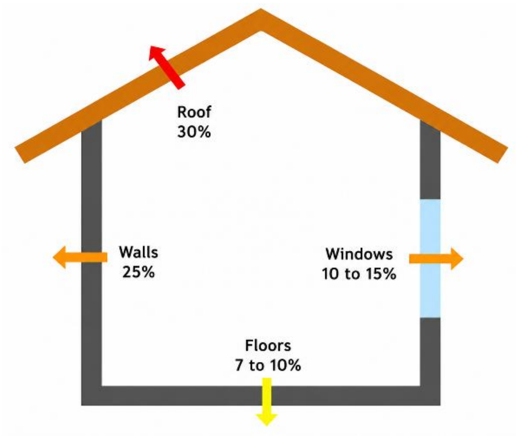

Fig 1: Distribution of heat loss through an envelope

Thermal insulation of walls can generally be achieved in three ways: interior insulation, insulation integrated into the load-bearing material, and exterior insulation.

3.1 Interior insulation

This insulation technique, which is simple to implement, consists of attaching the insulation (board, roll, foam) to the inside of the wall by stapling, gluing, or screwing. It is often the only option for renovating old buildings and restoring monuments, thus preserving their architectural quality. It costs less than exterior insulation and does not disturb the occupants. However, it reduces living space and creates thermal bridges that are difficult to deal with.

3.2 Insulation integrated into the load-bearing material

This type of insulation involves promoting new building materials that can be used both as insulation and as partially load-bearing materials, incorporating natural or artificial additives. These materials are generally used in new construction.

3.3 External insulation

Installing thermal insulation on the outside of walls is very effective in eliminating thermal bridges. In addition, the living space remains unchanged. However, this technique is costly and requires protection from the elements, so it is not suitable for older buildings and encroaches on public space, which is not always permitted.

4 Optimal thickness of thermal insulation

Determining the optimal and economical thickness of thermal insulation is now a key objective for international designers. Excessive thickness, even if it complies with standards, can have a negative impact on energy requirements, environmental impact, and economic analysis. In climates with mild winters and hot summers, excessive reduction of the thermal transmittance coefficient U can increase the energy demand for cooling, outweighing the savings in heating. In addition, an overly insulated envelope can make it difficult to evacuate excess heat at night in summer, negating the benefits of better insulation in winter.

"The optimal thicknesses of expanded polystyrene, polyurethane, and cork were determined based on a cost and life-cycle analysis, indicating that this thickness depends on the type of insulation material selected, the energy source used for heating and cooling, as well as the price of the insulation material (Fig. 2).

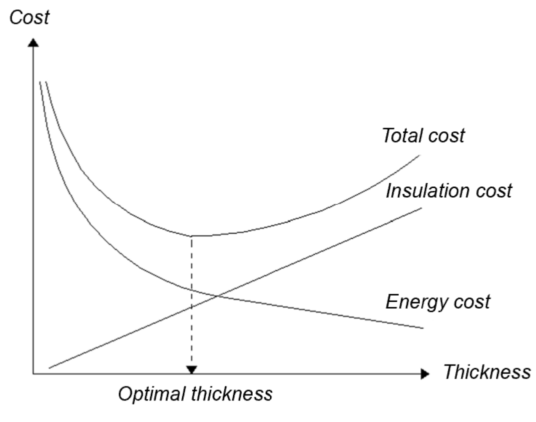

Fig 2: Optimization of Thermal Insulation Thickness

5 Thermal insulation materials

Thermal insulation in buildings mainly uses materials derived from petrochemicals, such as polystyrene, or natural sources in energy-intensive processes, such as glass wool and rock wool. These materials have negative environmental impacts due to the use of non-renewable resources and fossil fuel consumption. The concept of "sustainability" in construction has encouraged research into thermal insulation materials made from natural or recycled insulators. A summary of the thermophysical properties of various synthetic, natural, and recycled insulation materials will be presented in Figure 3.

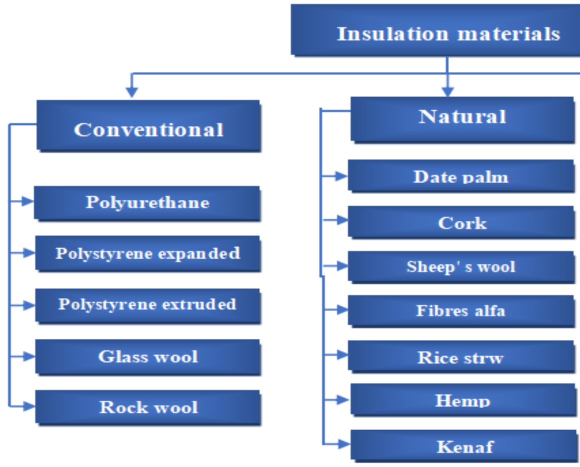

Fig. 3. Diagram showing the different conventional, natural, and recycled insulation materials.

6 Novel Insulation Materials

In place of traditional thermal insulation materials, various new insulation materials have been recently developed. These advanced insulation materials have been designed with the current context of global sustainability and reducing environmental impact in mind. New and advanced insulation materials are proving practical due to their thermal insulation qualities.

6.1 Aerogel

Hydrophobic phenolic/silica aerogel (Figure 4-a) composite materials (PSACs), prepared through autocatalytic sol-gel methods, show improved lightness and stability due to the co-condensation of resorcinol, formaldehyde, and APTES. PSACs show a high quality of thermal performance capability with a thermal conductivity of 0.021 $W.m^{-1}.K^{-1}$ and low density of only 0.10 $g.cm^{-3}$. When added to fiberglass paper, PSACs improve mechanical strengths and maintain high hydrophobic properties with a contact angle of approximately 138° [2].

6.2 Cellulose

Cellulose II aerogels (Figure 4-b) are obtained from date palm wood waste using a natural deep eutectic solvent and an EmimAc/DMF co-solvent. The aerogels have low densities (55-85 $kg.m^{-3}$) and low thermal conductivity values (0.038-0.074 $W.m^{-1}.K^{-1}$), which give them exceptional properties and classify them as the best-performing lightweight thermal insulation materials. The crystallinity and temperature resistance properties of cellulose have been validated by XRD, FTIR, SEM, and TGA analyses [3].

6.3 Wood fibers

Thermal conductivity data of around 0.055 $W.m^{-1}.K^{-1}$ were found in hybrid composites consisting of alpha fibers and wood. Both materials allow for simultaneous regulation of density and rigidity. The thermal content qualities denote the hybrid composite properties of both [4].

6.4 Rubber

Foamed concrete mixed with polypropylene fibers and rubber granules (FRPFC) (Figure 4-c) has a target density of 800 kg/m³ with reduced thermal conductivity: from 0.3608 to 0.2376 $W.m^{-1}.K^{-1}$ depending on the degree of sand substitution with rubber. The methodology consists of gradually substituting sand with rubber and analyzing its influence on mechanical and thermal properties through experimental testing and ANOVA [5].

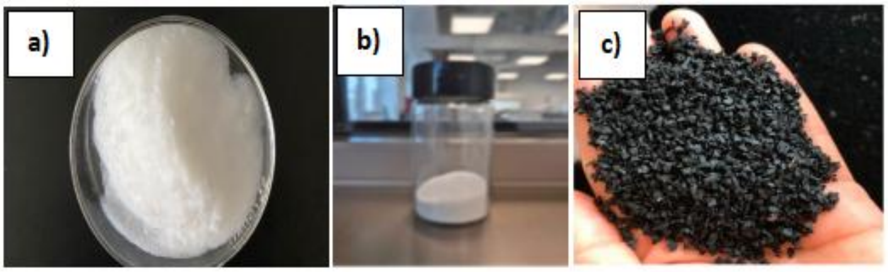

Fig. 4. a) Hydrophobic phenolic/silica aerogel, b) Pure cellulose, c) CR granules.

7 Natural materials

7.1 Sheep's wool

This study examines nonwoven insulation materials made from sheep's wool, optimized using the KONO-2 experimental method to evaluate the effects of fiber type, weight, and binder. Fine wool has low thermal conductivity 0.0216 $W.m^{-1}.K^{-1}$, with maximum performance for a 70% wool/30% bicomponent fiber blend at 250 $g.m^{-2}$, showing that density and weight directly control the thermal conductivity and stability of the material [6].

7.2 Cork

This study determines that the thermal transfer coefficient of a composite material based on clay and cork (Figure 5-a) is measured using the flash diffusion method and unidirectional heating plates. The use of cork makes it possible to obtain a material whose density varies considerably, from 1,261 $kg.m^{-3}$ to 620 $kg.m^{-3}$. Due to this reduction in density, the material has a significantly reduced thermal transfer coefficient, ranging from 0.356 to 0.130 $W.m^{-1}.K^{-1}$. Thus, a clay and cork-based composites material react effectively to reduce heat transfer [7].

7.3 Hemp

This research evaluates the thermal conductivity coefficients of hemp fiber-based (Figure 5-b) insulation materials with varying hemp/fiber ratios and bulk densities. The experiments were conducted using the TPS (Transient Plane Source) technique. The values range from

0.055 to 0.065 W.m⁻¹.K⁻¹ and depend on the density after compaction. Although higher than those of glass wool and polystyrene, these values allow identical R-values to be achieved while increasing the thickness [8].

7.4 Kenaf

Overall, their thermal conductivity ranges from 0.034 to 0.040 $W.m^{-1}.K^{-1}$ and plays a critical role in the thermal stability and insulation of composites. This characteristic is of particular interest in energy-intensive thermal resistance applications. Due to their excellent sound absorption properties, kenaf fibers (Figure 5-c) show promising potential as materials for sound insulation [9].

7.5 Fibres alfa

Composites made purely from "alpha" fibers (Figure 5-d) and treated using an alkaline treatment cycle have thermal conductivity values between 0.045 and 0.065 $W.m^{-1}.K^{-1}$. It should also be noted that their density is relatively low; therefore, these fuels are suitable for all applications where weight is a decisive factor. However, these fuels will be suitable for all relevant applications where the given factor is paramount [4]. The thermal conductivity of alfa-based composite varies between 0.071 and 0.111 $W.m^{-1}.K^{-1}$, and it also has a high volumetric heat capacity of 5.52×10^6 $J.m^{-3}.K^{-1}$. Its density varies between 92.78 and 196.98 $kg.m^{-3}$. The technique used involves the use of alpha fibers and a natural gum arabic matrix, which produces a porous material. The composite material is an efficient insulator with high thermal inertia, ideal for use in hot climates [10].

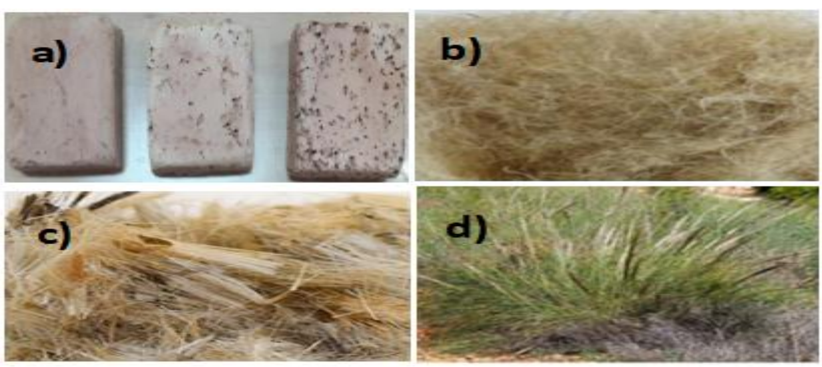

Fig. 5. a) clay-cork composites, b) hemp fiber, c) kenaf fibers, d) alfa (Stipa teacissim).

8 Recycled materials

8.1 Agricultural waste

1.1.1 Palm fibers

The composite that has the lowest thermal conductivity is the palm fiber (Figure 6-a) reinforced composite, with a thermal conductivity of 0.071 $W.m^{-1}.K^{-1}$. This composite, therefore, acts as the best insulator among the tested materials. The palm fiber-reinforced composite material also has a varying density of 92.78-196.98 $kg.m^{-3}$. This particular material is produced through the use of palm fibers, which are mixed with a gum arabic-based material. The material formation process is also optimized, hence the use of a forming and drying technique [10].

1.1.2 Pineapple Leaves

The density of composite sandwich panels (CSP) with a pineapple leaf fiber (PALF) (Figure 6-b) core varies between 210 and 303 kg/m^3. This depends on the thickness of the panels. The thermal conductivity values of CSPs with a PALF core of category M2 and panels covered with melina wood veneer vary between 0.19 and 0.25 $W.m^{-1}.K^{-1}$. This clearly highlights the potential of these panels for insulation. These panels were prepared with an M2-grade PALF core and covered with melina wood veneer. They were tested for density, water absorption, swelling, and other properties [11].

1.1.3 Bagasse

Insulating bagasse-type materials (Figure 6-c), produced using a fiber shaping process, offer low density, which helps improve thermal properties. Some specimens offer a minimum conductivity coefficient of 0.062 $W.m^{-1}.K^{-1}$ with a density of 0.26 $g.cm^{-3}$. These specimens effectively prove that reduced density correlates with better insulation properties. Thus, the manufacturing process is able to take full advantage of the low density of bagasse [12].

1.1.4 Coconuts

This new insulating material is made from a combination of coconut fibers (Figure 6-d) and sodium alginate. It has a thermal conductivity of 0.091 $W.m^{-1}.K^{-1}$. It has a relatively low density due to its porosity. This makes it lightweight, allowing it to serve as a good insulator. The manufacturing process requires increased amounts of water and binder to precisely improve its mechanical properties. This is preceded by research into its composition. The result is a new sustainable biocomposite that offers both thermal and acoustic insulation suitable for use in the building sector [13].

1.1.5 Fibres d'olivier

The thermal conductivity for the insulating material obtained from olive fibres (Figure 6-e) varies between 0.071 $W.m^{-1}.K^{-1}$ and 0.111 $W.m^{-1}.K^{-1}$. The density of the insulating material also lies within the range of the analysed data, fluctuating between 92.78 $kg.m^{-3}$ and 196.98 $kg.m^{-3}$. Insulation material fabrication can be carried out by using highly milled olive fibers suspended in a gum arabic compound that is dried afterwards. This method allows for the efficient use of agricultural by-products and results in a biodegradable insulation material [10].

Fig. 6. a) palm fiber, b) pineapple leaf fiber (PALF), c) bagasse, d) Coconut fibres after drying, e) olive fibres.

8.2 Industrial waste

8.2.1 Textiles

However, textile waste can potentially be a detour to ambient waste. To measure their specific insulating potential, it has been proposed to verify their thermal conductivity with a modified hot box apparatus. The results of this analysis show that the determining factor is the density of the panels. If textile waste is compressed to form a high-density panel, it is possible to achieve a conductivity of 0.065 to 0.067 $W.m^{-1}.K^{-1}$. However, low-density textile waste in the form of a composite of textile waste with a polyester matrix exhibits better thermal performance [14].

8.2.2 Plastic

Although these cases represent extreme conditions, there is a somewhat narrower range of values for the thermal conductivity of common isotropic polymers and more conventional engineering polymers: between 0.15 and 0.40 $W.m^{-1}.K^{-1}$ for PVC and HDPE, respectively. One report documented thermal conductivity measurements for a fairly wide selection of dense polyurethanes produced from conventional commercial forms of polyols and isocyanates. Their results indicated a fairly narrow range: (0.19 ± 0.03) $W.m^{-1}.K^{-1}$. This serves as a basis for comparison for the solid conduction part of a more detailed examination of potential new polyols and/or isocyanates for use in the production of polyurethane foam insulation with superior properties [15].

8.2.3 Glass

Cellular glass is a conventional insulating material with a thermal conductivity coefficient of 0.040 $W.m^{-1}.K^{-1}$. Its low density makes it a suitable choice for lightweight construction applications. This hard material has good stabilizing properties. However, it is much more delicate than plant-based compounds [4].

8.2.4 Summary of Thermophysical Properties of Insulation Materials

Table 1 summarizes the thermophysical properties of the cited insulation materials. Specific heat values for natural and recycled materials are scarce, while density and thermal conductivity data are widely available. Consequently, a detailed comparison of conventional, natural, and recycled materials' thermal performance is limited.

Among natural materials, the lowest thermal conductivity was measured for sheep wool (0.034 $W.m^{-1}.K^{-1}$) and pineapple leaves (0.035 $W.m^{-1}.K^{-1}$), with densities of 20 $kg.m^{-3}$ and 178 $kg.m^{-3}$, respectively. Pineapple leaf fibers deserve further study, as their low conductivity and high density suggest thermal performance comparable to rock wool if specific heat exceeds 1 $kJ.kg^{-1}.K^{-1}$. Wheat straw insulation has conductivity similar to conventional materials, but low density and specific heat reduce thermal diffusivity. Sheep wool, kenaf, and hemp exhibit similar density and conductivity to glass wool and rock wool, with higher specific heat (1.6 $kJ.kg^{-1}.K^{-1}$).

Insulation from textile waste, sugarcane bagasse, wheat, and rice straw is abundant and inexpensive, though less thermally efficient than pineapple leaves. Recycled materials generally outperform natural ones; recycled glass, for example, has thermal properties similar to rock wool, and recycled textile insulation is comparable to lightweight synthetic materials such as EPS and XPS.

Table 1: Comparative analysis of different thermal insulation materials.

Thermal insulation	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	Density ($kg.m^{-3}$)	References
Aerogel	0.021	100	[2]
Cellulose	0.038- 0.074	55- 85	[3]
Wood fiber	0,55- 0,038	-	[4]
Rubber	0,3608- 0,2376	800	[5]
Sheep's wool	0.0216	-	[6]
Cork	0,356- 0,130	1,261- 620	[7]
Hemp	0,055- 0,065	-	[8]
Kenaf	0,034 - 0,040	-	[9]
Palm fiber	0.071	92.78 - 196.98	[10]
Alfa	0,045- 0,065 0.071 - 0.111	- 92.78 - 196.98	[4 - 10]
Olive fibers	0.071 - 0.111	92.78 - 196.98	[10]
Pineapple Leaves	0,19- 0,25	210- 303	[11]

Bagasse	0,062	260	[12]
Coconuts	0,091	-	[13]
Plastic	0,15 - 0,40	-	[15]
Glass	0,40	-	[4]
Textile	0,065- 0,067	-	[14]

9 Criteria for choosing an effective insulator

Several thermal criteria must be taken into account when determining the most effective insulation material.

9.1 Hygrothermal criteria

Criteria related to behavior in response to humidity and heat.

9.1.1 Thermal resistance

Thermal resistance is the most important property for performance and energy savings. It is the ratio between thickness and thermal conductivity. The lower the conductivity, the more effective the insulation. It depends on the composition, structure, porosity, and water content, and varies with temperature. In general, the lower the density, the lower the conductivity.

9.1.2 Specific heat

A good insulator has a high specific heat, which increases the time required to absorb and transfer heat and improves indoor temperature stability.

9.1.3 Optimal thickness

Greater thickness improves comfort but can be disadvantageous in terms of cost, installation, and living space. Thickness is therefore a key indicator.

9.1.4 Reaction to moisture

Porous insulation materials exchange moisture depending on ambient conditions. Moisture increases thermal conductivity because water has a much higher conductivity than air. Crystallization at low temperatures can destroy the insulation. High moisture levels can cause corrosion, degradation, fungi, and mold, affecting the structure of the building and the health of its occupants.

9.2 Other criteria

9.2.1 Resistance to mechanical compression

Insulating floors, slabs, and underground structures subject to permanent loads requires insulation materials that are resistant to compression. This resistance depends on density. Low-density materials must be reinforced.

9.2.2 Fire resistance

For safety reasons, insulation materials must not be easily flammable. Insulation materials are classified as non-flammable, fire-retardant, or flammable depending on their reaction to fire.

9.2.3 Weather resistance

The material must be able to withstand prolonged exposure to outdoor conditions without significant loss of its thermal and mechanical properties.

9.2.4 Price

Price is a very important factor and varies depending on the market. The price of eco-friendly materials has fallen recently. Price comparisons depend on the unit chosen: volume, mass, or cost per square meter for a given resistance. Installation and maintenance costs must also be taken into account, as some cheaper insulation materials require more work and therefore incur higher costs.

10 Environmental impact

To assess the contribution of insulation materials to the environmental quality of a building, several impacts are taken into account: energy consumption, water consumption, air and water pollution, depletion of natural resources, solid waste production, etc. The selection of a thermal insulation material is generally summarized in Figure 7.

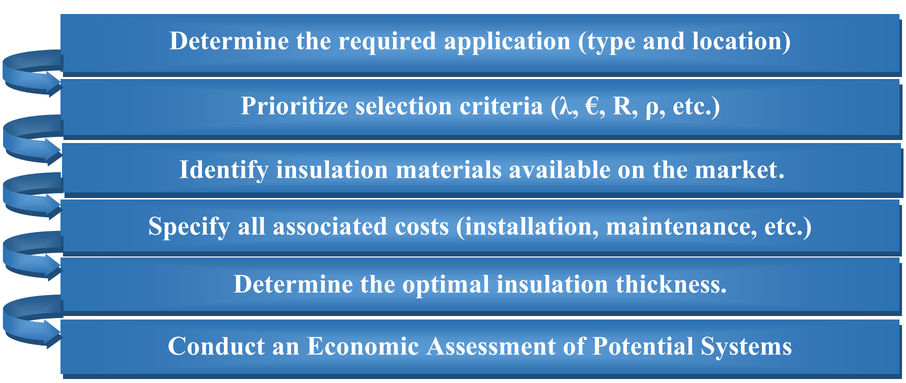

Fig. 7. Thermal insulation selection procedure.

11 Conclusion

In conclusion, an examination of various thermal insulation techniques shows that no single material can directly play a specific role in the energy efficiency of certain buildings. Due to their flexibility and moisture absorption properties, rubbers are exceptionally effective in ensuring the absolute sustainability of certain buildings. Aerogels, although refined, have exceptionally low thermal conductivity in all circumstances, to the extent that they can be used as the preferred choice when space is limited. They must, in fact, maximize the comfort value of certain premises. Fibrous insulators, which are reusable and environmentally friendly, can assist in stable thermoregulation in all circumstances while promoting sustainability. Finally, alfa glass, which is lightweight and fire-resistant, offers several advantages in improving the thermal quality of certain premises while reducing energy costs.

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