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A Parametric Analysis of Optimizing Cavity Wall Insulation in UK future homes

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Abstract: Due to the increasing urgency of climate change and the need for sustainable growth, governments worldwide, including the UK, are being pushed to implement rigorous energy efficiency standards in building maintenance and construction. Cavity wall insulation, or CWI, has gained a lot of attention in this context as a workable solution to lower energy expenses and improve thermal comfort in residential structures. Thus, this research explores how Cavity Wall Insulation (CWI) can improve energy efficiency and lower carbon emissions in buildings in the United Kingdom. It places special attention on how this technology might be applied to future housing and how it can help meet national climate change targets. It thoroughly assesses the thermal performance, economic viability, and environmental effects of a range of insulation materials, such as mineral wool, aerogel, expanded polystyrene (EPS), polyisocyanurate (PIR), and environmentally acceptable substitutes. Utilizing modern simulation tools such as TAS Manager, the research models numerous insulation situations, taking consideration of complicated variables such developing weather patterns, building geometry, and occupancy behaviours. Important technical issues are brought to light by the investigation, including moisture intrusion, thermal bridging, and the deterioration of insulating materials over time. Depending on the kind of building and the climate, results show that using Minitab analysis to optimize material selection and insulation thickness can lead to improvements in thermal performance of up to 25%, energy cost reductions of 15-20%, and a decrease in carbon emissions of 10-12%. Thus, in terms of insulation for sustainable construction practices, this work concludes that 250 mm of mineral wool and 250 mm of sheep wool are the best options available. These materials are perfect for environmentally responsible projects since they have low embodied carbon, good thermal performance and are reasonably priced.

Keywords: Climate Change, CO2 emissions, Building Regulations, U-value, Energy consumption, Heating demand, Energy Performance Asset Rating

1.Introduction

Governments everywhere, including the UK, are being forced to impose strict energy efficiency standards in building repair and construction due to the growing urgency of climate change and the need for sustainable growth. In this regard, cavity wall insulation, or CWI, has drawn a lot of attention as a practical way to save energy costs and enhance thermal comfort in residential buildings. The United Kingdom's aging building stock and aggressive carbon reduction targets make it necessary to investigate efficient insulation methods that will improve building thermal performance while lowering carbon emissions.

Cavity wall insulation is the process of using insulating materials, such as mineral wool, expanded polystyrene (EPS), aerogel, polyisocyanurate (PIR), and other environmentally friendly substitutes, to fill the spaces between a cavity wall's inner and outer layers. The thermal conductivity, cost, simplicity of installation, environmental impact, and long-term performance of these materials vary greatly. Therefore, choosing the right insulation material and figuring out how thick to make it are essential for optimizing energy savings and lowering expenses and environmental effect. The goal of this research is to present a thorough review of different insulation materials, looking at how well they work in various situations and environments.

The study models the CO2 emissions and energy consumption of buildings with various insulating materials and thicknesses using sophisticated simulation tools, particularly TAS Manager. The research aims to convey the complexity inherent in CWI applications by modeling real-world situations, such as changing weather patterns and various building geometries. Critical issues that can have a substantial impact on the performance and lifetime of insulation, including as thermal bridging, moisture control, and material degradation, are also addressed in this research.

Additionally, this research assesses the UK's current CWI laws and policies critically, pointing out any shortcomings and potential areas for development. The study takes look at the socioeconomic aspects that affect the uptake of insulating technology, including the effect of awareness and education campaigns, the intended purpose of government incentives, and the cost-benefit analysis for households. Through the integration of technical, economic, and policy perspectives, the study aims to offer a comprehensive comprehension of CWI's function in promoting sustainable building methods inside the United Kingdom.

Cavity Wall Insulation (CWI) and Climate Change in the UK

Significant impacts of climate change have been felt in the UK, including heatwaves that broke records, more rainfall, and severe flooding. For example, the winter of 2019–2020 was the wettest on record, while the summers of 2019 and 2020 were among the warmest on record, causing severe floods in areas like Yorkshire and the Midlands. There is a connection between rising global temperatures, increased atmospheric moisture, and greenhouse gas emissions and these extreme weather events. As a result, the UK government passed laws like the Climate Change Act and pledged to achieve net-zero carbon emissions by 2050. Improving climate resilience in public health, agriculture, and infrastructure is essential to lessening the effects of these severe and frequent calamities.

Challenges and Considerations in Implementing Cavity Wall Insulation (CWI) in UK Buildings

The objectives of cavity wall insulation (CWI) are to raise thermal comfort, lower carbon emissions, and increase energy efficiency in buildings. Its implementation, meanwhile, comes with a number of difficulties. It is necessary to evaluate the advantages of CWI objectively in light of various building kinds, operational settings, and design specifications. Important considerations are issues with moisture, the caliber of the installation, and the longevity of the insulation materials. Additional difficulties arise when retrofitting older buildings with CWI, such as fixing structural problems and making sure there is enough ventilation to avoid moisture buildup. Selecting the right materials and installing techniques are crucial to preventing long-term problems.

Complexities of CWI Effectiveness and Implementation in the UK

Complex elements like building layout, occupancy patterns, and weather fluctuations affect how successful CWI is. Theoretical advantages of CWI, such lower carbon emissions and heating expenses, might not necessarily translate into real-world results. To fully comprehend the true impact of CWI on energy savings and environmental advantages, empirical monitoring and assessment are essential. The performance of insulation is greatly influenced by variables such as thermal bridging, cavity diameter, and ventilation needs. In order to enhance the performance of CWI and prevent problems like condensation and moisture incursion, it is imperative that these variables be addressed.

Key Operational Variables

The following operational factors influence CWI effectiveness:

- Cavity Width: A measure of insulation performance and quantity.
- Ventilation requirements: necessary to keep interior air quality high and prevent moisture buildup.
- Thermal Bridging: May cause energy losses and lessen the efficiency of insulation.

It is essential to comprehend these factors and how they interact in order to apply CWI successfully. To get the best outcomes and minimize hazards, installation and maintenance require a thorough strategy that is adapted to the needs of the particular structure.

Comprehensive Appraisal and Regulatory Integration for Sustainable CWI

A thorough framework that consider upfront expenditures, ongoing expenses, long-term energy savings, and environmental advantages is required to properly appreciate the value of CWI. Given the urgency of climate change and the rise in energy costs, CWI offers a viable alternative. Evaluating and incorporating CWI properly into regulatory frameworks helps improve sustainability and guarantee that it reaches its full potential.

The Value Proposition of CWI

Investing in CWI is not just about the money right now. It entails future-proofing structures so they may continue to be ecologically and energy-efficient even in the face of changing circumstances. A better understanding of CWI's wider benefits enables stakeholders to make more informed choices.

Building Materials and Sustainability

A review of building materials available in the UK reveals a complicated web of regulations, standards, and environmental criteria. Comprehending these elements is essential to implementing CWI successfully.

Historical Development of Building Materials

The relevance of both old and new materials in contemporary construction methods is shown by tracing the progression of building materials in the UK from traditional craftsmanship to contemporary innovations. This historical viewpoint emphasizes how crucial it is to combine tried-and-true methods with cutting-edge innovations to increase productivity and sustainability.
The selection of insulation materials varies depending on temperature, humidity, and seasonal variations in different climate zones. All year long, insulation needs to function well in both hot and cold temperatures, respond to different moisture content, and deal with a variety of weather patterns. Insulation's main purpose is to lessen heat transmission, which is quantified by thermal resistance (R-value) and conductivity (lower conductivity and higher R-values signify superior performance). Durability and longevity are essential because robust materials minimize maintenance and replacement costs by maintaining performance over time. Another important factor to take into consideration is sustainability, which includes embodied energy (the total energy used in production and transportation), recyclability (the ability to reuse or recycle materials), and overall environmental impact (which includes resource depletion and carbon footprint).

Insulation Materials

Aerogel

Because of its remarkable thermal conductivity of 0.015 W/m·K, aerogel is a high-performance insulating material that works well even in thin layers. Its low weight makes handling and installation easier, and certain hydrophobic formulations keep out moisture to improve stability in hard-to-reach places. However, aerogel's utilization is limited, especially in large-scale projects, by its high cost and brittleness (Ramaswamy, 2021).

Polyisocyanurate (PIR)

With a thermal conductivity of 0.022 W/m·K, polyisocyanurate (PIR) insulation is among the high-performance alternatives with good resistance to heat flow and moisture intrusion, which is useful given the humid climate of the United Kingdom (Dileep et al., 2020). The closed-cell structure of PIR helps avoid moisture-related problems, preserving insulation efficacy and inhibiting the formation of mold. PIR insulation has disadvantages despite its advantages, such as being more expensive than materials like Mineral Wool and Expanded Polystyrene (EPS) and being more vulnerable to UV deterioration, which can lessen its efficacy and need the use of additional preventive measures. Because PIR can release harmful gasses in severe weather and has significant environmental effects during production, it also raises questions about fire safety.

Expanded Polystyrene (EPS)

Expanded Polystyrene (EPS) is a commonly used insulation material because it is inexpensive and simple to work with. EPS offers acceptable thermal performance with a thermal conductivity of 0.038 W/m·K, making it appropriate for a variety of insulation applications. Because of its lightweight design, installation is easier and labor expenses are lower. EPS, on the other hand, is combustible and can aid in the propagation of a fire by generating poisonous gases. Although they can reduce these dangers, fire retardants increase complexity and expense. In comparison to materials like aerogel and PIR, EPS likewise has a modest thermal performance. However, because it is not biodegradable and has a poor recycling rate, EPS has a considerable environmental impact. Additional preventive measures may be necessary as EPS may deteriorate over time due to physical damage and UV exposure (Olsø et al., 2024).

Extruded Polystyrene (XPS)

Extruded Polystyrene (XPS) is an excellent material for limiting heat transfer because of its excellent thermal performance and low thermal conductivity of 0.029 W/m·K. Because of its superior compressive strength and resistance to moisture, XPS is a good choice for demanding applications. Notwithstanding these advantages, XPS is more costly than EPS and its longevity may be shortened by UV deterioration. Furthermore, the manufacturing process of XPS releases strong greenhouse gases and adds to the pollution caused by plastics. XPS is still flammable even though it is less so than EPS, thus fire-resistant treatments are still necessary, which raises prices and complicates matters (Li et al., 2020; Ki et al., 2020; Lisienkova as al., 2022).

In conclusion, XPS and EPS both have significant disadvantages even if they both provide beneficial insulating qualities. While XPS offers superior performance at a greater cost and with environmental and UV degradation difficulties, EPS is more economical but has fire and environmental challenges. Making educated insulation decisions that strike a balance between performance, safety, and sustainability requires evaluating these variables.

Mineral Wool

Because of its exceptional fire resistance and sound insulation qualities, mineral wool—especially Rockwool—is the perfect material for applications where noise and safety are priorities. Its outstanding thermal performance improves comfort and energy efficiency. Its thermal conductivity is 0.035 W/m·K. But because of its denser nature, it requires more work and weight to install, and protective gear is necessary to avoid respiratory and skin problems. This can raise personnel costs and complexity, while the gains in safety and efficiency can outweigh the greater initial investment (Dickson et al., 2021; Adnan et al., 2021).

Phenolic Foam

Phenolic foam is very effective at regulating heat transmission and lowering energy expenses because of its exceptional thermal conductivity of 0.020 W/m·K. It is also fire resistant, however burning it might release harmful toxins that could be harmful to your health. Because of its fragility, the material can have greater lifecycle costs and make installation more difficult. Furthermore, the cost of phenolic foam can be a deterrent for projects with tight budgets. Because of this, using it necessitates weighing its excellent performance against factors including cost and safety (Jiang et al., 2023).

Sheep Wool

Sheep wool is an environmentally beneficial insulating material that regulates moisture better than other materials, reducing mold growth and preserving a cozy interior environment. It offers sufficient insulation with a thermal conductivity of 0.039 W/m·K, however it is not as effective as certain synthetic materials. Compared to synthetics, it is safer and easier to install, which lowers labor expenses and health risks. But because of its higher price and possible for insect problems, it needs to be treated and carefully considered. The cost and performance limits of sheep wool must be considered in relation to its advantages in terms of sustainability and convenience of installation (Hetimy et al., 2024; MASc et al., 2021).

Hempcrete

With a thermal conductivity of 0.060 W/m·K, hempcrete—a bio-composite made of hemp core and lime binder—is an impressively sustainable insulation material. It has good thermal mass and breathability, controlling humidity and temperature changes to avoid condensation and mildew. It is perfect for green building projects because of its many eco-friendly qualities, which include significant CO_2 absorption during growth and little pesticide use.

But because hempcrete doesn't perform as well as other materials when it comes to heat, thicker applications are required, which complicates design and raises expenses. Higher initial costs and the specialized construction procedure might also be a hurdle, especially for large-scale projects. Despite these difficulties, when properly planned and funded, hempcrete's sustainability and moisture management make it a desirable option for environmentally conscious construction (Essaghouri et al., 2023; Kore et al., 2021).

Optimal Insulation for UK Homes

For UK homes, combining aerogel with polyisocyanurate (PIR) provides an excellent option. Aerogel is a great thermal insulator that is low in heat conductivity, making it ideal for retrofitting and thin layer applications. PIR enhances this with its enhanced fire safety, moisture resistance, and affordability. By reducing energy consumption and carbon emissions, this combination improves total energy efficiency, complies with UK building rules, and promotes sustainable practices.

Building Energy Performance Simulation Tool

A building's usability, accuracy, and extensive simulation capabilities for thermal performance, ventilation, and daylighting are important considerations when selecting building energy performance simulation software, such as EDSL TAS Manager. The program should be affordable, compliant with local building codes, and have excellent user assistance and documentation. Software evaluation includes determining how easy it is to model, how well it performs analytically, and how well it may be optimized. Case studies and user reviews might offer further information to help you make a decision that is particular to your building design objectives.

2.Methodology

Using a quantitative methodology, this study explores how cavity wall insulation in future UK homes might be optimised for energy and thermal performance. The use of the Analytical Hierarchy Process (AHP), a multi-criteria decision-making framework, to systematically assess and rank insulating materials is at the heart of this investigation. Important factors are carefully evaluated, such as cost, convenience of installation, environmental impact, fire resistance, and thermal performance. A full review is ensured through the combination of sophisticated statistical analysis via Minitab and extensive thermal simulations through TAS Manager. This study seeks to provide practical insights and recommendations for optimal insulation techniques that match future sustainability goals and present regulations in the UK housing industry by concentrating on the best materials across a range of thicknesses.

Integrating TAS Manager and Minitab in Quantitative Methodology

When choosing EDSL TAS Manager for simulating building energy performance, one must consider factors such as ease of use, accuracy of results, and fit for a given simulation objective (such as energy consumption and thermal performance). It is critical to make sure the software is capable of accurately modeling scenarios, analyzing performance, and pinpointing areas that require optimization. Expert perspectives, case studies, and user reviews all contribute to the decision-making process. Minitab software is perfect for cavity wall insulation optimization because it provides strong statistical analysis, complex Design of Experiments (DOE), and efficient data presentation. Complete testing and scenario analysis are supported by its user-friendly interface and robust data storage features, which help choose the optimal insulation types and configurations for increased energy efficiency.

AHP METHOD

An organized method of decision-making for cavity wall insulation optimization in future UK homes is offered by the Analytical Hierarchy Process (AHP). AHP assists by decomposing difficult choices into elements that are easier to handle, like cost, ease of installation, fire resistance, thermal performance, and environmental impact. It incorporates both qualitative (e.g., installation simplicity, environmental sustainability) and quantitative (e.g., thermal conductivity, cost) criteria in pairwise comparisons to determine the relative relevance of each criterion. A consistency ratio is also included in AHP to

guarantee accurate findings.

Table 1 : Material evaluation depending on specific criteria

Material	Thermal performance (30%)	Environmental impact (25%)	cost (20%)	Fire resistance (15%)	Ease of installation (10%)	Total score
AEROGEL	10 (3.0)	7 (1.75)	5 (1.0)	10 (1.5)	6 (0.6)	8.7
PIR	9 (2.7)	6 (1.5)	7 (1.4)	8 (1.2)	8 (0.8)	8.4
PHENOLIC FOAM	9 (2.7)	6 (1.5)	7 (1.4)	9 (1.35)	7 (0.7)	8.2
MINERAL WOOL	8 (2.4)	8 (2.0)	6 (1.2)	10 (1.5)	5 (0.5)	8
SHEEP WOOL	8 (2.4)	10 (2.5)	5 (1.0)	6 (0.9)	10 (1.0)	7.8
HEMPCRETE	7 (2.1)	10 (2.5)	6 (1.2)	8 (1.2)	6 (0.6)	7.5
XPS	8 (2.4)	5 (1.25)	7 (1.4)	5 (0.75)	8 (0.8)	7.2
EPS	7 (2.1)	4 (1.0)	8 (1.6)	4 (0.6)	8 (0.8)	6.8

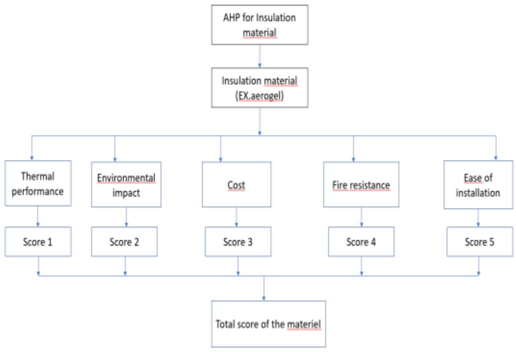

Figure 1 : Flow chart of AHP method

NOTE

After defining the total score of each material, the next step is selecting the top 5 materials (high scores).

Notes:

- Scores for each criterion are on a scale of 1 to 10.
- Weighted scores are in parentheses, calculated by multiplying the score by the weight of the criterion.
- Total score is the sum of the weighted scores for each material.

Optimal Thicknesses for Top Insulation Material

The best four thicknesses of the top five materials (Aerogel, PIR, Phenolic Foam, Mineral Wool, and Sheep Wool) based on the AHP approach will be taken into consideration in order to simulate the best materials in TAS Manager.

Table 2 : 4 different thicknesses for each material

Material	Thickness 1	Thickness 2	Thickness 3	Thickness 4
AEROGEL	40 mm	50 mm	60 mm	70 mm
PIR	25 mm	50 mm	75 mm	100 mm
PHENOLIC FOAM	50 mm	75 mm	100 mm	125 mm
MINERAL WOOL	100 mm	150 mm	200 mm	250 mm
SHEEP WOOL	100 mm	150 mm	200 mm	250 mm

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These references serve as a basis for the thicknesses chosen, guaranteeing that they are in line with what is widely accessible and employed in the sector to maximise thermal performance in cavity wall insulation.

Simulation steps in TAS MANAGER

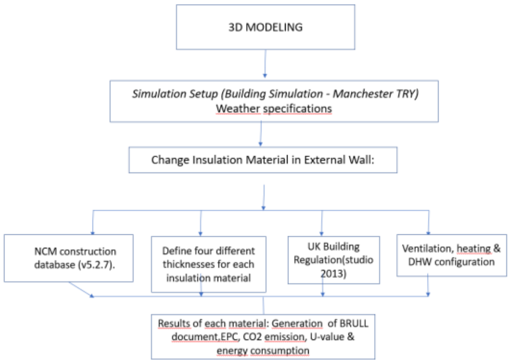

Figure 2: simulation flow chart

According to the statistics, aerogel provides the best insulation performance with the lowest U-value and consistently excellent Energy Performance Asset Ratings (EPR), even with its high initial CO2 emissions. PIR insulation performs well at first, but as it gets thicker, it uses less energy for heating and produces a lot of CO2. Sheep wool and mineral wool exhibit consistent performance across thicknesses while exhibiting little CO2 emissions and heating energy use. Similar balanced performance is provided by phenolic foam, however its CO2 emissions vary. In conclusion, Aerogel is the best option for energy efficiency and insulation performance because PIR has significant energy consumption and CO2 emissions while Aerogel performs exceptionally well in both areas.

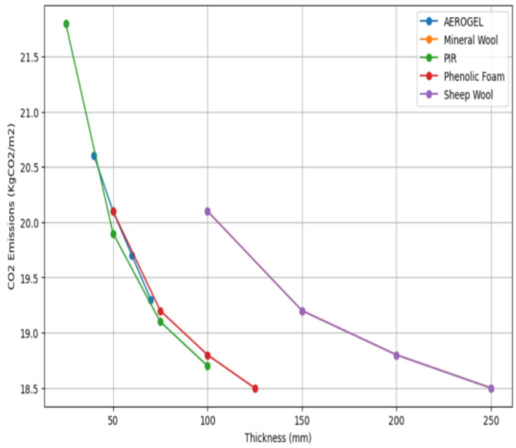

Figure 3: Material vs thickness

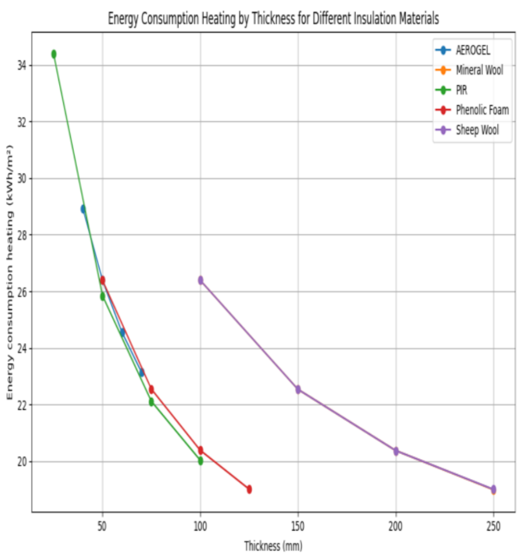

Figure 4: Thickness vs Energy consumption

Table 4: cost of each material

Material	thickness(mm)	cost(£/meter square)
AEROGEL	40	80
	50	96
	60	120
	70	144
PIR	25	8
	50	12
	75	16
	100	20
PHENOLIC FOAM	50	25
	75	35
	100	50
	125	60
Mineral wool	100	10
	125	12
	150	15
	200	20
SHEEP WOOL	100	25
	125	30
	150	35
	200	45

Summary of key findings

Aerogel at 70 mm has an EPR of 41, CO_2 emissions of 19.3 kgCO2/m², and heating energy usage of 23.14 kWh/m² for the best insulation performance. With 18.5 kgCO2/m² CO_2 emissions, 19 kWh/m² heating energy consumption, and an EPR of 40, Mineral Wool works best at 250 mm. With 18.7 kgCO2/m² CO_2 emissions, 62.35 kWh/m² heating energy consumption, and an EPR of 40, PIR insulation performs best at 100 mm. With 18.5 kgCO2/m² CO_2 emissions, 59.15 kWh/m² energy consumption, and an EPR of 40, Phenolic Foam performs quite well at 125 mm. With 18.5 kgCO2/m² CO_2 emissions, 19.01 kWh/m² heating energy consumption, and an EPR of 40, sheep wool at 250 mm also performs well.

Table 3 : Best thickness of each material

MATERIAL	BEST THICKNESS
Aerogel	70 mm
PIR	100 mm
Mineral wool	250 mm
Phenolic foam	125 mm
Sheep wool	250 mm

Cost

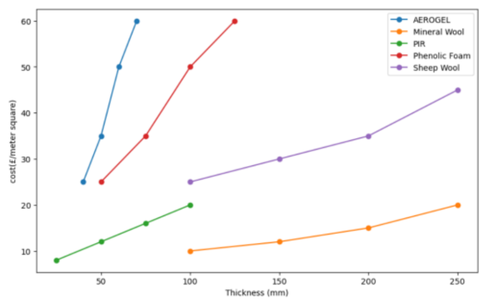

Figure 5 : Cost vs thickness of each material

The cost (£/m2) against thickness (mm) of several insulation materials is shown in the line graph. Aerogel is the most expensive alternative since it exhibits the steepest cost rise with thickness. For instance, at 50 mm, it costs roughly £20.1/m2, while at 200 mm, it costs £18.8/m2. The price declines for Sheep Wool and Mineral Wool are more mild; at 25 mm, Sheep Wool costs £21.8/m², while at 250 mm, Mineral Wool costs £18.5/m². At 50 mm, Mineral Wool costs £20.1/m². The pricing increases for PIR and Phenolic Foam are minor; PIR is approximately £20.1/m² at 50 mm and £18.8/m² at 100 mm, while Phenolic Foam is similarly priced between £20.1/m² at 100 mm and £18.8/m² at 200 mm. This analysis shows that although Aerogel provides better insulation, its high cost may prevent it from being used in some situations. In contrast, Mineral Wool and Sheep Wool are more affordable options for projects requiring thicker insulation.

Embodied carbon

Table 5 : Embodied carbon od each material depending on their optimum thickness

Total Surface Area of Building meter square: 187.7

Material	Optimum Thickness of Material (m)	Volume of Material Used (m_3)	Density of Material (kg/m_3)	Quantity (kg)	EC Coefficient /factor ($kgCO_2e/kg$)	EC Embodied Carbon
Aerogel	0.07	13.139	0.15	1.971	10	19.7085
Mineral wool	0.25	46.925	140	6569.500	1.5	9854.25
PIR	0.1	18.77	40	750.800	3.5	2627.8
Phenolic foam	0.125	23.4625	30	703.875	2.5	1759.6875
Sheep wool	0.25	46.925	18	844.650	0.1	84.465

Based on embodied carbon (EC) values, the table shows how insulation materials affect the environment. Aerogel performs well, yet despite its high EC value of 19,708.5 $kgCO_2e$ and EC coefficient of 10, it is environmental least friendly. With an EC coefficient of 1.5 and 9,854.25 $kgCO_2e$, Mineral Wool is more environmentally friendly. With EC coefficients of 2.5 and 3.5, respectively, PIR and Phenolic Foam have moderate embodied carbon values of 1,759.6875 $kgCO_2e$ and 2,627.8 $kgCO_2e$. With an EC coefficient of 0.1, an ideal thickness of 0.25 m, and an EC of only 84.465 $kgCO2_2e$, sheep wool is clearly the greenest choice. This study emphasizes the necessity of striking a balance between insulating performance and sustainability.

Best choice

Considering embodied carbon, performance, cost, and energy efficiency, Mineral Wool and Sheep Wool at 250 mm are the best choices for sustainable insulation, delivering low embodied carbon, good thermal performance, and cost-effectiveness. Despite having great thermal efficiency, aerogel at 70 mm has a high embodied carbon, which might reduce its benefits for sustainability. Because of its greater embodied carbon, PIR at 100 mm and Phenolic Foam at 125 mm are less suitable for environmentally friendly applications.

4. Conclusions

Concluding remarks:

This study emphasizes how important cavity wall insulation (CWI) is for raising energy efficiency and lowering carbon emissions in homes in the United Kingdom. Utilizing cutting-edge simulation methods and examining materials such as Mineral Wool, Aerogel, PIR, and EPS, the study emphasizes how crucial it is to choose the appropriate insulation type and thickness for both best performance and lowest cost. Important conclusions show that although certain materials have smaller carbon footprints and superior thermal efficiency, other important criteria include building design, the surrounding environment, and the caliber of the installation. According to the study, the best materials for sustainable building are Mineral Wool and Sheep Wool, both of which have a 250 mm thickness and combine good thermal efficiency, low embodied carbon, and affordability. Conversely, because of its high embodied carbon content, aerogel is less appropriate for environmentally friendly projects even though it has a higher thermal efficiency. Less advantageous are PIR and phenolic foam, which have greater environmental expenses. As a result, giving materials like mineral wool and sheep wool priority can greatly aid in achieving sustainable building objectives.

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