PROSPECTS FOR RECYCLING THERMAL INSULATION MATERIALS

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Abstract. This research aims to summarize and update the topic of recycling thermal insulation materials, exploring methods for their reuse and, when recycling is not possible, their disposal. The increasing amount of construction waste from demolished buildings, particularly thermal insulation materials, poses a challenge for the environment and human health. This challenge is especially evident in Ukraine, where the amount of construction waste from the war damage is growing daily. To reduce the impact on landfills, ecology, and to introduce a promising direction in the economy, it is necessary to implement measures for recycling and reusing such materials. The focus is on existing efficient recycling methods at the international level, disposal, and reuse of thermal insulation materials, as well as studying new technologies that could be adapted during the post-war reconstruction of Ukraine in the context of current environmental, economic, and technological challenges. The research includes the theoretical study of the physicochemical properties of materials for their use and recycling. In cases where recycling of certain materials is not feasible, methods for their energy recovery are considered. The research methodology involves a comprehensive evaluation of methods for determining their suitability for reuse, a comparative analysis of recycling technologies, combining theoretical, economic, and environmental approaches. The conclusions contain recommendations for implementing a more effective method of recycling thermal insulation materials in Ukraine, taking into account international experience and Ukrainian realities. This will contribute to the creation of sustainable models for managing construction waste, reducing negative environmental impacts, conserving resources, and enhancing the energy efficiency of reconstructed facilities.

Keywords: recycling; thermal insulation materials; reuse; construction waste; disposal.

Introduction

The current state of the construction industry and active military operations in Ukraine have led to a significant increase in construction waste. Separately, it is worth highlighting the materials used for insulation. In particular, expanded polystyrene, mineral wool, foam glass and polyurethane foam. Their recycling is critically important from the point of view of economy and ecology, as these materials are difficult to biodegrade, and overflowing of landfills with these materials leads to environmental pollution.

Thermal insulation materials are an integral part of construction. By reducing heating costs and improving the energy efficiency of buildings, we reduce carbon dioxide emissions into the atmosphere. The life cycle of thermal insulation materials, including production, use and disposal, has a significant impact on the environment. Most common insulation materials, such as expanded polystyrene (EPS), extruded polystyrene (XPS), mineral wool, polyurethane foam (PUR/PIR) and foam glass, are made from non- renewable resources and require significant energy consumption during production. Therefore, it is important to implement measures aimed at minimizing landfilling of construction waste and making the industry more flexible and able to meet closed-loop strategies.

A circular approach to the use of building materials helps reduce the environmental burden, save primary resources, and reduce the cost of producing new materials. In the context of Ukraine's post-war reconstruction, the issue of effective waste management of thermal insulation materials requires a comprehensive approach that takes into account both international experience and best practices, as well as local conditions and opportunities.

To effectively plan the systematic recycling of insulation materials, it is necessary to take into account many factors that determine the feasibility of recycling, as not every material is worth it. For example, the cost of recycling EPS is 200-300 euros per tonne, while the cost of the virgin material can be 1200-1500 euros per tonne.

Materials and methods

The aim of this research is to evaluate the properties of thermal insulation materials used in construction by analyzing the possibility of recycling or reuse. It involves studying practical data and comparing them with theoretical views.

Strategy and data collection

Data on thermal insulation materials were obtained from scientific articles and regulatory documents. The use of data from previous research provides the opportunity for theoretical analysis that will precede practical research.

Analysis methodology

Various data analysis methods were used for accurate evaluation of the collected data, including determining critical properties and comparing them according to key indicators. Comparative analyses were conducted in order to form a program of practical research based on the conclusions of previous theoretical studies.

Table 1 presents a comprehensive analysis of the main physical and technical characteristics of materials used for insulation, based on the results of scientific research published in peer-reviewed journals and monographs.

Table 1

Physical and technical properties of heaters [1-8]

Property	**Expanded polystyrene (EPS, XPS)**	**Polyurethane foam (PUR/PIR)**	**Mineral wool**	**Foam glass**
Materials of manufacture	Polystyrene resins	Polystyrene resins	Rocks	Finely crushed glass
Thermal conductivity, $W \cdot (m \cdot K)^{-1}$	0.032-0.040 (EPS); 0.028-0.034 (XPS)	0.022-0.028	0.035-0.050	0.045-0.060
Density, $kg \cdot m^{-3}$	15-35 (EPS); 25-45 (XPS)	30-60	30-180	100-165
Moisture absorption, %	1-4 (EPS); 0.2-0.5 (XPS)	1-3	1-1.5	< 0.5
Vapor permeability $mg \cdot (m \cdot h \cdot Pa)^{-1}$	0.013 - 0.05 (EPS); 0.005 - 0.013 (XPS)	0.05-0.15	0.3-0.5	0
Compressive strength, kPa	50-200 (EPS); 200-700 (XPS)	100-250	10-60	400-1600
Temperature range, °C	-50... + 75	-60… + 150	-60... + 600	-260... + 430
Fire resistance	G3-G4	G2-G4	NG	NG
Chemical resistance	Average (EPS); High (XPS)	High	High	Very high
Elasticity	Low (brittle under mechanical stress)	Medium (flexible, but depends on density)	High (fiber structure allows for easy deformation)	Very low
Resistance to UV radiation	Low	Low	High	Very high
Sound insulation, dB	25-35	30-45	45-60	35-45
Frost resistance, cycles	50-150 (EPS); 100-200 (XPS)	80-150	50-100	> 300
Hydrophobicity	Average (EPS); High (XPS)	High	Low	Very high
Durability, years	30-50	30-50	50 +	> 100

Table 2 shows the recyclability of the insulation materials that are the subject of this study. It shows the energy consumption for processing and possible emissions, the ability of these materials to decompose naturally, and their environmental impact. Methods of recycling and environmental safety during use are also summarized. It is worth noting that the results of the analysis show significant differences between insulation materials in terms of their environmental characteristics. Some materials have high energy consumption for processing and significant emissions of toxic gases during disposal, making them less attractive for use in terms of environmental friendliness. Others, on the contrary, have low emissions and high recyclability, which reduces their environmental impact. It is also worth considering environmental safety aspects during operation, as some insulation products can emit volatile organic compounds and dust, which can negatively affect human health during installation and operation.

Table 2

Comparison of heaters for recyclability [1; 4; 5; 9-14]:

Parameter	**Expanded polystyrene (EPS, XPS)**	**Polyurethane foam (PUR/PIR)**	**Mineral wool**	**Foam glass**
Recyclability	Can be recycled	Difficult to recycle	Can be recycled	Can be recycled
Energy consumption for processing, $MJ \cdot kg^{-1}$	Medium (35-50)	High (50-70)	Low (15-25)	Low (20-30)
Disposal emissions	High (toxic gases)	Very high (toxic gases)	Low	Very low
Biodegradability	Low, decomposes for hundreds of years)	Very low, practically non-degradable	Does not decompose naturally	Low
Environmental impact	High (contains styrene, releases toxins when burned)	High (may contain isocyanates that pollute the atmosphere)	Moderate (extraction of raw materials has an impact on the environment, but less toxic emissions)	Moderate (impacts the environment)
Secondary use	Possible (shredding reuse in production)	Almost impossible	High (can be used as a filler or bulk insulation)	High (fillers, building materials)
Environmental safety during use	Moderate (depends on additives, may emit volatile organic compounds)	Low (toxic substances are used in production)	High (safe when properly installed, but can produce dust)	Very high

Table 3 presents the main methods of recycling and disposal of popular types of insulation, including technical, thermal and chemical recycling, energy recovery, reuse and landfilling.

The selected recycling methods are applied to all types of insulation under study. The suitability of each of them for use and the consequences that will result from the use of the recycling method are determined.

An example of the suitability of the material for reuse is also given if its quality characteristics meet the requirements. Unfortunately, this is not always possible for use, due to the fact that a significant part of the materials in Ukraine are obtained from buildings damaged as a result of the war.

Innovative methods are described separately, which deserve attention and are only being developed, but have the prospect of development and implementation as alternatives.

The main advantage of alternative methods is their environmental friendliness and the possibility of a double effect of efficiency as a result of obtaining a resource from recycled thermal insulation materials.

Table 3

Methods of processing heat-insulating materials

Recycling/disposal methods	Expanded polystyrene (EPS, XPS)	Polyurethane foam (PUR/PIR)	Mineral wool	Foam glass
Mechanical processing	Crushing and reuse for production of new insulation boards or as aggregate [1; 15]	Crushing for use as secondary aggregate [11; 12]	Crushing and use as bulk insulation or aggregate [14; 15]	Grinding and use as aggregate in construction materials [3;5]
Thermal processing	Thermal depolymerization to produce styrene or pyrolysis to produce liquid fuels [12; 15]	Glycolysis, pyrolysis, or hydrolysis to decompose the original components [10; 13]	Not applicable due to non-flammability [9]	Remelting at high temperatures [5; 8]
Chemical processing	Dissolution in organic solvents for polymer recovery [9; 11]	Chemical depolymerization to produce polyols [11; 13]	Not applicable due to inorganic nature [14; 15]	Chemical processing for use as a raw material for production of silicates [8]
Energy utilization	Combustion with energy production (38-40 MJ·kg^{-1}), but with the formation of toxic gases [9; 12]	Combustion with energy production (26-32 MJ·kg^{-1}), but with high levels of toxic emissions [9; 11; 13]	Not suitable for energy utilization due to non-combustibility [9; 14]	Not suitable for energy utilization due to non-flammability [13]
Reusability	It is possible to reuse undamaged slabs in other construction projects [14; 15]	It is possible to reuse undamaged plates, but limited due to changes in properties over time [11]	Can be reused as a soundproofing material [14; 15]	Can be reused without processing due to its high durability [5; 8]
Burial	It takes up a large amount of space in landfills and does not decompose for hundreds of years [9; 12]	Virtually non-biodegradable, long- term negative impact on soil and groundwater [9; 13]	Inert material, decomposes very slowly, but has less impact on the environment [9; 15]	Inert, non-degradable material that has minimal environmental impact [8; 13]
Composting	Not biodegradable [12]	Not biodegradable [13]	Not biodegradable [14]	Not biodegradable [13]
Innovative methods	Methods of enzymatic decomposition using specific bacteria are being developed [12]	Experimental methods using fungal cultures for biodegradation [11; 13]	Studies of its use as an additive in cement and concrete [14; 15]	Use as a component for geopolymers and green building materials [8]

Results and discussion

It is worth noting that each of the presented thermal insulation materials has its own advantages and limitations that determine the optimal areas of their application: Expanded polystyrene (EPS, XPS) is optimal for use in conditions of limited budget and moderate mechanical loads. XPS is especially effective for thermal insulation of foundations and underground structures. Polyurethane foam

(PUR/PIR) is best suited for projects where the minimum thickness of the thermal insulation layer is critical with maximum thermal insulation efficiency. Mineral wool is the best choice for facilities with increased requirements for fire safety and sound insulation, as well as for thermal insulation of complex curved surfaces. It is advisable to use foam glass in structures with high mechanical loads, in conditions of high humidity, and for facilities with requirements for a long service life without reducing performance.

Based on the data presented in Table 2, foam glass appears to be the best thermal insulation material from an environmental point of view. This material has low energy consumption for processing, very low emissions from disposal, high recycling potential and very high environmental safety in use. Although its biodegradability is low, this disadvantage is compensated by the possibility of recycling and reuse. Mineral wool is in the second place, which also demonstrates good environmental performance, especially in terms of low energy consumption for processing and high recycling potential. Expanded polystyrene and polyurethane foam have worse environmental performance due to high disposal emissions, significant environmental impacts and recycling problems (especially in the case of polyurethane foam).

When analyzing recycling and disposal methods, foam glass proves to be the most environmentally acceptable material. It has wide possibilities for mechanical recycling, thermal recycling through melting, chemical recycling for the production of silicates, and reuse without processing due to its high durability. When disposed of, foam glass has a minimal impact on the environment due to its inertness. Mineral wool comes in second because it has good opportunities for mechanical recycling and reuse and is also inert when disposed of. Expanded polystyrene and polyurethane foam, although they have a variety of processing methods (mechanical, thermal, chemical, energy), pose significant environmental problems due to the formation of toxic gases during combustion and long-term negative impact on soil and groundwater during disposal.

Thus, we have come to the realization that thermal insulation materials should be chosen not only for their primary characteristics, but also for their full life cycle - from production to disposal and reuse. The future of insulation lies in materials that are not only efficient in use but also do not create an environmental debt at the end of their life cycle. Foam glass and mineral wool can become the basis for green building, while polymeric insulation requires innovations in safe disposal or biodegradation.

Conclusions

1. The study emphasizes the need to recycle thermal insulation materials as a critical aspect of the environmental sustainability of the construction industry. The growing volume of waste, including insulation, poses significant challenges for the environment, as most of it is low biodegradable and takes up large areas in landfills.
2. An analysis of different types of insulation materials has shown significant differences in their recycling and reuse capabilities. Foam glass has the best environmental performance, as it is characterized by low energy consumption for processing, high durability and minimal environmental impact. Mineral wool is also promising due to its recyclability and inertness during disposal. In contrast, polymeric insulation, such as expanded polystyrene and polyurethane foam, has proven to be more problematic due to toxic emissions from disposal and the complexity of their recycling.
3. Given the global trend toward closed-loop resource use, it is advisable to introduce modern technologies that will reduce the environmental footprint of the construction industry. In particular, mechanical and chemical recycling can significantly reduce waste, while innovative methods, such as enzymatic decomposition or the use of geopolymers, open up new prospects.
4. Mechanical recycling methods are suitable for all types of insulation, which is the most efficient and easiest method to implement, along with recycling. In turn, chemical and energy recycling methods are unfriendly and require significant energy inputs. Composting or landfilling is neither efficient nor environmentally friendly.
5. In the context of Ukraine’s post-war reconstruction, international experience in construction waste management should be taken into account and adapted to local realities. An integrated approach to the utilization of insulation will not only reduce the environmental burden, but will also contribute to increased efficiency of resource use and development of a circular economy.

Author contributions

Search for relevant literature and analysis of available sources - AK; Formulation of the research objective - AK; Formation of tables of material characteristics - ON; Analysis of key decisions and comparison - MS; Preparation of the list of references according to the template - ON; Writing the conclusion of the article - AK. All authors have read and agreed with the published version of the manuscript.

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